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DEVELOPMENT OF SPITS ON GRAVEL BEACH TYPE IN CHANGING STORMINESS AND SEA LEVEL CONDITIONS

Abstract

TLÜ KIRJASTUS
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Hannes Tõnisson

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Abstract

Institute of Mathematics and Natural Sciences, Tallinn University, Estonia.

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LIST OF PUBLICATIONS

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II. H. Tõnisson, K. Orviku, A. Kont, Ü. Suursaar, J. Jaagus, R. Rivis 2007. Gravel-pebble shores on Saaremaa Island, Estonia, and their relationships to formation conditions. – Journal of Coastal Research, SI 50 (Proceedings of the 9th International Coastal Symposium). Gold Coast, Australia, 810–815.

III. Ü. Suursaar, H. Tõnisson, T. Kullas, K. Orviku, A. Kont, R. Rivis, M. Otsmann 2005. A study of hydro-dynamic and coastal geomorphic processes in Küdema Bay, the Baltic Sea. – C. A. Brebbia, C. Cunha (eds.). Coastal Engineering VII. Southampton, Boston, WIT Press, 187–196.

IV. A. Kont, E. Endjärv, J. Jaagus, E. Lode, K. Orviku, U. Ratas, R. Rivis, Ü. Suursaar, H. Tõnisson 2007. Impact of climate change on Estonian coastal and inland wetlands – a summary with new results. – Boreal Environment Research, 12: 653–71.

Other publications in the relevant area:

V. H. Tõnisson 2004. Coastal formations of Koorunõmme and their forming processes. – E. Kadastik, J.-M. Punning (eds.). Geoecological Studies. Tallinn Pedagogical University, Institute of Ecology, Tallinn, Publications 8, 117–132 (In Estonian with English summary.)

VI. H. Tõnisson, K. Orviku, J. Jaagus, Ü. Suursaar, A. Kont, R. Rivis, U. Ratas 2006. Coastal Damages in Estonia Caused by Cyclone Gudrun. – A. Tubielewicz (ed). Coastal Dynamics, Gomorphology and Protection. "Littoral 2006" 8th International Conference "Coastal Innovations and Initiatives". Gdansk University of Technology, Gdansk, Poland, 2, 18–26.

VII. K. Orviku, J. Jaagus, A. Kont, U. Ratas, R. Rivis, H. Tõnisson 2005. Activation of coastal processes associated with climate change in Estonia. – A. Raukas (eds.). Yearbook of the Estonian Geographical Society. Tallinn: Estonian Encyclopaedia Publishers, 35, 75–100 (In Estonian with English summary.)

VIII. A. Kont, J. Jaagus, K. Orviku, U. Ratas, R. Rivis, H. Tõnisson, Ü. Suursaar 2004. Climate changes in Estonia during the second half of the 20th century and their impacts on increasing activity of coastal processes. – D. R. Green (ed). Proceedings of the 7th International Conference. Delivering Sustainable Coasts: Connecting Science and Policy. Aberdeen, Scotland, UK, 652–653.

IX. H. Tõnisson, R. Rivis, U. Ratas, A. Kont, K. Orviku 2005. Sediment transport and coastline changes in west Estonian archipelago. – J. Piechura, J. (ed). Proceeding of the 5th Baltic Sea Science Congress. The Baltic Sea changing ecosystem. Abstracts, Sopot, Poland, 156–157.

Author's contribution

Publication I: The author is principally responsible for the collection of fieldwork data at the coastal study sites in Saaremaa, data processing and analysis, interpretation of dependence of the measured changes in shoreline position and beach profiles morphology on storm-induced sea-level characteristics. He was also principally responsible for preparing the manuscript and most of the figures.

Publication II: The author is principally responsible for the collection of fieldwork data at the coastal study sites in Saaremaa, data processing and analysis on coastal processes and related storm data. He was also principally responsible for preparing the manuscript on the chapters containing information about coastal processes. He was responsible for preparing most of the figures.

Publication III: The author is principally responsible for the parts concerning shoreline changes and coastal processes. He also made the figures of the coast and participated in preparation of the manuscript.

Publication IV: The author is responsible for the parts concerning collection, analysis and interpretation of the data on changes in shoreline position and morphology of beach formations. He compiled part of the figures and participated in the preparation of the manuscript.

Publication V: The author is fully responsible for this publication.

Publication VI: The author is principally responsible for collection and analysis of the data on shoreline and shore profiles. He also made most of the figures and was principally responsible for preparing the manuscript of this publication.

Publication VII: The author was partly responsible for the parts concerning shoreline data collection and analysis (Harilaid study site). He also participated in preparation of the manuscript.

Publication VIII: The author was partly responsible for data collection and analysis about beach formations. He also participated in preparation of the manuscript.

Publication IX: The author was principally responsible for preparing manuscript for this publication.

PREFACE

This thesis presents the results of investigations on changes in shoreline position and contours of beach ridges on gravel beaches and their relationship to changing storminess and sea level conditions over the past fifty years on Saaremaa Island, Estonia. The thesis focuses particularly on analyzing quantitative characteristics. Of great importance is the refinement of the formats of the earlier data with new data collected by the author and the creation of GIS datasets and cartographic analysis. Considering the character of expected climate change for the nearest future, this new approach provides a solid basis for making decisions concerning coastal management.

The main objectives were 1) to investigate changes in shoreline and beach formations on selected gravel beaches; 2) to analyze the frequency of storm days and high sea level events in predefined sub-periods in order to ascertain robustly the trends over the last about 50 years; 3) to analyze the impact of a single exceptionally powerful storm on the development of selected gravel beaches; 4) to analyze and verify quantitatively the relationships between the characteristics of shore processes and storminess and high sea level events.

Four study areas with similar geomorphic structure but different exposure to the open sea were studied. Aerial photographs, orthophotos and topographic maps originating from different times and data obtained from direct observations were used to identify changes in shoreline positions and in contours of beach ridges. Detailed studies were carried out in the western part of Saaremaa Island: at study sites located at Koorunõmme, Küdema and Kelba. The Sõrve study site served to identify changes caused by Gudrun, an extremely strong storm in January 2005. The number of storm days and the values of the highest sea levels during each storm day were obtained from the storm database, and analyzed in relation to the main objectives of the current study. A quantitative parameter “critical sea level” was defined to determine the actual number of storms affecting the gravel shores. The time series of changes in the area of the beach ridges were related to storm and sea level data in order to analyze the expected increase in the velocity and magnitude of shore processes.

The analysis shows that the velocity of changes in area in the study sites has increased 2-8 fold. At the same time the number of storm days has increased 1.7 times. More importantly, the mean maximum annual sea levels during the storms have increased from 88 to 132 cm using the sub-periods of the current study. Significant erosion (making up approximately half of the cumulative changes) has been measured in the proximal parts of the spits.

These results show that more frequent storms with high sea level do not allow enough time for the beach ridges to restore their profiles during the periods between storms. Therefore, each new storm affects the already vulnerable beach profile and enhances erosion. Such an increase in sea levels during the storms causes the erosional area to encroach landward with each successive strong storm and the older beach formations, particularly those well exposed to the open sea, are subject to erosion in the areas of previous drift. In general, it can be concluded that isostatic land uplift has been overshadowed by land subsidence as a result of more frequent high sea level events.

The results of the thesis can be used as a basis for determining the hydrodynamic conditions of extreme events over the last half century (by comparing similar beach formations from the past and present) and for predicting changes in the morphology of gravel beaches in the future with respect to changes in storminess and sea level conditions. Additionally, Estonia is situated at the latitudes of the greatest winter warming. This study serves as an etalon with which to analyze possible changes in similar types of coasts resulting from global temperature and concurrent sea level rise.

1. INTRODUCTION

1.1. ESTONIAN COASTS AND CLIMATIC CHANGE

Estonia is a relatively small country (approximately 45,000 km^2), but is rich in different types of landscapes and ecosystems. 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.

Estonia has a comparatively long shoreline (approximately 3,800 km) due to numerous peninsulas, bays and islands (over 1,500 islands). The coast is geologically rather diverse and serves a variety of societal functions. The Estonian seacoast in general is characterized by its embayed nature with a variety of beach types experiencing land uplift ranging from 0.5 to 2.8 mm/year (Vallner *et al.*, 1988). Accumulative coastal landforms, such as spits, beach ridges and tombolos, develop by a variety of means at different locations (Orviku, 1974). Most depositional shores are very dynamic and change quickly under the impact of changing climatic conditions.

Global temperatures have increased an average of 0.6±0.2°C since the beginning of the 20th century (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). The decrease in the duration of snow cover in Estonia and ice cover in the Baltic Sea (Haapala & Leppäranta, 1997; Jevrejeva, 2000; Jaagus, 2006a) is also a clear consequence of the higher mean air temperature in northern Europe.

Estonia lies within the region where the most significant increase in air temperature has been observed over the last decades (IPCC, 2001). The annual mean air temperature in Estonia has increased by 1.0–1.7°C during the second half of the 20th century (Jaagus, 2006b). A statistically significant increase in monthly mean temperature is present only during the period from January to May with the greatest increase in March. The rest of the year has seen little change in annual mean air temperature (Jaagus, 2006a).

The duration of sea ice has decreased significantly during the second half of the 20th century (Jevrejeva, 2000; Jaagus, 2006a). Over this period, the date of ice appearance has been rather constant, but the date of disappearance has become earlier (IV, Fig. 3). The maximum extent of sea ice in the Baltic Sea has decreased by approximately 50,000 km^2 according to linear trend during the second half of the 20th century. In general, the end of winter and start of spring occur much earlier than before.

Changes in atmospheric circulation over Estonia have taken place during the last decades (Rajasalu & Keevallik, 2001; Tomingas, 2002; Jaagus, 2006b). The most important trend detected is a significant increase in the intensity of zonal circulation, i.e. westerlies in winter. Parameters of meridional circulation show an increase in southerly airflow and decrease in northerly airflow in March and October.

1.2. CYCLONIC ACTIVITY IN NORTHERN EUROPE

A significant increase in cyclonic activity over the North Atlantic has been observed during the second half of the 20th century (Gulev *et al*., 2002; Sepp *et al*., 2005; Schmidt *et al*., 1998). As a result, there has been an increase in storminess in the NE Atlantic and NW Europe (Alexandersson *et al*., 1998; Paciorek *et al*., 2002; Pryor *et al*., 2003), and trends towards higher storm surge levels have recently been reported for various locations of northern Europe (Langenberg *et al*., 1999; Lowe *et al*., 2001; Johansson *et al*., 2003, 2004; Meier *et al*., 2004; Jylhä *et al*., 2004), including Estonia (Jaagus *et al*., 2004; Orviku *et al*., 2003; Suursaar *et al*., 2006b). Hurricanes and strong storms consist of large wind fields driven by pressure gradients from a central low pressure system and temperature gradients in the atmosphere. The winds create storm surges by pressing seawater against the eastern coast of the Baltic Sea. The destructiveness of a storm surge depends on its magnitude, duration, and associated wind driven waves.

This has lead scientists to foresee vitalization of coastal geomorphic processes and changes in existing equilibrium of coastal development due to anticipated rises in sea level and increasing storminess (e.g. Kont *et al*., 2003; Suursaar *et al*., 2004). Therefore, understanding how coastal processes are affected by changing meteorological forces and the occurrence of occasional cyclones and storm surges is of great importance.

1.3. IMPACT OF CLIMATE CHANGE ON SEASHORES

The effects of climate change on seashores are expressed in:

- more frequent storms (disturbing the natural development of shores);
- higher sea levels during storm surges (reaching older beach formations);
- reduced ice cover (unfrozen sediments and coastal sea).

The changes in sea level regime include global, regional and local mechanisms. Firstly, the induced global sea level rise rate is estimated to be 1.5±0.5 mm/yr (Church *et al*., 2001; IPCC, 2001). The latest studies suggest a sea level rise of about 10–50 cm during the next century (Church *et al*., 2001; Dawson, 2004).

Regional sea level trends usually deviate from the global trend, primarily due to isostatic movements of the Earth's crust. Thus, while a clear regression of the shoreline is still evident in Finland (Johansson *et al*., 2004), the current global sea level rise is more or less compensated by land uplift in western Estonia.

There is, however, an additional local sea level change component caused by variations in the water balance of semi-enclosed marine areas as a result of regional changes in wind regime (Suursaar *et al*., 2006a). Hydrodynamic model simulations (Suursaar *et al*., 2003; 2006a) identified a mean sea level rise in some windward bays of the Gulf of Riga by 5–6 cm under a simulated average wind speed increase of 1–2 m/s. The rise could be as high as between 9–11 cm under conditions of greater variability. An increase in mean wind speed by only 2 m/s above the present day average (6.5 m/s) roughly doubles the annual amount of hydrodynamically-induced bottom stresses in Estonia's coasts (Suursaar *et al*., 2006b).

Increased storminess together with increased frequency of mild winters and higher storm surge level has an indisputable impact on the intensification of shore processes and the dynamics of coastal geomorphology. The presence of sea ice tends to retard the surface movement of water and also to protect the shoreline from the erosive effects of waves. Conversely, a decrease in sea ice duration or the absence of ice cover altogether enables water to "pile up" as a result of storm wind stress and exposes the shores to wave action.

Extensive erosion and alteration of depositional coasts, such as sandy beaches, have been observed over the last decades. Increasing growth rates of accumulative gravel spits have been observed in Saaremaa and many other places (Orviku, 1992; 2006a; 2006b; Rivis, 2004). The lack of evidence for a substantial mean sea level rise during this period suggests that beach erosion is largely due to recent increased storminess in the eastern portion of the Baltic Sea (Orviku, 1992; Orviku *et al*., 2003). The greatest alteration potential on Estonian coasts occurs on depositional coasts that are well exposed to waves. The most marked coastal changes in Estonia result from a combination of strong storms, high sea-levels induced by storm surges, ice free seas and unfrozen shore sediments, all of which enhance erosion and transport of sediments inland the mean shoreline.

1.4. SHORE PROCESSES

Shores can be classified by age into two types: ancient shores and contemporary shores. Contemporary shores are subdivided by activity of coastal processes into active shores and passive (dynamically "dead") shores (Orviku, 1993). On active shores, the shore platform is narrow and the wave breaker zone lies near the shoreline. Active shores are influenced by a variety of shore processes. Non-active shores are characterized by a low and wide shore platform and waves break far from the shoreline. The main shore processes on passive shores are inundation by high sea-level events and their associated weak waves. Active shores occur either as advancing (accumulation or deposition) or retreating (erosion) shores. The current thesis addresses only active shores.

Wind-generated waves serve as important energy-transfer agents whose energy can act as the primary cause of erosion or may generate a variety of near-shore currents and sediment transport patterns (Komar, 1998). Breaking waves are the main force for shoreline modification (Davis and FitzGerald, 2004). Wave energy is influenced by the fetch, velocity and duration of winds (Bird, 2000). The activity of coastal processes and storm impact also depend on coastal geomorphology (near-shore topography, sediments, shoreline configuration etc.) and exposure to waves (Dean & Dalrymple, 2002). Coastal formations and 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 play an important role in shore processes on the coasts of the nearly tideless Baltic Sea. It is worth noting that storm surges in Estonia are caused by storms with higher velocity winds (i.e., wind speeds in excess of 20 m/s) blowing from the southwest, west, or northwest. Very strong easterlies result in low sea level events, also known as "negative surges", which have no significant geomorphic effects. The highest sea levels recorded in Estonia have always occurred during storms with westerly winds.

An increase in the frequency of storms in coastal waters may result in the erosion of beaches that have been previously stable or even advancing. A series of storms over a short time period is particularly destructive because the subsequent events occur on beaches already reduced to a vulnerable concave eroded profile (Zenkovich, 1967).

1.5. OBJECTIVES

The main aim of this thesis is to analyze shore processes and their relationships to changes in storminess and higher storm surge levels. The objectives are:

- to investigate the changes in shoreline and beach formations on selected spits of gravel beaches during the last 50 years;
- to analyze the occurrence frequency of storm days and high sea level events over the last 50 years;

- to determine and analyze the impact of a single exceptionally powerful storm (Gudrun) on the development of selected spits on gravel beaches with different exposure to the open sea;
- to prove and analyze quantitatively the relationships between the characteristics of shore processes and storminess and high sea level events at four different locations.

Hypothesis:
The velocity of shore processes on gravel beaches in Estonia has increased during the last 50 years, which is partly caused by the increased storminess, but mainly by more frequent and higher storm surges.

2. STUDY SITES

Coastal topography, sedimentary rocks, unconsolidated deposits and offshore hydrology have resulted in the formation of a diverse range of shore types in Estonia. Orviku (1992) distinguished seven major shore types based on geology, the slope of the primary relief, and prevailing shore processes: till shore (35% of the total length of the Estonia's shoreline), silty shore (30%), sandy shore (16%), gravel shore (11%), cliff and rocky shore (5%), artificial shore (2%) and scarp shore (approximately 1%). Each shore type responds differently to wave activity and other influencing factors. Till and silty shores are very common in Estonia but dynamically inactive. All the other shore types are usually active. Gravel beaches are often dependent on sediments eroded from cliffs. The development of sandy beaches is often dependent on the dynamics of scarp shores.

Four different study sites – Koorunõmme, Küdema, Kelba and Sõrve – were examined in the current study. All the study sites are located on Saaremaa Island (2,671 km^2), the largest island of the west Estonian archipelago. The main geomorphic features of the coasts in Saaremaa reflect the preglacial relief, the last glacial phase and postglacial isostatic land uplift. The main shore types in northern part of Saaremaa are rocky shores at the tops of peninsulas, accumulative gravel beaches on the sides of peninsulas, and sandy beaches found at the ends of the bays (Orviku, 1974; 1993).

The study sites were selected for two main reasons. Firstly, they are all spits on gravel beach type, but each has a different exposure to the open sea and different geological history. Secondly, the coast was a restricted zone during the Soviet period and coastal geologists had very limited access to only a few sites. All the study sites used in the current research were already monitored during the Soviet period thereby providing the longest possible dataset on shore dynamics.

Koorunõmme

Koorunõmme study site is located on Ninase Peninsula, the eastern coast of Tagalaht Bay in NW Saaremaa (Fig. 1). The study site is 0.9 km long and 0.3 km wide, with a north-south orientation, and is characterized by gravel beach and fronting shallow sea. The site is exposed to the Baltic Sea proper to the north and northwest. The deepest point in the bay (27 m) is located 3.5 km northwest of the study site. A 2-m isobath is located 100 m offshore on the fronted steep slope of the limestone bench (V). The bedrock in Koorunõmme consists of Lower Silurian limestone of Jaagarahu Stage (Perens, 2002).

The gravel beach consists of material that has been eroded by continuous wave activity from the limestone bench between the fronting steep slope and the backing shoreline. The crests of the beach ridges extend 1–2 m above sea level. Previous studies indicate that all the sediment in the beach ridges have eroded from the fronting limestone bench. Abula cliff is further inland behind the gravel beach and beach ridges to the north are separated by a small cove (Tõnisson, 2004). The sediment deficit due to the limited abrasion area inhibits the development of the beach ridges and the spit.

The development of the Koorunõmme gravel beach can be divided into phases. During the first phase ("infant phase") the eroded material from the limestone bench was deposited onto the bedrock knolls that were pushed above sea level in the 18th and 19th centuries (Tõnisson, 2004). Deposited material initially formed U-shaped beach ridges around these bedrock knolls. U-shaped beach ridges were connected during the next phase as a result of continuous accumulation, longshore drift and land uplift. Nowadays the northern and central parts of the study site consist of a complex of beach ridges (up to 2.3 m a.s.l.) formed as a result of dominating onshore and supporting longshore drift. The sediment particles are angular because of dominant short distance cross-shore transport. The southern part of the site ends with a 180-m long spit produced by the dominating longshore drift of the sediment from the northern and central part of the study site. The sediment particles on the spit are smaller and more rounded than in the central and northern part of the study site.

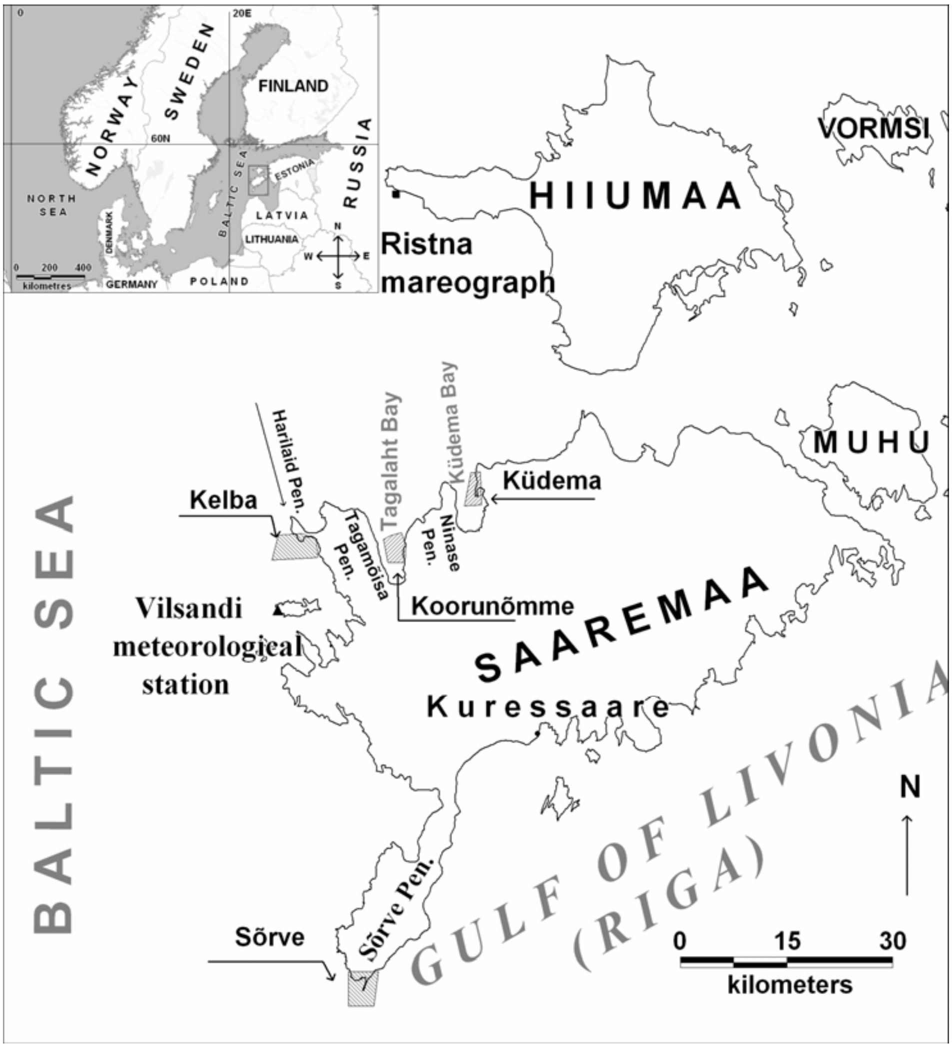

Figure 1. Location of study sites, Vilsandi meteorological station and Ristna mareograph.

Küdema

Küdema study site is situated on the eastern coast of Küdema Bay (Fig. 1). A complex accumulative coastal formation (a spit nearly 3 km long, 0.5 km wide and up to 3.5 meter high) is the principal evolving relief structure the formation and development of which depend greatly on the erosion of Panga Cliff to the north (Orviku, 1992). The cliff is well exposed to the Baltic Sea proper to the west, northwest and north. Küdema Bay is relatively deep near the shoreline, reaching 22 m about 1 km west of the Panga Cliff. A 15-m isobath is located about 100 m from the eastern coast of the bay, at the foot of the submerged cliff. On the top of the submerged cliff the sea is 2–3 m deep and becomes gently shallower approaching the shoreline. The coastal sea in front of the Küdema spit is relatively shallower compared to the sea in front of the Panga Cliff. The 10-m isobath is approximately 200–250 m from the shoreline, and is located at the foot of the submerged cliff. The 2-m isobath is about 200 m from the shoreline on the top of the submerged cliff bordering the limestone bench.

Panga Cliff (up to 21.3 m high) begins north-west of Panga village with rapidly increasing dimensions. The length of the Panga Cliff is approximately 2.5 km and it is the highest cliff on the northern coast of Saaremaa and Muhu Island. The highest elevation of the cliff is a few hundred meters south of its northwestern most point (Klaamann, 1959). The Panga Cliff is a typical Silurian cliff (Aaloe & Miidel, 1967) emerging right on the shore. The waves reach the foot of the cliff during high sea level.

The Küdema spit has formed as a result of two main coastal processes – sediment transport and connecting former islands. Some earlier studies (Orviku, 1974; Tõnisson, 2004) indicate that there were initially several small islands in the current location of the spit. The small islands grew larger and higher in elevation as a result of land uplift and onshore transport of sediment. U-shaped beach ridges can be found behind the younger ridges containing angular sediment particles. Those U-shaped beach ridges mark the positions of former islands. Massive amounts of sediments drifting along the shore from the Panga cliff to the south initiated the southward growth of the Küdema spit. The shallow sea between the former islands has been gradually filled as a result of continuous longshore transport of sediment eroded mainly from the cliff. The much more rounded and smaller sized sediment of the younger (seaward) beach ridges also prove that most of the sediment was transported from longer distances. It can be concluded that nowadays the longshore drift of the sediment is dominant and onshore drift plays only a marginal role in the development of the Küdema spit.

Kelba

Kelba study site is situated in the southern part of Harilaid Peninsula (Fig. 1). Harilaid is a smaller trapeze-shaped peninsula with a northwest-southeast orientation and joined to the much larger Tagamõisa Peninsula by a narrow tombolo. The bedrock consists of Lower Silurian marl of Jaani Stage (Raukas *et al*., 1994). The primary landform of the peninsula is a northwest-southeast trending glaciofluvial ridge. The portion of the ridge subject to wave activity has been affected by land uplift. Erosion by waves has changed the shape of the submarine portion of the emerging ridge.

Deeper waters (over 10 m) lie west of the study site. The near-shore bottom is strongly inclined, and the 2-m isobath is only a few meters from the shoreline (Tõnisson, 2004). The study site is exposed to the Baltic Sea proper to the SW, W and NW. The Kelba study site consists of a series of beach ridges forming an approximately 1-km long spit. The spit consists mainly of well-rounded crystalline gravel, pebble, cobble and even some boulders (at the foot of the beach ridges) and the beach ridges within it form distinct increments of different age. The heights of the crests of the beach ridges are usually less than 2 m a.s.l., and a few higher crests attain 2.5 m. The highest crests of the beach ridges on the root of the spit are up to 3.8 meters a.s.l. There are lagoons and small lakes behind the spit (VI; VII).

The general developmental trend of the Kelba spit over about the last hundred years has been the continuous accumulation of new beach ridges elongating the spit in its distal direction. Most of the material deposited on new ridges is probably loose eroded Quaternary sediments full of crystalline particles from the submarine shoals southwest of Harilaid that have been transported by westerly and particularly northwesterly storm surges. An earlier study (Orviku, 1974) shows that the deposits forming the beach ridges in Kelba are initially derived from the shoals near the shore.

Sõrve

Sõrve study site is located at the southernmost point of the Sõrve Peninsula, SW Saaremaa (Fig. 1). The area consists of beach ridges consisting mainly of gravel, pebble and cobble continuing to the south and southwest in the form of islets (Vesitükimaa, Siiasaar, Lombimaa) of similar composition and origin emerging above an extensive and narrow submarine ridge called Pikasääremaa (II, Fig. 7a). The islets change shape due to storm wave activity from different directions.

The Sõrve study site is one of the most exposed shores to the open sea in Estonia and subject to the strongest winds (Kull, 1996). The hydrological conditions influencing shore dynamics at this location are very different from the other study sites due to its open exposure to both the Baltic Sea proper and the Gulf of Livonia. The shores in Sõrve are shaped by storm wave activity from the W, SW, S, SE and E. Deeper waters lie east of the Sõrve study site. A 5-m isobath is located approximately 500 meters SE from the shore. The sea is much shallower (5-m isobath over 3 km from the shoreline) in the western part of the study site.

Earlier investigations show that the deposits of the beach ridges forming Cape Sõrve are derived from an extensive meridional submarine ridge, a part of the glacial marginal formation (Orviku, 1934) as a result of erosion, longshore sediment transport from south to north and accumulation to the beach ridges on the islets and cape.

3. METHODS AND DATA

3.1. TERMINOLOGY

The terminology used in this thesis is that according to Kaarel Orviku (Orviku, 1974; 1992; 1993; and Orviku *et al.*, 2003) and the Encyclopedia of Coastal Science (Schwartz, 2006). Some specific terms, such as “critical sea level”, are introduced by author.

Accretion – A gradual or intermittent natural process of deposition of sediment by wind, wave or current action, resulting in the natural raising or extension of land area on the shore.

Beach – An accumulation on the shore of generally loose, unconsolidated sediment, ranging in size from very fine sand up to pebbles, cobbles and occasionally boulders.

Beach ridge – Ridge of beach material piled up above high sea level by swash action.

Bedrock knoll – small elevated area in the bedrock.

Bench – A wave cut flat or gently sloping rock ledge, terrace or platform, typically 5–50 m wide, but sometimes much wider, backed and fronted by steep slopes.

Cliff – A steep coastal slope cut into rock formations, produced by basal wave erosion (undercutting), but occasionally by faulting or earlier fluvial or glacial erosion.

Critical sea level – sea level (in the current study according to Ristna mareograph) affording waves to the levels of finer-grained sediments (mostly gravel and pebble) on the beach ridges (in case of gravel beaches) to reshape this part of the ridges.

Coast – The whole zone between the highest and the lowest shorelines related to sea-level changes during the Quaternary.

Cross-shore sediment transport (drift) – The movement of beach sediment cross the shore by waves arriving perpendicular to the shoreline and by swash generated by such waves.

Fetch – The distance of open water across which the wind generates waves approaching a coastline from a particular direction.

Finer-grained sediments – The size of sediment grains mainly varies from gravel to pebble (for the current study).

Gravel beach type – Gravel beach is a term that includes shingle beach and mixed beach. Various investigators refer to gravelly beach material as having a median diameter between 5 and 75 mm and shingle larger than 2mm.

Longshore sediment transport (drift) – The movement of beach sediments along the shore by waves arriving at an angle to the shoreline and by currents generated by such waves.

Orthophoto – is an aerial photograph that has been geometrically corrected (“orthorectified”) such that the scale of the photograph is uniform, meaning that the photo can be considered equivalent to a map.

Root of the spit – shore just before the starting point of the spit (where the spit is connected to mainland).

Scarp – A steep coastal slope (usually more than 40 degrees) cut into the soft sediments (sand etc.), produced by basal wave erosion (undercutting).

Shore – The zone where the waves influence shore sediments starting from the lowest depth of the coastal sea where the wave energy starts to influence the bottom sediments and ending on the highest elevation of the coast where the storm waves may reach.

Shoreline – The waters edge, moving to and fro as the sea level rise and fall or land uplifts and subsides.

Shore platform – a flat or gently sloping smooth or relatively smooth rock surface formed between mean shoreline and steeper underwater shore slope.

Spit – A finger-like ridge or embankment of beach material built up above high sea level as a result of longshore sediment transport, diverging from the land at one end (proximal) to terminate (distal end) usually in one or more increments (recurves) or hooks curving landward.

Storm day – A day when at least one observation of a storm was recorded. Storm in the current study is defined when mean wind speed is 15 m/s or higher during a single observation of 10 minutes.

Storm surge – A temporary abnormal rise of sea level on a coast, as when an exceptionally high sea level is accompanied by strong wave action generated by an onshore gale (cyclone, hurricane).

Swash zone – The zone regularly covered and uncovered as breaking waves generate swash and backwash.

Tombolo – A ridge or barrier of soft sediments built above high sea level in such a way as to link a former island to the mainland, or unite two islands.

3.2. ASSESSMENT OF SHORELINE CHANGES AND CHANGES IN THE POSITION AND CONTOURS OF BEACH RIDGES

Aerial photographs of the study sites from 1955 and 1981 (Kelba), 1985 (Küdema), 1957 and 1980 (Koorunõmme) were compared to orthophotos from 1998 and 2005. In addition, the data obtained from a survey of the beach ridges by K. Orviku in 1963 at Küdema spit and aerial photos taken in 1980 and 1990 at Koorunõmme study site and Kelba study site were used to analyze the geomorphology and character of shore processes at the study sites. Topographic maps from the beginning of the 1900s were used to analyze shoreline changes over longer periods.

The maps and aerial photographs were mainly on a 1:10 000 scale, except the oldest map from 1900, which was on a 1:42 000 scale. Data from the 1900 map were used to determine long-term changes in the coastal formations at the study sites. These data were not used to analyze the relationship between storminess and high sea level events due to their low accuracy. Accuracy of the maps since the start of the 20th century is approximately 10 m. The oldest map of the Koorunõmme study site was too imprecise to use for the current study. The accuracy of the orthophotos (50–75 cm) and aerial photographs (2 m) is much higher, equaling or surpassing the accuracy of GPS devices. The collected data were processed using *MapInfo* software. This software was also used to calculate changes in the area of the investigated spits. Only the portions of the spits occupied by beach ridges were considered in calculating the area changes in order to minimize the changes caused by land uplift.

Field observation records and photos taken at identical locations at the study sites during the last roughly 40 years (Orviku *et al.*, 2003) provide another means with which to assess shoreline displacement. GPS measurements were also taken to ascertain short-time changes in shoreline position, contours of the beach ridges and location of their crests over the last six years (i.e., 2000–2005). Shoreline position is not always the same as the contours of the beach ridges. It is roughly the same in Kelba spit and Sõrve study site but the shoreline might be a few meters seaward from the foot of the beach ridges, for instance in Küdema and Koorunõmme. Therefore, only the contour lines of beach ridges were measured on the spits of these two study sites. Measuring the positions of the crests of the beach ridges is important for extreme storms with high sea level when the contours of the beach ridges are roughly the same but the positions of the crests have changed (for instance, in Küdema after the storm Gudrun). Garmin 12 and Garmin 60CS were used for GPS measurements, both of which are accurate to within 3 m. Connection of GPS-marked points in mapping the shoreline or contour lines of the beach ridges reduces the error even more. It is estimated that accuracy of the mapped shorelines are close to 1 meter (according to the repetitive test measurements by the author). Sea level fluctuations during the GPS measurements were 5–20 cm above or below the mean sea level (Kronstadt zero). Due to the steep topography at the Kelba and Sõrve study sites and higher elevation of beach ridges at the Koorunõmme and Küdema study sites, the sea level variations were insignificant. It can be concluded that the accuracy of mapped contours of beach ridges for detailed analyses varied between 50 cm and 2 m.

Shoreline changes and changes in the contour lines of beach ridges over given time intervals were expressed in meters; changes in area covered by beach ridges in square meters. In some cases, the rates of erosion and accretion were calculated more precisely and estimated volumes are expressed in cubic meters. In areas of development in one direction (increments of the spits) the changes are expressed in mean annual characteristics. The mean annual parameters might contain inadequate information on the actual changes in specific years but give an explicit overview (trend) of changes in the longer term. Therefore the second half of the 20th century – when the most detailed studies and analyses were carried out – was divided into three sub-periods in order to generalize the results and compare the study sites. The three sub-periods used in the current analysis are as follows: 1) from the middle of the 20th century through the beginning of the 1980s; 2) from the beginning of the 1980s to 1997; and, 3) from 1998 to 2005. The chosen sub-periods are of different length but reflect similar intervals in terms of storminess and yearly maximum sea levels. The last period is relatively short compared to the previous periods but is still unique as it was not possible to find any similar conditions over the longer sub-periods.

The relationships between storm data and shoreline changes during 1954–2005 were examined using a simple method of comparison. The time series of the storm data is continuous but the data on changes in area of beach ridges are irregular (depending on available maps and fieldwork data). The correlation between the data on storms and changes in the area of beach ridges were based on periods whose start and end dates were additionally determined either on the availability of aerial photos, orthophotos, fieldwork or GPS. The area changes in a given time interval were compared with the number of storm days, mean annual maximum sea level and number of storms exceeding critical sea level conditions.

3.3. ANALYSIS OF THE IMPACT OF A SINGLE STORM

Topographic surveys were conducted to assess beach profiles at the study sites. The surveys were taken on the profiles at Koorunõmme, Küdema and Kelba study sites before and just after Gudrun in January 2005 (II, Fig. 2). All the profiles were surveyed along the proximal portions of the spits, where older beach ridges are situated behind younger ones, thus, creating a precondition to formation of the highest possible beach ridges in an area. The highest sea level during Gudrun – 209 cm – was measured in Ristna. This figure was used to calculate the heights of the beach ridges formed during the storm. Shoreline changes were analyzed at all the study sites. Shorelines were measured (using GPS) in December 2004 in Kelba and Sõrve study sites and in July 2004 in Koorunõmme and Küdema, which gave us the initial shoreline positions before the storm. The shorelines were measured again at all the study sites in January, just after the storm, and again in April when the sea level was low, roughly the same as in July 2004.

3.4. STORM DAYS, MAXIMUM- AND CRITICAL SEA LEVEL DATA

The storm and sea level data were obtained from the storm catalogue compiled by J. Jaagus (Orviku *et al*., 2003). The storm data were recorded in Vilsandi and the data on sea levels in Ristna (Fig. 1) by the Estonian Meteorological and Hydrological Institute (EMHI). A storm was declared when the mean wind speed was at least 15 m/s during a single 10-minute observation. A storm day was defined as a day when at least one storm was recorded. The average number of storm days per year for each sub-period was calculated.

The sea level data set includes maximum sea levels during each storm measured at Ristna over the period 1950–2005. The mean annual maximum sea level was calculated for the sub-periods using the highest recorded sea levels during a storm day each year and calculating the average for each sub-period. The sea level heights are given according to the Baltic System 1977 with its reference zero-benchmark at Kronstadt, near St.Petersburg. At present, the Kronstadt 0 is nearly equal the long-term mean sea level for the Estonian coast.

Critical sea level parameters were calculated for the three studied spits. In addition, the grain sizes of the deposits on the profiles of actively developing sites were also considered. The mean levels of occurrence of finer-grained sediment (mainly gravel and pebble) were defined for each study site. Finer-grained deposits from the seaward slopes near the surge level are usually completely eroded by strong storms. It was assumed that the storm surges not reaching the finer-grained deposits had no particular effect on the beach ridges. It was also assumed that the lower limit of occurrence of finer-grained material has not changed considerably during the study period. As wave run up reaches higher the mean sea level, special coefficients were calculated for each study site. The coefficients are based on the sea level recorded in Ristna and measurement results in the study sites just after Gudrun. The coefficients were as follows: Koorunõmme 1.1, Küdema 1.6 and Kelba 1.8. Only high sea levels during the storm days were considered. The mean annual number of storms for the sub-periods when storm surges exceeded the critical sea level was calculated for all the study sites based on the measurements and coefficients.

4. SUMMARY OF THE RESULTS AND DISCUSSION

4.1. CHANGES IN SHORELINE AND BEACH FORMATIONS ON SELECTED GRAVEL BEACHES AT THE STUDY SITES DURING THE LAST 100 YEARS

The changes in contour of beach ridges at the study sites were recorded in different periods at different time intervals depending on the available datasets and fieldwork. The detailed studies were conducted on the spits at Koorunõmme, Küdema and Kelba. To analyze the general trend of the development of the spits, the four most descriptive periods (in terms of spit development) were examined for each spit. Sõrve study site was used to determine the magnitude of the changes caused by the cyclone Gudrun.

Koorunõmme

The following sub-periods were established to understand better the general trend of development of the spit in Koorunõmme: 1) 1957–1979; 2) 1980–1989; 3) 1990–1997; 4) 1998–2005 (Fig. 2). During the first sub-period, the area of beach ridges (made up of gravel, pebble and cobble) increased by approximately 1,030 m^2. The annual changes (Table 1) provide a rough indication of the dynamics of the overall trend of development. The spit grew by approximately 30 meters. In addition to elongation, the distal part of the spit widened by up to 3 meters (Table 1).

Table 1. Changes in area and length of the Koorunõmme spit.

Period	Accretion (m^2)	Erosion (m^2)	Length changes/ year (m)	(Erosion+accretion)/ Period length=(m^2) per year
1957–1979	1030	~0	1.3	45
1980–1989	1080	~0	3	108
1990–1997	1250	~0	3	156
1998–2005	760	450	2	151

During the second sub-period, the growth of the spit was more than two times faster. The spit lengthened by 30 meters. The distal part of the spit widened by up to 6 meters, which is twice as much as during the preceding sub-period. During the third sub-period, the growth of the spit was the fastest. The spit became longer by about 20 meters as a result of accumulation in the distal part. There is no clear evidence on widening of the spit during this period (Fig. 2).

During the last sub-period, the area of beach ridges increased by approximately 760 m^2. However, there has been also erosion by about 450 m^2 in the proximal part of the spit. The spit elongated by approximately 15 meters. In addition to elongation, the distal part of the spit widened by about 5–6 meters. The width of the proximal part of the spit decreased by about 6 meters as a result of erosion. Considering the precision level of the data, we can estimate that the average annual changes during the third and fourth sub-period were roughly the same.

Küdema

The following sub-periods were established for the development of the spit at Küdema study site (Fig. 3): 1) 1900–1962; 2) 1963–1984; 3) 1985–1997; 4) 1998–2005. During the first period, the area of gravel-pebble beach ridges increased by approximately 25,000 m^2. The spit elongated by about 320 meters. Due to missing data on the size and shape of the gravel-pebble beach ridges at the beginning of the 20th century, it is difficult to assess changes in area of the spit over the sub-period during 1900–1962. The estimate is based on comparison of shorelines depicted on the 1900 map and the results of 1963 survey. The increment of the spit was calculated solely based on the southward elongation of the beach ridges and do not consider changes on the western side (Table 2). There were likely several small islands south of the spit that were joined with the spit as a result of southward lengthening of the beach ridges. These islands allowed the spit to grow faster as there were small beach ridges on the islands already and the beach ridges growing southward partly accumulated on the islands and on the older beach ridges in the result of longshore sediment transport (Tõnisson, 2004).

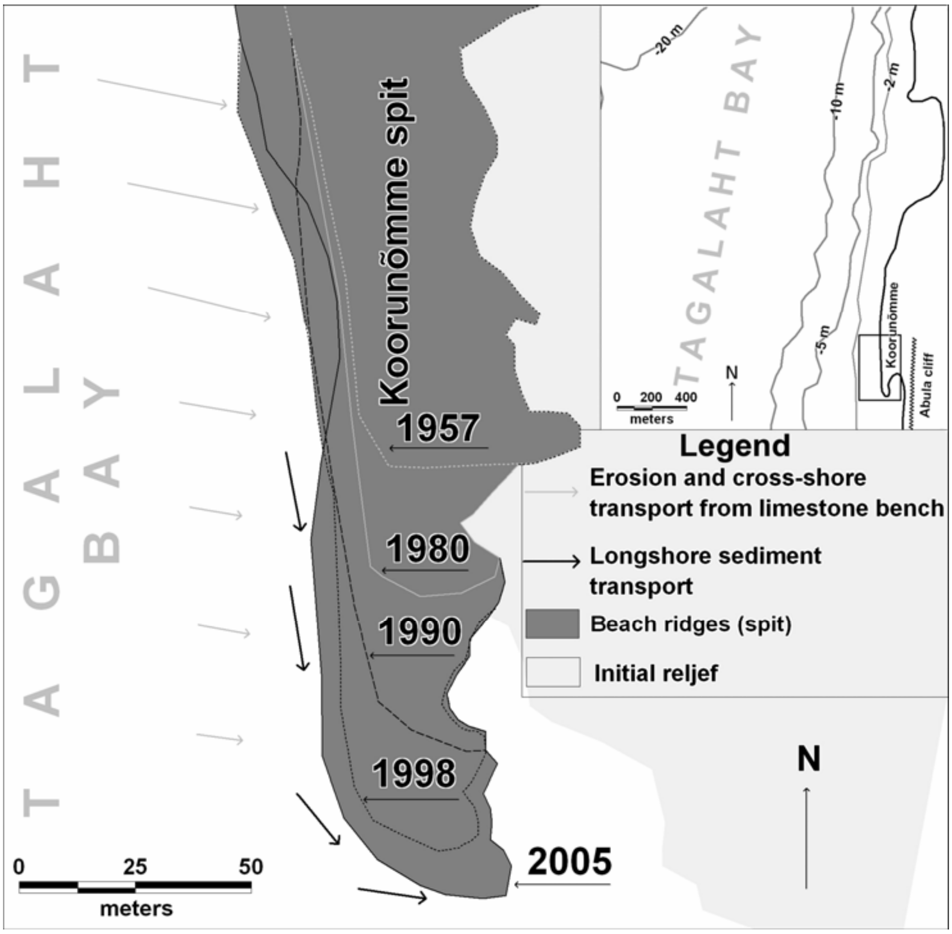

Figure 2. Development of the Koorunõmme spit. See general location Fig. 1.

Table 2. Changes in area and length of the beach ridges on Küdema spit.

Period	Accretion (m^2)	Erosion (m^2)	Length changes/ year (m)	(Erosion+accretion)/period length=(m^2) per year
1900–1962	25000	~0	5	397
1963–1984	7100	~0	10	323
1985–1997	7200	~0	16	554
1998–2005	2500	3400	7	738

During the second sub-period, the increment of the area of the beach ridges was nearly the same as the first sub-period (Table 2). The spit containing beach ridges elongated by approximately 200 meters, which is approximately two times faster than during the first sub-period. During the penultimate sub-period, the area of the beach ridges increased even faster than during the second sub-period and the spit grew about 210 m. During the last sub-period, the area increased by about 2,500 m^2. However, there was also erosion of about 3,400 m^2 in the proximal part of the spit. The spit elongated by approximately 55 meters. In addition to elongation, the distal part of the spit widened by about 6–8 meters. In the proximal part of the spit the width has decreased by up to 8 meters as a result of erosion.

Additional measurements to assess wave parameters and current patterns under different wind regime conditions were carried out in Küdema (III). Wind-induced currents in Küdema Bay show roughly equal north-and southward movement but the longshore wave energy is directed predominantly southwards, inducing the southward growth of the spit (III). Over 80% of the annual stress created by wave motion was directed southwards (III). While the SW wind with its high velocity in Estonia is sheltered by land, the secondary frequent westerlies and north-westerlies have the longest fetch at Küdema and Panga. Induced by westerlies and north-westerlies the maximum wave height 1 km off the cliff (depth 15 m) can be up to 3 m, as it was, for instance, in 1999 (III). These waves can erode the cliff significantly and transport the sediment southward. The waves yielding northward sediment movements are only up to 0.5 m high and therefore do not reach the beach ridges positioned at higher elevations (III; VII, VIII).

Kelba

The following sub-periods were established for the development of the Kelba spit: 1) 1900–1954; 2) 1955–1980; 3) 1981–1997; 4) 1998–2005 (Fig. 4). During the first sub-period, the south-western part of the spit became wider and the distal part elongated to the north-east (IV). The area of the spit increased by approximately 6,800 m^2 (Table 3).

From 1955 to 1980, new beach ridges were formed in the southern and south-easternmost part of the spit and an increase of the area of the spit were about five times faster compared to the previous sub-period (Table 3). There was also erosion in the south-westernmost part by about 500 m^2 during the same period. During the third period, the spit continued to grow to the east and north-east. As a result of accumulation, the area increased by 43,600 m^2. However, concurrent intensive erosion reduced the area by about 9,300 m^2 in the proximal part of the spit. From 1998 to 2005, the velocity of changes increased even more. Accretion in the distal part of the spit and in the lagoons reached about 25,100 m^2. The rate of erosion at the proximal portion of the spit over the same period is estimated up to 24,100 m^2.

It can be concluded that the increment of the spit in Kelba during the last sub-period was caused mainly by erosion in the older parts of the formation and accumulation of the eroded material on the top of the spit and into the lagoons.

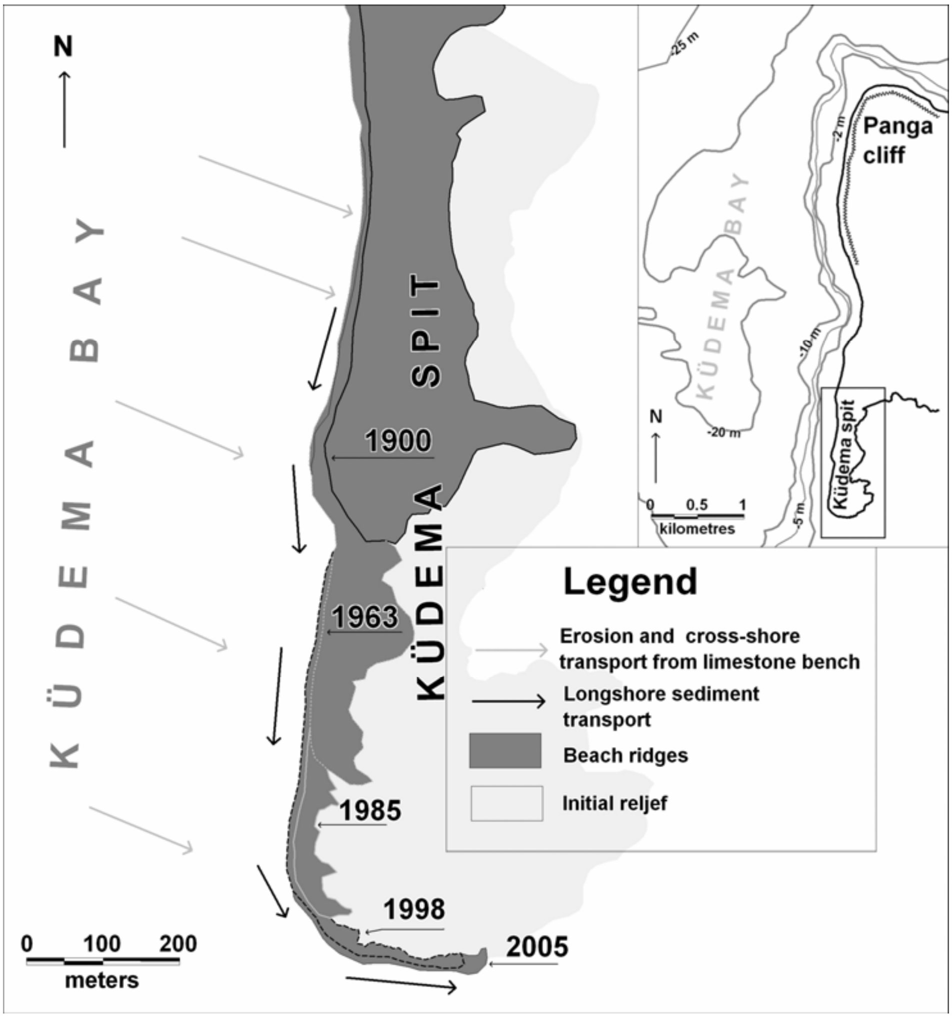

Figure 3. Development of the Küdema spit. See general location Fig. 1.

Table 3. Changes in area on Kelba spit.

Period	Accretion (m^2)	Erosion (m^2)	Length changes/ year (m)	(Erosion+accretion)/ period length=(m^2) per year
1900–1954	6800	~0	N/A	124
1955–1980	18500	500	N/A	731
1981–1997	43600	9300	N/A	3112
1998–2005	25100	24100	N/A	6150

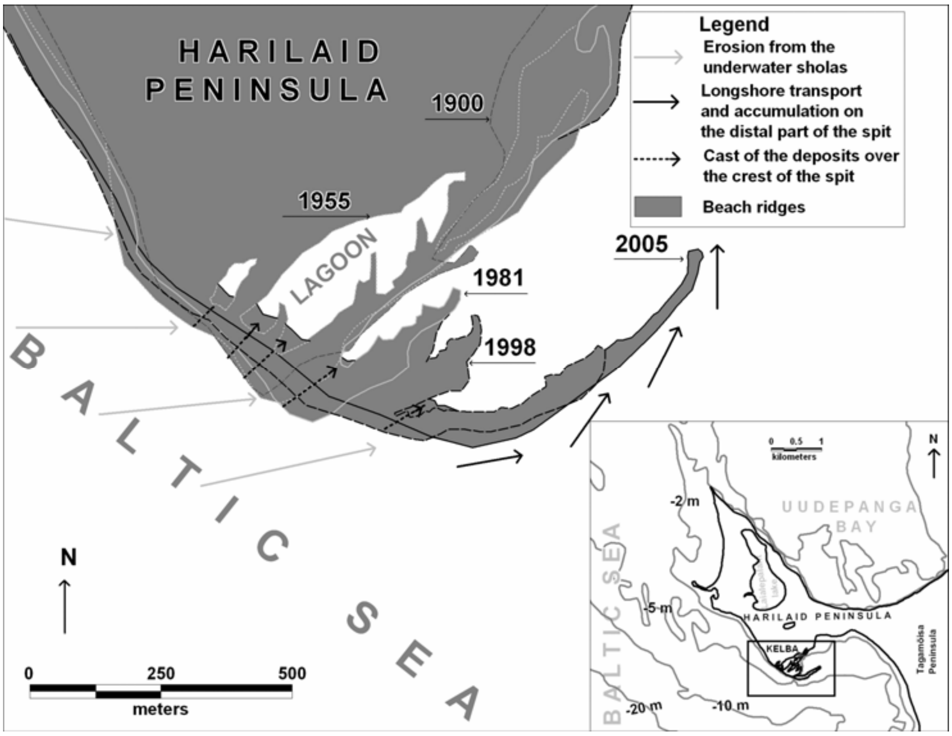

Figure 4. Development of the Kelba spit. See general location Fig. 1.

4.2. IMPACT OF A SINGLE VERY STRONG STORM (GUDRUN)

A cyclone known in the Nordic Countries as Gudrun developed above the North Atlantic and traveled over the British Isles, Scandinavia and Finland January 7–9, 2005. Gudrun reached hurricane strength on the Saffir-Simpson hurricane scale based on the maximum wind speeds measured by the Danish Meteorological Institute (maximum gusts measured in Estonia reached to 38 m/s). As a result of high initial sea level on the Baltic Sea, the fast traveling cyclone with a favorable trajectory and strong SW-W winds produced a new record high storm surge in Pärnu (275 cm), as well as in many other locations along the West Estonian coast (Suursaar *et al*., 2006b). The last recorded storm surge with comparable height (253 cm) in Estonia took place 38 years earlier. Storm Gudrun induced visible changes in the development of shores and the dynamics of beach sediments throughout Estonia. In Latvia and Lithuania the main changes were observed within the limits of sandy beaches. There were no significant shore changes reported in other Baltic Sea countries.

Measuring the heights, contours and positions of the shore formations before and after a single storm with precisely determined parameters is one of the simplest methods to assess the impact of storms and sea levels on the development of the spits in different locations and under varying conditions.

In the study sites that are better protected from waves, such as *Koorunõmme,* new beach ridges were formed with crests only 30 cm over the highest measured sea level (209 cm) (I; II) during the storm. These beach ridges are composed of angular, mostly pebble-sized limestone particles. Higher and more powerful waves did not reach the beach there for most of the storm. By the time the storm wind turned to the north and northwest, the sea level had already fallen. The small exposure of the spit shoreline to the NW and N (i.e. not exposed to the strongest storm winds and waves) is one reason for the relatively slow development of the spit and minor changes in the shape and position of the beach ridges as a result of the storm.

The relatively shallow coastal sea with limestone bottom might be another contributing factor. Erosion from the limestone bench is very slow and according to some authors influenced largely by weathering conditions (primarily alternating freezing and melting of water inside the cracks of the limestone bench, Are *et al*., 2008). The measurement of contour lines of the beach ridges showed an increase of the distal part of the spit at Koorunõmme study site by about 100 m^2 (Fig. 5A) while the most distant beach ridge elongated by only 5 meters.

Signs of fresh accumulation were observed along a roughly 50-m long stretch in the distal part of the spit. A 150-m long section of the spit north of the accumulation area was eroded and reduced in area by approximately 300 m^2. The greatest recession of the beach ridges (up to 4 m) occurred at the proximal part of the spit. The beach ridges consisting of angular limestone particles were transported landwards and to higher elevations. The storm resulted in no notable changes on the underwater limestone bench, which is the sediment source area during typical storms. Therefore it can be concluded that accumulation caused by Gudrun on the distal part of the spit was almost in balance with erosion from the older beach ridges to the north in Koorunõmme study site.

Gudrun displayed a remarkably stronger impact on the formation of the beach ridges at *Küdema* study site. In this area, the crests of new beach ridges were formed about 1.3 m above the highest sea level during the storm (I; II). Sediment accumulation at such an elevation could happen only as a result of very strong wave activity. This, in turn, is attributable to the openness of the site, and, moreover, to its exposure to the strongest winds during the storm. There are no clear shoreline changes and changes in the contours of the beach ridges at the Küdema study site. However, Gudrun changed the position and morphology of the beach ridges (II; IV). The seaward slopes of the beach ridges became steeper and the youngest ridges consisting mainly of gravel, pebble and cobble elevated by approximately 1 m (IV). Pebble and cobble sized limestone particles, which typically can be eroded and removed only by swash, were deposited on older vegetated ridges in many places at Küdema.

The most significant changes took place at the distal part of the spit. The crest of the youngest and highest beach ridge shifted 10 m landward to the formerly vegetated and relatively low part of the spit (Fig. 5B, Profile b). The distal part of the Küdema spit consists of a single beach ridge formed as a result of longshore drift, which readily changes its shape in high sea level conditions. A clear consequence of the January storm is a freshly-formed beach ridge at the proximal part of the spit that is much higher than the older ones behind it (Fig. 5B, Profile a). This freshly-formed beach ridge is made up of well-rounded limestone particles. Good particle roundness indicates a long transport (seemingly from the Panga cliff) along the shore before accumulation on the beach ridges at higher elevations.

The underwater shore slope along the Küdema spit was formed in the limestone bedrock as in Koorunõmme – erosion too slow to be observed from a single storm. The very small share of angular limestone particles (less than 5%) in the freshly-formed beach ridge also indicates that erosion and cross-shore transport of sediments from the limestone bench during Gudrun was very low. Similar trends of roundness level can be observed on the older beach ridges as well. Therefore, it is impossible to distinguish the sediment transported from Panga cliff during the storm and the sediments eroded from the older beach ridges. It can be only concluded that most of the sediments was transported by longshore drift.

The Küdema study site was sheltered from the direct impact of Gudrun’s winds and waves for most of the storm. Accordingly, the high sea level was the dominant factor influencing the shore. Prevailing wind directions from the W, SW and S did not favor longshore drift of sediment eroded from the Panga cliff, which is the main source of material for the beach ridges. This is also confirmed by the absence of new beach ridges and the generally stable position of the southernmost top of the spit. Thus, it can be concluded that the principle effect of the January storm at this study site was onshore drift limited to the former beach rides along the western shore of Küdema spit. As a result of this onshore drift, the crests shifted landward and their seaward slopes became steeper.

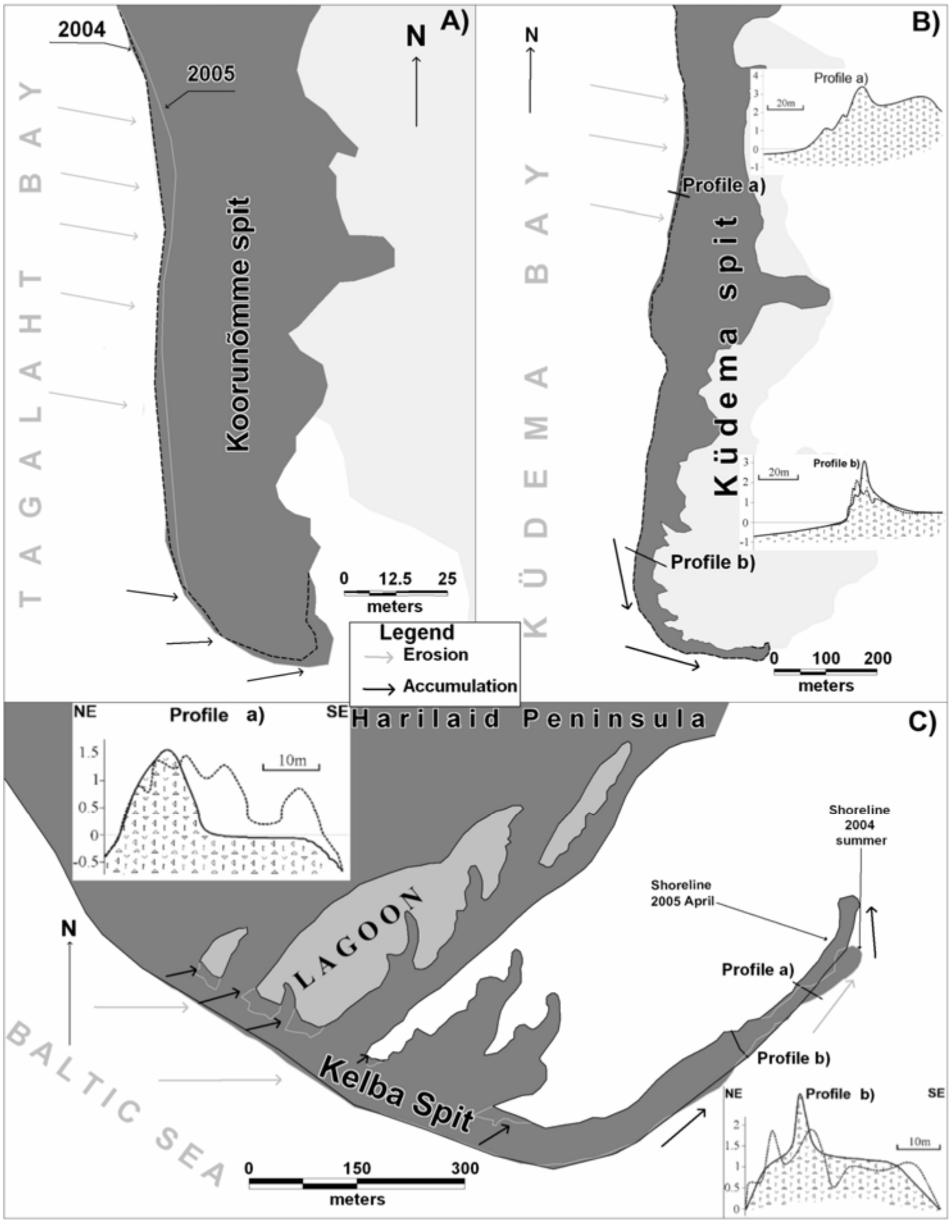

Figure 5. Changes in contour lines and in morphology of beach ridges caused by Gudrun in Koorunõmme A), Küdema B) and Kelba C) study site.

The spit at *__Kelba__* (Fig. 1) study site was subjected to the greatest changes by Gudrun. The crests of its beach ridges formed up to 1.7 m above the highest sea level (I; II). This shore was exposed to the winds and waves for almost the entire duration of the storm. The wind direction was perpendicular to the shoreline during the peak. This enhanced onshore drift of sediments and the formation of the highest ridges. The highest beach ridge consisting mainly of crystalline gravel, pebble and cobble is located at the root of the spit. The beach measurements taken in Kelba between July, 2004 and April, 2005 show a considerable increment of the spit due to intensive accumulation (Fig. 5C). At the same time, the distal part of the spit, consisting of finer-grained sediments such as gravel and pebble, shifted by 15–30 m to the north. The total area of the spit increased by about 4,300 m^2 over the same period. However, most of this increment comes from filling the backing lagoons and small lakes by sediments. Due to erosion of the seaward proximal slope of the spit and the cast of deposits over the crest of the spit into the lagoons, the older and smaller beach ridges have been leveled and the proximal part of the spit has widened towards the lagoons. When the waves crossed the crest of the beach ridges they formed so called “flow channels” and carried massive amounts of sediments (up to boulder size) across the spit. The amount of sediment carried across the spit and accumulated into the lagoons in the proximal part of the spit was between 30 and 60 m^3 per meter of shoreline. The total amount of sediments accumulated into the lagoons is approximately 12,000–13,000 m^3.

In addition to changes in the area of the Kelba spit, substantial changes in elevation were observed. The seaward slope of the youngest beach ridge (made up of gravel and pebble) in the distal part of the spit was smoothed as a result of the storm (II). The largest morphological changes in young beach ridges are particularly noticeable on this profile (Fig. 5C, profile b). The crest of the youngest ridge elevated by nearly 1 m (from 1.9 to 2.8 m, II), while the width of the spit has remained almost the same (Fig. 5C, profile b). Part of the beach ridge material that was cast over the crest into the backing lagoons by swash formed a characteristic steep slope.

In more distal part of the spit (Fig. 5C, profile a) at a point about 170 m from its top, the older beach ridges (made up of gravel and pebble) on the seaward side were completely destroyed by the storm, but the submarine base of the spit remained stable. It can be said that not even such strong waves can carry sediment away from a depth greater than 1–2 meters below normal sea level. The rate of erosion has been estimated to be about 15 m^3 of deposits per meter of shoreline (i.e., over 3,000 m^3 in the distal part of the spit) resulting in the northward elongation of the spit by 75 m. Therefore, it can be assumed that the material for accumulation on the top of the spit came from the beach ridges transported not more than 200–250 meters. The main process was redistribution of the sediments within the limits of the beach ridges in Kelba spit.

The shift of the gravel-pebble spit and the substantial changes in its morphology suggest a combination of unusually strong forces and high sea level in this region during the January storm. Moreover, as a result of high sea level and the abrupt end of the storm the waves influenced mainly the beach formations at higher elevations. The shore face was completely covered by boulders after the storm, which indicates that smaller sediment particles were carried to the higher beach ridges and the almost no sediment was added from the bottom of the sea. This might have occurred because the storm ended quickly and most of the wave energy was transferred to the higher elevations and did not reach the near-shore bottom during most of the storm.

The changes caused by Gudrun at the top of the *Sõrve* spit are noticeable by simply comparing the photographs taken before and after the storm (II, Fig. 6). The measurements taken before and after the storm demonstrate that the most significant change caused by the storm was shortening of the spit by nearly 20 m (Fig. 6). The eastern side of the spit receded 2–8 m. Erosion of the southern tip and the eastern shore led to the final collapse of the stonewall that was initially erected by Soviet border guards decades earlier (II, Fig. 6). On the other hand, the western side of the spit advanced 2–7 m (a full 10 m on the south-westernmost part) due to accumulation. As a result of strong erosion on the eastern shore and the southern tip, the overall area of the Sõrve study site decreased by about 2,000 m^2, while nearly 1,300 m^2 accumulated on the western shore (II; VI). As the measurements were taken just before and after the storm, one can conclude that the area of the spit decreased by about 700 m^2 as a result of erosion. On the beach face we found mainly cobble and even some boulders.

Accumulated material on the beach is mostly well-rounded gravel and pebble. This shows that finer-grained sediments were carried away from the beach face to higher elevations and more inland. As a result of accumulation, the elevation of the gravel beach increased by approximately 20–30 cm in a 20–30 m wide area along the shore on both sides of the spit. Analyzing the wind parameters and the duration and maximum magnitude of the storm (based on the observation data in Ruhnu) in relation to the measurement results, it is possible to assess the storm impact on the shore.

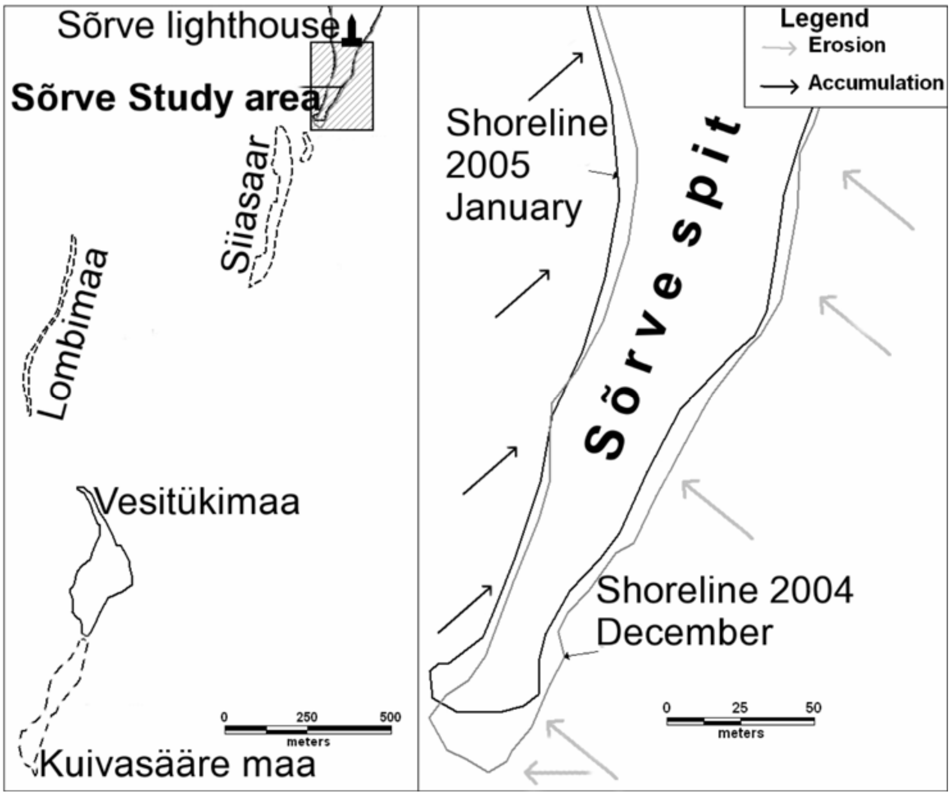

Figure 6. Location of the Sõrve study site and shoreline changes caused by Gudrun at the Sõrve study site.

At the beginning of the storm the sea level was already high and the wind blew from southwest and west turning gradually to the northwest, thereby creating conditions for intensive erosion and onshore sediment transport on the western shore. Due to the underwater shoals (south of the tip of the spit) and resulting refraction, strong storm waves reached the western shore as well. Evidence of intensive wave activity is a relatively thick layer of gravel and pebble accumulated on the pathways along both sides of the spit (I). At the peak of the storm, the northwestern winds caused sediment transport to turn primarily southward, towards the southern tip of the spit. During and just after the peak of the storm, the eastern and western shores remained largely on the leeward side of the Sõrve Peninsula and the low-lying islets. The wind turned southward by the end of the storm, and the sediment deposited at the top of the spit was re-transported along the western shore and re-deposited. This process is illustrated by the portion of the spit that is widened and bulges out along the western edge of its tip (Fig. 6).

In general, Gudrun caused remarkable changes on gravel beaches. The main process at each study site was transport of finer-grained sediments to higher elevations. Several smaller beach ridges (containing gravel, pebble and cobble) formerly located near the shoreline were “pushed” into a single beach ridge positioned further inland at higher elevation. As a result the gravel beaches widened and the median composition of the sediments near the shoreline changed from gravel, pebble and cobble to cobble and boulder size. Such significant morphological changes are usually recorded once in 10–15 years. Shoreline changes on gravel beaches during Gudrun are roughly equivalent to the annual changes caused by typical storms. It can be concluded that the changes in morphology on gravel beaches resulting from Gudrun were the most significant during the last half-century.

Shoreline changes as well as morphological changes were much greater on the sandy beaches (II). The changes of shoreline on sandy beaches can be roughly compared to the total changes caused by typical storms over a period of 15–20 years period.

4.3. COMPARISON OF CHANGES AT THE STUDY SITES AND THEIR RESPONSES TO CHANGING STORMINESS AND RELATED HIGH SEA LEVEL EVENTS

The results of the current research confirm the conclusions of earlier studies (Orviku *et al.*, 2003; Rivis, 2004; IX etc.) showing the increasing trend of storminess and vitalization of shore processes. However, this thesis distinguishes the second part of the 20th century (earlier data were excluded due to the low accuracy level of the older maps) into three sub-periods and focuses on quantitative analysis based on the relationships between storm days, sea levels and shore changes at three study sites. Although the time intervals for the study sites do not coincide precisely, a clear trend over the last half-century is evident in each case.

A comparison of storm and sea level data with the collected data of changes in the shape and area of beach ridges in the study sites reveals a strong association.

During the first sub-period – i.e., the period from the mid-20th century to the 1980s – erosion, sediment transport and accumulation processes were relatively inactive resulting in 2–8 times fewer cumulative area changes compared to the second sub-period. The most significant changes during the first sub-period saw an increasing area of shore formations through prevailing accumulation. Unlike the other sub-periods, some marginal erosion (less than 5% of cumulative changes) was evident only at Kelba, where the spit is most exposed to the open sea. The number of storms per year (17) was also the lowest compared to the second and third sub-periods (I). Relatively low mean annual maximum sea levels (between 88 and 92 cm) during the first sub-period were probably caused by relatively low cyclonic activity.

From the beginning of the 1980s through the second part of the 1990s (the second sub-period) the annual average changes (Fig. 7A) at the study sites largely sheltered from the open sea (Küdema and Koorunõmme) accelerated about two to three times, while at Kelba – the most exposed study site to the open sea – the annual average cumulative changes were over four times greater than in the first sub-period. Both erosion (nearly 20% of cumulative changes) and accumulation increased remarkably on Kelba spit during this sub-period. Accumulation was recorded in Küdema and Koorunõmme without signs of erosion. Therefore, we can assume that accumulation was the dominant process during the second sub-period at those sites better protected from waves. The share and magnitude of erosion increases with the exposure to the open sea, and can be usually identified in the proximal parts of the spits consisting of older beach ridges. The second sub-period can be considered the stormiest sub-periods. During the second sub-period, the mean annual number of storms was 1.7 times (Fig. 7B) that of the first sub-period. The mean value of the annual maximum sea levels rose, albeit marginally, to the level of 104–105 cm above the Kronstadt 0. Consequently, it can be concluded that the greater erosion during the second sub-period is the result of two main factors – increased number of storm days and higher sea levels during the storms. Thus, it can be assumed that more frequent storms left inadequate time for the beach ridges at Kelba to restore their profiles between the storms. Thus, every next storm reached the already vulnerable beach profiles and led to erosion. An earlier study shows that the deposits forming the beach ridges in Kelba are initially derived from shoals composed of loose Quaternary sediments near the shore (Orviku, 1974). Because the sea level was a bit higher during the strong storms, the wave energy during these storms with higher sea levels was likely insufficient to transport gravel, pebble and cobble from the shoals, or there might have been a deficit of finer-grained sediments. The wave energy was largely directed at the beach face, which initiated erosion. It is known that gravel, pebble and cobble are usually not transported from deeper parts of the near-shore sea bottom (Massel, 1999). Consequently, the erosion process at Kelba during the second sub-period might have been caused also by a deficit of sediments on the shoals.

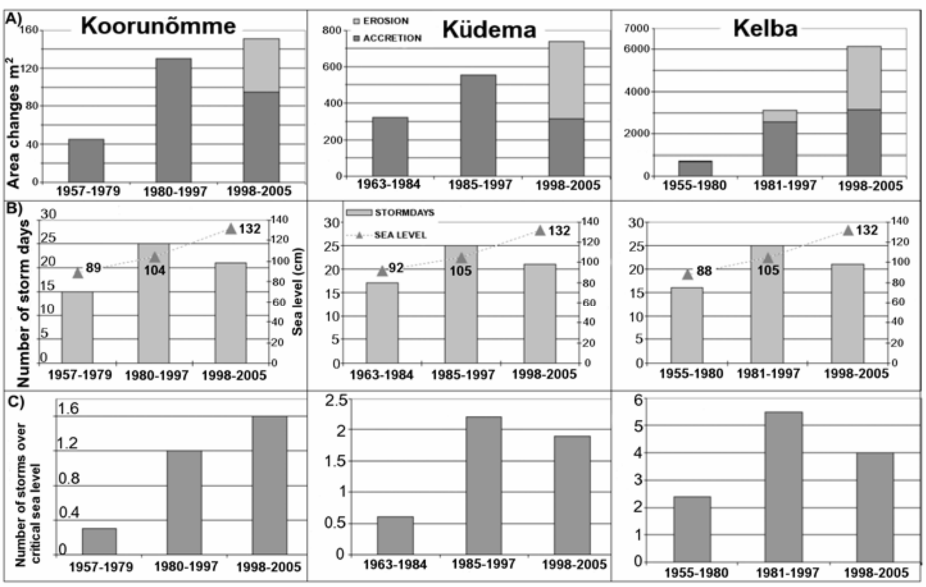

Figure 7. Changes of beach ridges over the period of last fifty years and the respective storm characteristics: A) Annual changes – (erosion + accretion)/period; B) mean number of storm days per year and average max yearly sea level; C) average number of storms over critical sea level per year.

During the third sub-period (from 1998 until 2005) cumulative changes in the area of beach ridges in Küdema and Koorunõmme increased by 1.2–1.5 times, and at Kelba by over two times compared to the second sub-period. The spits in Küdema and Koorunõmme formed at elevations only a few cm above or below sea level during the entire study period. The distal part of the Kelba spit developed at depths of 2 m below sea level during the first two sub-periods. At the beginning of the third sub-period the distal part of the Kelba spit reached depths of 4–4.5 meters and continues to develop at similar depths. Thus, we can summarize that the total volume of changes on Kelba spit during the last sub-period is nearly four times greater than the preceding sub-period.

Unlike the preceding two sub-periods, the share of erosion of beach ridges has grown substantially, particularly in recent years. Erosion accounts for about 35% of the cumulative changes at Koorunõmme, nearly 50% at Kelba and even 60% at Küdema (I) (Fig. 8a, 8b, 8c). At all the study sites erosion dominates in the older (proximal) parts of the spits whereas accumulation dominates in the distal parts. Erosion of the proximal part of the spits supports the conclusion that a deficit of sediment is an important factor leading to greater erosion of the older beach ridges. Thus, the new ridges at the distal parts of the spits are mostly built up of material eroded from the proximal parts of the same landforms. The third sub-period can be characterized by a slightly decreasing trend in storminess but the frequency of storms nonetheless remains 1.3 to 1.4 times higher than during the first sub-period. At the same time, the annual maximum sea levels steadily increased to over 132 cm (Fig. 7B). This is about 1.5 times higher than in the 1960s. This rise might be caused by the mild winters when the duration of ice cover in the sea is very short or entirely absent. Despite the slight decrease in storminess, the shores remain dynamic and the changes in the beach ridges are still accelerating. It can be concluded that much greater erosion during the third sub-period in the proximal part of the Kelba spit was caused by more frequent strong storms with high sea levels despite smaller number of storms. In general, it can be said that frequent high sea level events exceed the tectonic land uplift at the Kelba study site.

Somewhat different conclusions can be drawn in respect to the Koorunõmme and Küdema spits. These two study sites are less exposed to the open sea and are composed mainly of limestone particles of different size. At both sites the sediments are eroded from the limestone bench. The Küdema spit receives additional material from Panga Cliff. Some studies affirm that at higher latitudes erosion on such kind of shores is much more dependent on weathering of rocks than on storm characteristics (Are *et al.,* 2008). Warmer winters with less ice cover and fewer temperatures below freezing have the opposite effect in this area. While the sea level during the storms has risen, the amount of sediment in the feeding area has decreased. As at Kelba, the erosion area has shifted landward, causing changes to the already existing beach ridges. Therefore, the main process in these two study sites during the third sub-period were redistribution of sediments on the beach ridges of the spits.

Analysis of the storm characteristics and the morphometric parameters of the shore formations demonstrate that the greatest changes in their position, contour and size are more closely dependent on the high sea level during storms than on the frequency of storms. The ridges consisting of gravel and pebble are usually located above the mean sea level and the boulders are concentrated near the shoreline to form an abrasion platform. Such sediment distribution is indicative of the dominance of high sea level events when finer-grained material accumulates on higher ridges.

Some quantitative characteristics appropriate to each study site were inferred from the presented assumptions. These characteristics make it possible to determine the actual number of storm days affecting the formation of beach ridges at a site. The calculations show that the sea level should be at least 70 cm above mean (the sea levels are given according to the Ristna mareograph) to affect the development of finer-grained parts of the beach ridges on Kelba spit, 90 cm at Küdema and 1 m at Koorunõmme (Fig. 7C).

This suggests that there were 2.4 storms a year on average during the first sub-period to shape the beach ridges at Kelba (Fig. 7C), 0.6 at Küdema and 0.3 at Koorunõmme. These rates increased 2–4 times, ranging from 1.2 to 5.5 storms (depending on the study site) a year on average during the second sub-period. The third sub-period revealed an unexpected tendency of a decrease in storm days with sea levels exceeding the critical value at the Kelba and Küdema study sites but an increase at the Koorunõmme study site. This is in good accordance with the increasing trend of maximum sea levels and accelerated shore processes. Based on the observation data and calculated characteristics, one can conclude that the frequency of faint storms with relatively low surge levels is decreasing. Similar conclusions have been drawn by climatologists whose recent research indicates a decreasing trend of faint cyclones and an increase in deep cyclones by about 20% in the Baltic Sea Region (Sepp, 2007). The increasing number of deep cyclones together with changes in their trajectories results in increasing frequency of extremely strong storms, higher storm surges and more intensive storm damage. The trajectories of durable cyclones have shifted northward and cross into southern Finland (Sepp *et al*., 2005). As the strongest winds blow about 200–300 km south of the cyclone center (II), the influence these changed trajectories on the frequency of strong storms in Estonia is evident. Due to the exposure of the Koorunõmme study site to the NW and N, the changed trajectories of SW storms does not greatly affect shore processes there. The greatest effect can be seen in the study sites exposed to SW or W, such Kelba, where the magnitude of changes has increased at least twice during the last decade (four times in terms of volumes of moving sediments).

Storms that do not create higher than average sea level conditions cannot produce waves that can reach gravel ridges at higher elevations, and therefore, no significant changes occur on the shore. However, such storms can cause changes below sea level by moving the finer-grained sediments on the shore slopes below sea level near the shoreline. During storms that create high sea level conditions, these relocated sediments can be subsequently thrown by waves onto the higher ridges. If there are many successive strong storms, the small ridges normally formed during the faint storms are lacking and the proximal parts of the spits, which are mostly either areas of sediment transport or accumulation, might be subject to erosion.

Similar or even higher mean annual maximum sea levels can be expected for the future as storminess increases. For instance, when the data on 2006 and 2007 is added to the third sub-period, the average number of storm days remains the same but the average annual maximum sea level increases from 132 to 137 cm above the mean level. This suggests that the extraordinary conditions during the third sub-period are not simply an artifact caused by the shortness of the period. The intensity of shore processes has remained roughly the same at Kelba. We can expect ongoing erosion in the proximal parts of the spits until a new equilibrium state corresponding to the annual maximum sea levels has been achieved. The other possibility is a decrease in annual maximum sea level and an increase in the frequency of faint storms with lower sea levels. In such case the erosion area should migrate seaward and cumulative area changes of the spits should decrease significantly.

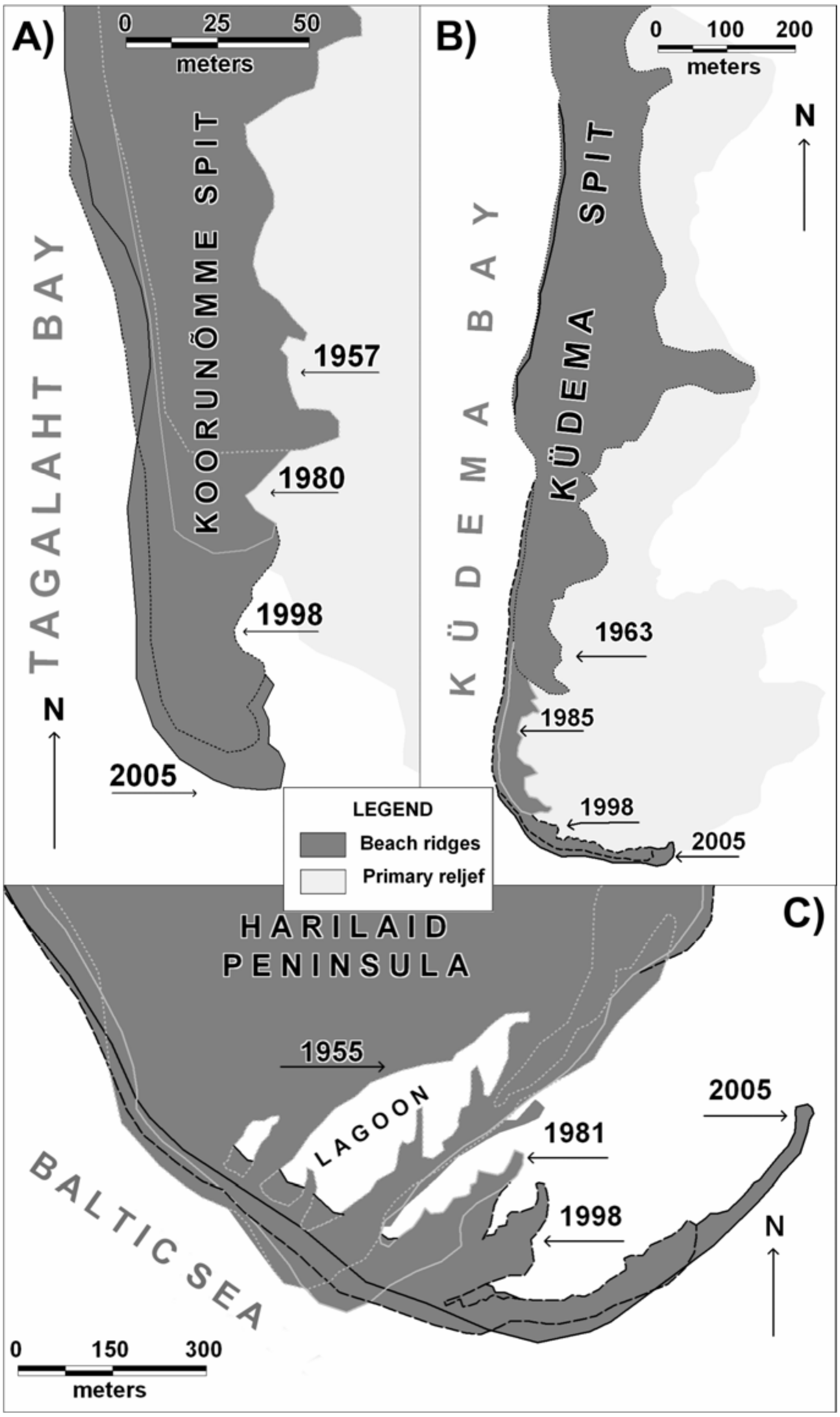

Figure 8. Erosion and accretion of the spits at: A) Koorunõmme, B) Küdema and C) Kelba study sites.

CONCLUSIONS

Externally similar spits are developing at completely different rates. The annual average changes can vary by over 100 times at different locations. At the sites studied in this thesis the maximum annual area change (nearly 7,000 m^2 on average per sub-period) was recorded on Kelba spit during the last sub-period, whereas the minimum annual area change (approximately 50 m^2 on average per sub-period) characterized the Koorunõmme study site during the first sub-period. The difference in the rate of change is a function of different exposure of the study sites to prevailing storm waves, geological structure of the study sites, availability of loose sediments and changing storm and sea-level conditions.

Warmer winters and concurrent increased cyclonic activity have had noticeable impacts on the natural environment on the coasts of Estonia. A clear increase in the frequency of storm days can be observed in western Estonia during the second half of the 20th century. The maximum number of storm days – 25 storm days per year on average – was recorded in the period from the beginning of the 1980s until the mid 1990s. The frequency of storm days has more or less stabilized over the last decade, but the maximum sea levels during storm surges continue to increase. The increasing number of deep and durable cyclones together with changes to their trajectories results in increasing frequency of extremely strong storms, higher storm surges and more intensive damage to the shore.

An extremely strong storm, such as Gudrun, can cause significant changes to gravel shores. In the case of Gudrun, the principal dynamic at work was the transport of finer-grained sediments to higher elevations. Smaller beach ridges formerly located near the shoreline were pushed into a single beach ridge positioned further inland and at higher elevation. Such huge beach ridges can be formed once in 10–15 years. As a result of this process, the gravel beaches became wider and the grain size of the sediment particles near the shoreline increased. Since the shoreline changes to the gravel shores during Gudrun were equal to the mean annual changes, and thus not inordinately strong, we view the changes to the morphology of the gravel beaches as a result of Gudrun to be the storm's most significant impact.

An extensive increase of the area of gravel spits has been observed in recent decades. The frequency of very strong storms with high sea level (over 100 cm above mean) has substantially grown. Consequently, more frequent storms with high sea level do not leave enough time for beach ridges to restore their initial profile during the quieter periods between strong storms. Therefore, each subsequent storm reaches the already vulnerable beach profile and erosion starts. Such an increase in sea levels during storms has caused the typical erosion area to move landward with each strong storm, and the older beach formations, particularly those well-exposed to the open sea, are subjected to erosion in areas of previous drift. In general, it can be concluded that the tectonic land uplift on the Estonian coast has been balanced or even exceeded at some locations by frequent high sea level events.

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KRUUSA-VEERISTIKURANDLATES ESINEVATE MAASÄÄRTE ARENG MUUTUVA TORMISUSE JA MERETASEMETE TINGIMUSTES

Kokkuvõte

Seoses kliima soojenemise ja maailmamere eeldatava veetaseme tõusuga on kogu maailmas suurenenud teaduslik huvi randades toimuvate protsesside vastu. Eesti Vabariigi taassünniga ja seoses endise Nõukogude Liidu piiritsooni kadumisega on tugevnenud nii rekreatiivne kui ka majanduslik surve Eesti rannikule tervikuna. See on omakorda tinginud praktilise vajaduse rannaprotsesside ja randade üldiste arengusuundade paremaks tundmiseks. Lisaks sellele on Eesti rannad maailmas võrdlemisi omanäolised, kus tõusu ja mõõna osakaal on väga nõrk, ent tormilainetuse mõju väga tugev. Lisaks sellele on tegu piirkonnaga, kus on registreeritud üks suuremaid aasta keskmise õhutemperatuuri tõuse ning seda peamiselt talvise poolaasta arvel.

Eesti rannajoon on valdavas osas väga liigestatud ning iseloomulik on eri rannatüüpide rohkus ning nende kiire vaheldumine. Eestis on kokku üle 1500 saare ja koos saartega ulatub siinse rannajoone pikkus ligi 3800 kilomeetrini. Eesti rannik on ka tugevasti mõjutatud maakerkest, mis Loode-Eestis ulatub 2,8 mm/aastas ja põhjustab aina uute alade kerkimist üle merepinna. Töös käsitletud uuringualad on kõik kruusa-veeristikurandlad ja asuvad Saaremaal. Sealse piirkonna rannikut iseloomustavad kulutusrandadega poolsaarte tipud (valdavalt lubjakivi-pangad), kulutus-kuhjelised kruusa-veeristikurannad poolsaarte külgedel ning kuhjelised liivarannad poolsaartevahelistes lahepärades.

Töös käsitletud uuringualad on väliselt võrdlemisi sarnased ja geomorfoloogiliselt on tegemist mitmest rannavallist koosnevate kuhjeliste rannamoodustiste – maasäärtega. Välisele sarnasusele vaatamata on eespool nimetatud maasääred kujunenud erinevates looduslikes tingimustes, nad on eri mõõtmetega, erisuguse tekkelooga ning arenevad eri kiirusega.

Töö põhilisteks ülesanneteks olid:

1) uurida rannajoonte ja rannamoodustiste muutusi valitud uuringualadel viimase umbes 100 aasta jooksul;
2) analüüsida tormipäevade esinemise dünaamikat ja nendega kaasnevate kõrgete meretasemete esinemist iseloomustavaid karakteristikuid;
3) analüüsida ühe ekstreemse tormi (Gudrun) mõju erinevates tingimustes arenevatele ja erisuguse iseloomuga kruusa-veeristikurandadele;
4) analüüsida ja tõestada kvantitatiivseid seoseid tugevate tormituulte, kõrgete meretasemete ja kruusa-veeristikurandade arengu vahel töös käsitletud uuringualade näitel.

Käesolev töö keskendus neljale uuringualale, millest detailsem analüüs viidi läbi kolmel alal – Koorunõmmes, Küdemal ja Kelbas. Sõrve uuringuala kasutati ainult ekstreemse tormi Gudrun mõju analüüsimiseks.

Kruusa-veeristikurandlas olevate rannavallide pindalade muutuste kindlakstegemine põhines peamiselt erivanuseliste aerofotode ja ortofotode võrdlemisel. Lisaks sellele on kasutatud geo-loogiadoktor Kaarel Orviku varem mõõdistatud plaane ning doktorandi ja artiklite kaas-autorite poolt välitöödel kogutud andmeid. Viimasel kümnendil on lisandunud GPS-iga määratud rannajoonte ja rannavallide muutuste andmed. Välitööde käigus looditi rannaprofiile ning tehti kindelpunktidest korduspildistusi.

Doktoritöös ja artiklites kasutatud meteoroloogilised andmed pärinevad Eesti Meteoroloogia ja Hüdroloogia Instituudi ilmajaamade vaatlusandmetest ja professor Jaak Jaaguse koostatud tormide kataloogist. Tormituulte andmed on mõõdetud Vilsandi ilmajaamas ning meretaseme andmed Ristna mareograafiga.

Pindalaliste muutuste puhul on arvesse võetud ainult rannavallide alla jäävat ala, mis võimaldab elimineerida maakerkest tingitud muutusi. Keskmiste muutuste arvutamiseks ja trendi esiletoomiseks kasutatud all-perioodid on määratud olemasoleva andmestiku põhjal, mistõttu nad ei ole ühepikkused. Sellele vaatamata võib kõikide uurimisalade arengus eristada kolme võrdlemisi sarnast allperioodi: 1) 20. saj keskpaik – 1980ndate algus; 2) 1980ndate algus kuni 1997 ning 3) 1998–2005.

Käeoleva töö tulemusena võib öelda, et tormipäevade arv 20. sajandi keskpaigast kuni tänapäevani on näidanud selget kasvutendentsi, saavutades seni kõrgeima taseme 1980ndatel aastatel (2. allperioodil). Viimasel allperioodil on tormipäevade arv küll pisut vähenenud (25 tormilt 21 tormini aastas), kuid seevastu on tõusnud tormiaegsed maksimaalsed meretasemed (102-lt – 132 cm-ni).

Kuna vaadeldavate rannamoodustiste muutuste tempo on kogu vaatlusperioodi vältel ühtlaselt kasvanud, saame järeldada, et kruusa-veeristikurandades esinevad suurimad muutused on seotud eelkõige just kõrgete meretasemetega. Tormipäevade arvul on väiksem tähtsus.

Lühikese aja jooksul üksteisele järgnevad tugevad tormid, millega kaasneb meretaseme eriti suur tõus, viivad kruusa-veeristikurandade arengu normaalsest tasakaalust välja. Selle tulemusena hakatakse murrutama setete edasikande piirkonnas asuvaid vanemaid rannavalle. Kui maasäärte toitealadelt nõrgemate tormide käigus värsket materjali piisavalt juurde ei tule, siis toimub setete ümberpaiknemine juba kuhjunud rannavallide piires, s.t varem kujunenud rannavallide kulutus on ligikaudu võrdne värskelt moodustunud rannavallide ruumalaga.

Nagu uuringud kinnitasid, võib erakordselt tugeva tormi mõju kruusa-veeristikurandade arengule eri piirkondades olla väga erinev. Uuringualadel, mis on tormituultele avatud lühiajaliselt üksnes tormi raugemise faasis (Koorunõmme), esinevad vaid suhteliselt väikesed muutused. Tormituultele pea kogu tormi vältel avatud uuringualadel (Küdema ja Kelba) on toimunud erakordselt suured nii rannamoodustiste kuju, kõrguse kui ka paiknemise muutused. Värskete rannavallide harjade kõrgused võivad ulatuda isegi kuni paar meetrit üle tormiaegse maksimaalse meretaseme. Niisugused kõrge meretaseme ning tugeva lainetuse tingimustes kujunenud rannamoodustised asuvad sageli keskmisest veepiirist kaugel sisemaal ja püsivad seal muutumatuna tõenäoliselt veel kaua.

REFERENCES

AALOE, A., MIIDEL, A. 1967. Eesti pangad ja joad. Tallinn, 72 (in Estonian).

ALEXANDERSSON, H., SCHMITH, T., IDEN, K., TUOMENVIRTA, H. 1998. Long-term variations of the storm climate over NW Europe. – Global Atmosphere and Ocean System, 6, 97–120.

ARE, F., REIMNITS, M., GRIGORIEV, M., HUBBERTEN, H.-W., RACHOLD, V. 2008. The Influence of Cryogenic Processes on the Erosional Arctic Shoreface. – Journal of Coastal Research, 1, 110–121.

BALLING, R. C., VOSE, R. S., WEBER, G.-R. 1998. Analysis of long-term European temperature records: 1751–1995. – Climate Research, 10, 193–200.

BIRD, E. C. F. 2000. Coastal geomorphology: an introduction. John Wiley & Sons, Chichester, 322.

CHURCH, J. A., GREGORY, J. M., HUYBRECHTS, P., KUHN, M., LAMBECK, K., NHUAN, M. T., QIN, D., WOODWORTH, P. L. 2001. Changes in Sea Level. – J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, C. A. Johnson (eds.). – Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 639–694.

DAVIS, R., FITZGERALD, D. 2004. Beaches and coasts. Blackwell Publishing, Malden (MA)/Oxford/Victoria, Australia, 419.

DAWSON, A. G. 2004. Estimating the Vulnerability of Scotland's Coastline to the Effects of the Future Sea Level Rise and North Atlantic Storminess. – D. R. Green (ed). Delivering Sustainable Coasts: Connecting Science and Policy. Littoral 2004, proceedings 1. Cambridge Publications, UK, 385–389.

DEAN, R. G., DALRYMPLE, R. A. 2002. Coastal Processes with Engineering Applications. Cambridge University Press, Cambridge, England, 475.

FOLLAND, C. K., KARL, T. R., CHRISTY, J. R., CLARKE, R. A., GRUZA, G. V., JOUZEL, J., MANN, M. E., OERLEMANS, J., SALINGER, M. J., WANG, S.-W. 2001. Observed Climate Variability and Change. – J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, C. A. Johnson (eds.). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 99–182.

GULEV, S. K., JUNG, T., RUPRECHT, E. 2002. Climatology and inter annual variability in the intensity of synoptic-scale processes in the North Atlantic from the NCEP-NCAR reanalysis data. – Journal of Climate, 15, 809–828.

HAAPALA, J., LEPPÄRANTA, M. 1997. The Baltic Sea ice season and the changing climate. – Boreal Environment Research, 2, 93–108.

HEINO, R. 1994. Climate in Finland during the period of meteorological observation. – Finnish Meteorological Institute Contributions. 12, 1–209.

IPCC. 2001. Climate change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. – J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, C. A. Johnson (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881.

JAAGUS, J. 1998. Climatic fluctuations and trends in Estonia in the 20th century and possible climate change scenarios. – T. Kallaste, P. Kuldna (eds.). Climate Change Studies in Estonia. Stockholm Environment Institute Tallinn Centre, Tallinn, Estonia, 7–12.

JAAGUS, J., POST, P., TOMINGAS, O. 2004. Storminess on the western coast of Estonia in relation to large-scale atmospheric circulation. – H.-J. Isemer (ed). Fourth Study Conference on BALTEX. Bornholm, Gudhjem, Sweden, 127–128.

JAAGUS, J. 2006a. Trends in sea ice conditions on the Baltic Sea near the Estonian coast during the period 1949/50–2003/04 and their relationships to large-scale atmospheric circulation. – Boreal Environment Research, 11, 169–183.

JAAGUS, J. 2006b. Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. – Theoretical Applied Climatology, 83, 77–88.

JEVREJEVA, S. 2000. Long-term variability of sea ice and air temperature conditions along the Estonian coast. – Geophysica, 36, 17–30.

JOHANSSON, M. M., KAHMA, K. K., BOMAN, H. 2003. An improved estimate for the long-term mean sea level on the Finnish coasts. – Geophysica, 39 (1–2), 51–73.

JOHANSSON, M. M., KAHMA, K. K., BOMAN, H., LAUNIAINEN, J. 2004. Scenarios for sea level on the Finnish coast. – Boreal Environment Research, 9, 153–166.

JOHANSSON, M., KAHMA, K. K., BOMAN, H. 2004. Scenarios for sea level on the Finnish coast. – Boreal Environment Research, 9, 153–166.

JYLHÄ, K., TUOMENVIRTA, H., RUOSTEENOJA, K. 2004. Climate change projections for Finland during the 21st century. – Boreal Environment Research, 9, 127–152.

KLAAMANN, E. 1959. Panga pank. – Eesti Loodus, 2, 108–109 (in Estonian).

KOMAR, P. D. 1998. Beach processes and sedimentation. Prentice-Hall, New Jersey, USA, 544.

KONT, A., JAAGUS, J., AUNAP, R. 2003. Climate change scenarios and the effect of sea-level rise for Estonia. – Global and Planetary Change, 36, 1–15.

KULL, A. 1996. Estonian Wind Atlas. Tartu, Estonia, University of Tartu, Master's thesis, 135 (in Estonian).

LANGENBERG, H., PFIZENMAYER, A., VON STORCH, H., SUENDERMANN, J. 1999. Storm-related sea level variations along the North Sea coast: natural variability and anthropogenic change. – Continental Shelf Research, 19, 821–842.

LOWE, J. A., GREGORY, J. M., FLATHER, R. A. 2001. Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using dynamic storm surge model driven by the Hadley Centre climate models. – Climate Dynamics, 18, 179–188.

MASSEL, R. S. 1999. Fluid Mechanics for Marine Ecologists. Springer-Verlag, Berlin Heidelberg, Germany, 565.

MEIER, H. E. M., BROMAN, B., KJELLSTRÖM, E. 2004. Simulated sea level in past and future climates of the Baltic Sea. – Climate Research, 27, 59–75.

MOBERG, A., ALEXANDERSSON, H. 1997. Homogenization of Swedish temperature data. Part II: Homogenized gridded air temperature compared with a subset of global air temperature since 1861. – International Journal of Climatology, 17, 35–54.

ORVIKU, K. 1934. Sõrve. Loodus ja inimene. Tartu: Tartu University Press, 59 (in Estonian).

ORVIKU, K., SEPP, U. 1972. Stages of geological development and landscape types of the islets of the West-Estonian Archipelago. – Geographical Studies, 15–25.

ORVIKU, K. 1974. Estonian seacoasts. Tallinn: Valgus, 112 (in Russian).

ORVIKU, K. 1992. Characterisation and evolution of Estonian seashores. Tartu: Tartu University, Summary of doctoral thesis, 20.

ORVIKU, K. 1993. Nüüdisrandla. – J. Lutt, A. Raukas (eds.). Geology of Estonian Shelf, Tallinn, 29–39 (In Estonian with English summary.)

ORVIKU, K., JAAGUS, J., KONT, A., RATAS, U., RIVIS, R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. – Journal of Coastal Research, 19, 364–375.

ORVIKU, K. 2006a. Rannaprotsesside teadusliku tõlgendamise vajalikkusest rakenduslike küsimuste lahendamisel rannikul. – M. Sammul (ed). Eesti Loodusuurijate Seltsi Aastaraamat 84. Tartu, 94–113 (in Estonian).

ORVIKU, K. 2006b. Developmental ties between Järve-Mändjala beach and Nasva harbour. – S. Keevallik, A. Järvik (eds.). Eesti Mereakadeemia Toimetised 3. Tallinn, 7–18.

PERENS, H. 2002 Pealiskord. – H. Kään, H. Mardiste, R. Nelis, O. Pesti (eds.). Saaremaa 1. Tallinn, 23–36 (in Estonian).

PACIOREK, C. J., RISBEY, J. S., VENTURA, V., ROSEN, R. D. 2002. Multiple indices of Northern Hemisphere cyclone activity, winters 1949–1999. – Journal of Climate, 15 (13), 1573–1590.

PRYOR, S. C., BARTHELMIE, R. J. 2003. Long-term trends in near-surface flow over the Baltic. – International Journal of Climatology, 23, 271–289.

RAJASALU, R., KEEVALLIK, S. 2001. Winds on the 500hPa isobaric level over Estonia. – Year-book of the Estonian Geographical Society, 33, 66–76 (in Estonian with English summary).

RAUKAS, A., BIRD, E., ORVIKU, K. 1994. The provenance of beaches on the Estonian islands of Hiiumaa and Saaremaa. – Proceedings of the Estonian Academy of Sciensec, Geology, 43 (2), 81–92.

RIVIS, R. 2004. Changes in shoreline positions on the Harilaid Peninsula, West Estonia, during the 20th century. – Proceedings of the Estonian Academy of Sciences. Biology. Ecology, 53 (3), 179–193.

SEPP, M., POST, P., JAAGUS, J. 2005. Long-term changes in the frequency of cyclones and their trajectories in Central and Northern Europe. – Nordic Hydrology, 36, 297–309.

SEPP, M. 2007. Läänemere piirkonnas tekkinud tsüklonid: nende pikaajalised muutused, seosed Põhja-Atlandi ostsillatsiooni ja Eesti ilmastikunäitajatega. – J. Jaagus (ed). Uurimusi Eesti kliimast. Tartu: University of Tartu, 19–31 (in Estonian).

SCHMIDT, T., KAAS, E., LI, T. S. 1998. Northeast Atlantic winter storminess 1875–1995 re-analysed. – Climate Dynamics, 14, 529–536.

SUURSAAR, Ü., KULLAS, T., OTSMANN, M. 2003. Modelling of flows, sea level variations and bottom stresses in the coastal zone of West Estonia. – C. A. Brebbia (ed). Coastal Engineering and Marina Developments VI. WIT Press, Southampton–Boston, UK–USA, 43–52.

SUURSAAR, Ü., KONT, A., JAAGUS, J., ORVIKU, K., RATAS, U., RIVIS, R., KULLAS, T. 2004. Sea level rise scenarios induced by climate change, and their consequences for the Estonian seacoast. – C. A. Brebbia (ed). Risk Analysis IV. WIT Press, Southampton–Boston, UK–USA, 333–343.

SUURSAAR, Ü., JAAGUS, J., KULLAS, T. 2006a. Past and future changes in sea level near the Estonian coast in relation to changes in wind climate. – Boreal Environment. Research, 11 (2), 123–142.

SUURSAAR, Ü., KULLAS, T., OTSMANN, M., SAAREMÄE, I., KUIK, J., MERILAIN, M. 2006b. Hurricane Gudrun and modelling its hydrodynamic consequences in the Estonian coastal waters. – Boreal Environment Research, 11 (2), 143–159.