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Changes in Latvia's seacoast (1935-2007)

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Abstract This paper presents the first compilation of available published scientific material from the 20th century and results of research during the past 15 years in the seacoast process monitoring system. Using the first Latvian coastal land surveys from the 1930's and analysis data from topographic maps from the 1980's, changes in the Baltic coastline (growth and erosion) over a period of 50 to 60 years have been determined and maps of these changes have been made. The data indicates significant seacoast erosion that exceeds 50–60 m at the open Baltic seacoast, but reaches a maximum of 100–200 m, especially influenced by the large ports (Ventspils, Liepāja). Coastal erosion is significantly less along the coast of the Gulf of Riga. Coastal growth by the accumulation is seen along limited portions of the coast. During the last 15 years, coastal erosion due to severe storms has increased significantly by a factor of 1 to 3 times compared with the rate observed during the last 50–60 years of the 20th century.

Keywords *Baltic Sea, coastal processes, storms, cartographic material analysis, change tendencies, influence of harbors, deficit of sediments.*

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INTRODUCTION

Latvia's seacoast is approximately 497 km long, including 253 km along the Gulf of Riga. By its configuration and exposure to dominant southwesterly (SW) and westerly (W) winds, the coastline can be divided into three main sections that differ according to coastal morphology and morphodynamic processes: the open Baltic seacoast (Nida – Ovīšu cape), the Irbe Strait coast (Ovīšu cape – the Cape of Kolka), and the coast along the Gulf of Riga. The latter can be further divided into three lesser coastal subsections: the Kurzeme coast stretching from the Cape of Kolka to the city Jūrmala, the southern coast from Jūrmala to the port of Skulte, and the Vidzeme coast form Skulte to Ainaži (Eberhards 2003) (Figs. 1, 8).

The first published scientific information concerning the morphology of Latvia's seacoasts, geological structure, and coastal processes date from the 1930's and 1940's (Sleinis 1937; Rutkis 1960; Saule-Sleinis 1960). The first extensive look at coastal formation, morphology, and coastal processes during the first half of the 20th century is the monograph by V. Ulsts (1957) and the book „Latvian SSR geology" (Ulsts 1961), as well as publications by P. Revelis (1938) and V. Gudelis (1967).

Publications by R. Knaps (1966, 1968, 1982), I. Korobova (1974) and I. Kozhuhovs (1968) are devoted to the transport and flow of sediments along the eastern coast of the Baltic Sea, while works by V. Ulsts (1959, 1963, 1964, 1968) are concerned with the differentiation of the transport of deposits and the analysis of concentrations of heavy minerals in the lithodynamic zone. In the second half of the 20th century research continued in contemporary processes, coastal evolution, and lithodynamics (Ulsts *et al.* 1967; Veinbergs *et al.* 1982; Veinbergs & Daņilāns 1992; Venska 1990; Shuisky 1969, 1982; Boldirev 1981, 1992). Wider information about the conditions of Latvia's seacoast can be found in reports to the All-Union Marine

Geology Institute by V. Ulsts, I. Veinbergs, V. Venska, I. Daņilāns and B. Saltupe; they are not published, but the main results are summarized in the research by V. Ulsts (1998) "The Baltic Sea's Latvian coastal zone".

From 1987 the Geography (now the Geography and Earth Science) Faculty of the University of Latvia began systematic study of the processes and relief of the Latvian coastline, establishing a coastal monitoring network that, by 1993–1994, covered the entire coastline (Eberhards & Saltupe 1999), and mapped the various types of seacoast, dunes and beaches. The results of studies by the University of Latvia's Geography and Earth Science Faculty at the end of the 20th and beginning of the 21st centuries concerning the seacoast, including aeolian (wind-generated) processes, coastal erosion, and the influence of ports on coastal changes, have been compiled in various publications (Eberhards & Saltupe 1995; Eberhards 1998, 2003; Lapinskis 2005). Separate publications are dedicated to the evaluation of coastal erosion and damage done by the severest storms during the recent years 2001 and 2005 (Eberhards *et al.* 2006; Eberhards & Saltupe 2006; Eberhards 2006).

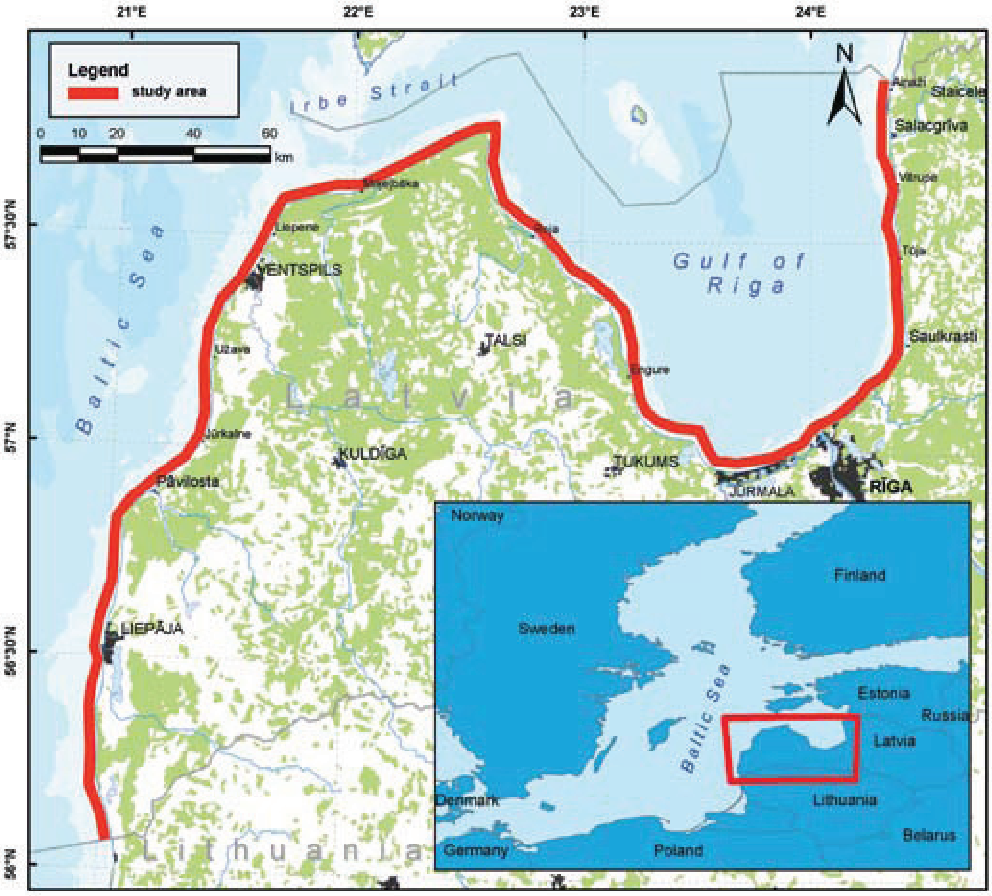

Fig. 1. Map of the region of study. Compiled by G. Eberhards and J. Lapinskis.

MATERIALS AND METHODS

In order to determine changes in Latvia's coastline during the last century, the first coastal land survey plans were used (1935/37, 1938) with a scale of 1:2500 and 1:5000, as well as port and city plans (1900–1990), and topographic maps issued by the USSR Main Geodesic and Cartography Board during the years 1980–1987 (scale 1:10 000).

The first topographic survey plans included only those Latvian coastal zones that were given to farmers for agricultural use in the first half of the 20th century. For those portions of the coast that consisted of dunes and forests (state forests), such topographic materials did not exist. Therefore it was not possible to analyze changes, based on cartographic material, for those sections of the coast consisting of forests outside of populated areas. Here the changes during the last half of the 20th century were estimated by interpolation of coastal mapping, morphology and geological structure by comparing with adjoining populated area changes and the coastal zone's relief and structure.

For the populated sections of coastline with buildings, roads, and a hydrographic network, definite (chosen) lines perpendicular to the coast from the same objects (buildings, road intersections) according to topographic maps from 1935/37 or earlier and from the 1980's were used to determine changes in distances to the tops of the coastal cliffs. For certain portions of the coast erosion and receding from 1980 to 1990–1995 were surveyed with instruments. This made it possible to determine the maximum predominant coastal receding or growth among the low–lying coastal areas such as Bernāti – Pērkone, Jūrmalciems, and the fishing villages along the Kurland coast of the Gulf of Riga.

After an analysis of the data obtained from the cartographic materials and on-site mapping, a map of the predominant coastal processes of Latvia during the last century (1935/37–1990) was made (Figs. 2, 3), maximum coastal changes (receding or growth) were determined, and the long-term rate of coastal erosion was calculated (m/year). After regular study of the coastal zones and mapping materials from 1990 to 2007 inclusive, coastal erosion maps after the severest storms were made, and by measurements taken at monitoring stations, the extent of coastal erosion during the last 15 years was determined (Figs. 4, 5).

Using morphological and geological data on the Latvian coastal zone, a map of the Latvian seacoast's development trends during the past 2500–2000 years, the time of formation of the Post–Litorina Sea, was made (Fig. 6). Local information about coastal erosion and sedimentary accumulation was given by the research of V. Venska (1985–1990) in the context of the Latvian SSR Geological Board (later the state enterprise "Latvia's Geology") at several locations (Liepāja, Bernāti, Pērkone, Staldzene, Kolka and Siliņi). Information about changes in the coastline due to the activity of Latvia's ports during the past 50–100 years is compiled in the coastal change map of the past century. The analysis of all of the aforementioned data and materials enabled us to come to conclusions about changes in Latvia's coastline during the past century and about the continuing tendencies in these processes in the early 21st century, in relation to climate changes.

RESULTS AND DISCUSSION

The map (Fig. 6) that shows the predominant features of coastal processes after the regression of the Litorina Sea during the past 2500–2000 years, according to geological structural and morphological data, is the first point of evidence that can be used comparatively in assessing developments of the seacoast in the 20th century and nowadays, as well as of the degree of inheritability of the processes.

There is no historical cartographical information about the processes of the Baltic seacoast and the Gulf of Riga during the first half of the 20th century. Only the monograph by V. Ulsts (1957) discusses the morphology of the Gulf of Riga's coast and sketches the coastal processes.

Another point of evidence that makes it possible to determine primary changes in the Latvian seacoast and their tendencies from the 2nd half of the 20th century to the present time, is found of the changes in the coastal features since 1967/69 due to the most damaging storms, divided into erosion of various features-dunes,

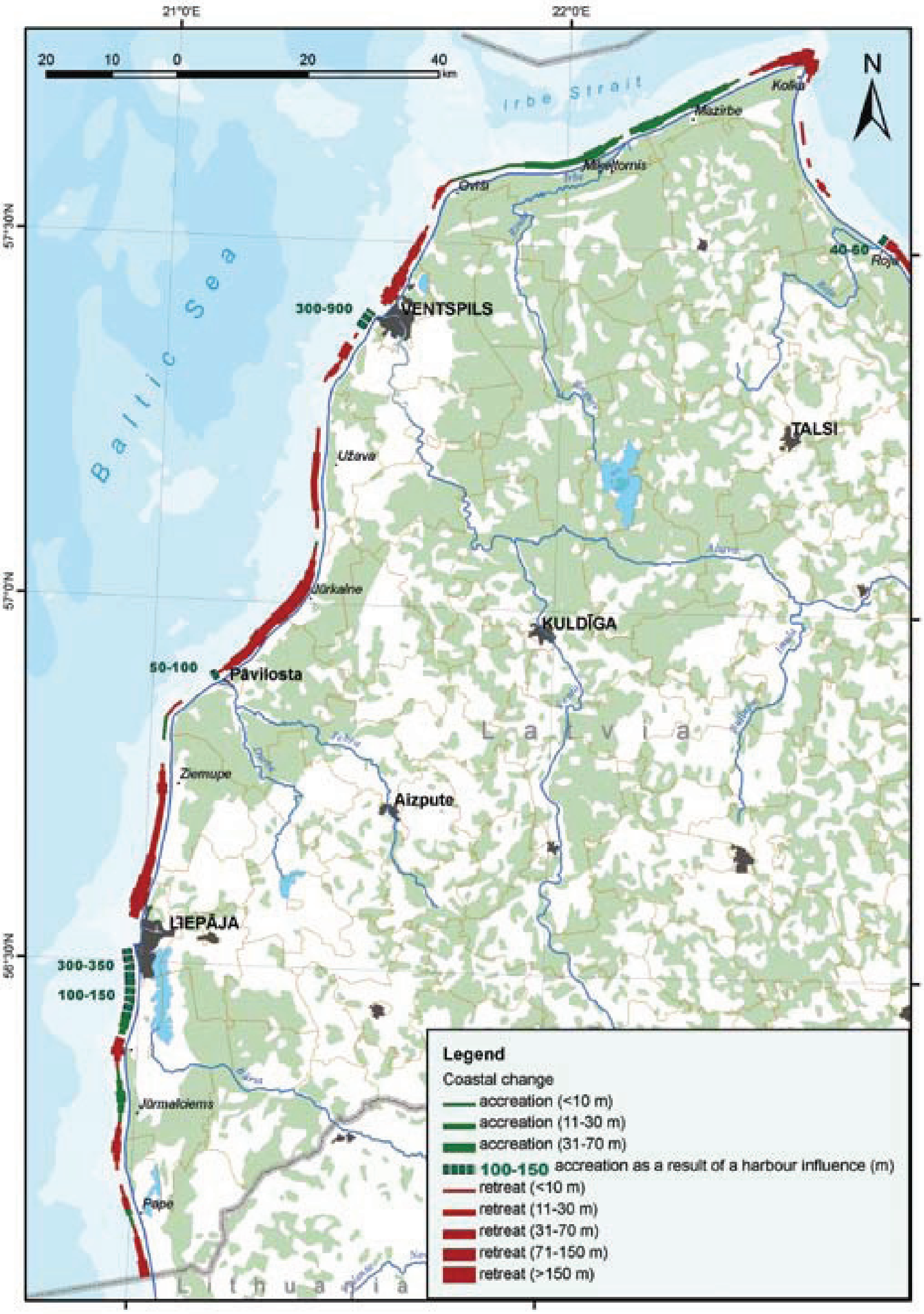

Fig. 2. Changes to the Kurzeme coast of the Baltic Proper (1935–1990). Compiled by G. Eberhards and J. Lapinskis.

cliffs, terraces—that characterize the sum of long-term coastal changes of the last 30–35 years. Some information is to be found only about the Gulf of Riga's coast, because there are well–preserved morphological erosional features and accumulated formations (terraces above the beaches and foredunes).

In 1984, L. Ļakmunds („Ļenmorprojekt"), according to the unpublished materials of R. Knaps, created a map–scheme of the Latvian seacoast, in which the coast on the whole was judged as relatively stable (dynamic balance, weak erosion and accumulation), but pronounced erosion was found in only small locales (Fig. 7). These conclusions were based on the partial investigation and evaluation of the coastal zone after the strong storm of 1982, which was the strongest since the damaging storm of 1967/69. However, the most complete information about changes in the Latvian seacoast during the last century (1935/37–1990) are given by the aforementioned map made according to the analysis of coastal township plans and topographic maps (Figs. 2, 3).

A comparison of the maps (Figs. 2, 3, and 6) gives evidence that the primary locations of erosion and accumulation along the Latvian seacoast are inherent, that is, long-term erosion and accumulation, possibly with interruptions, have characterized the same coastal locations during the entire Post–Litorina time. V. Ulsts (1998) had already indicated such characteristics.

Based on repeated Latvian coastal research data (1956, 1963, 1967, 1976, and 1987) V. Ulsts (1998) concluded that during the second half of the 20th century (until 1990–1997) the zones of coastal erosion, which could have been attributable to global or regional climate change, had not expanded. It was noted that along the entire open Baltic seacoast, only in 1956 and 1967, during especially strong storms, regional erosion took place, including accumulative coasts with foredunes, from Nida to Kolka. Still, during the time between these storms, there was a dynamic balance or accumulation, with erosion only in local coastal areas, mainly along the cliffs of Ulmale – Jūrkalne and at Kolkasrags (the Cape of Kolka).

After mapping of the coast after storms and according to data obtained from monitoring stations from 1990 to 1998, the length of coastline subject to active erosion reached 120–150 km, or 25–30% of the total coastline (Eberhards & Saltupe 1993; Eberhards 2003).

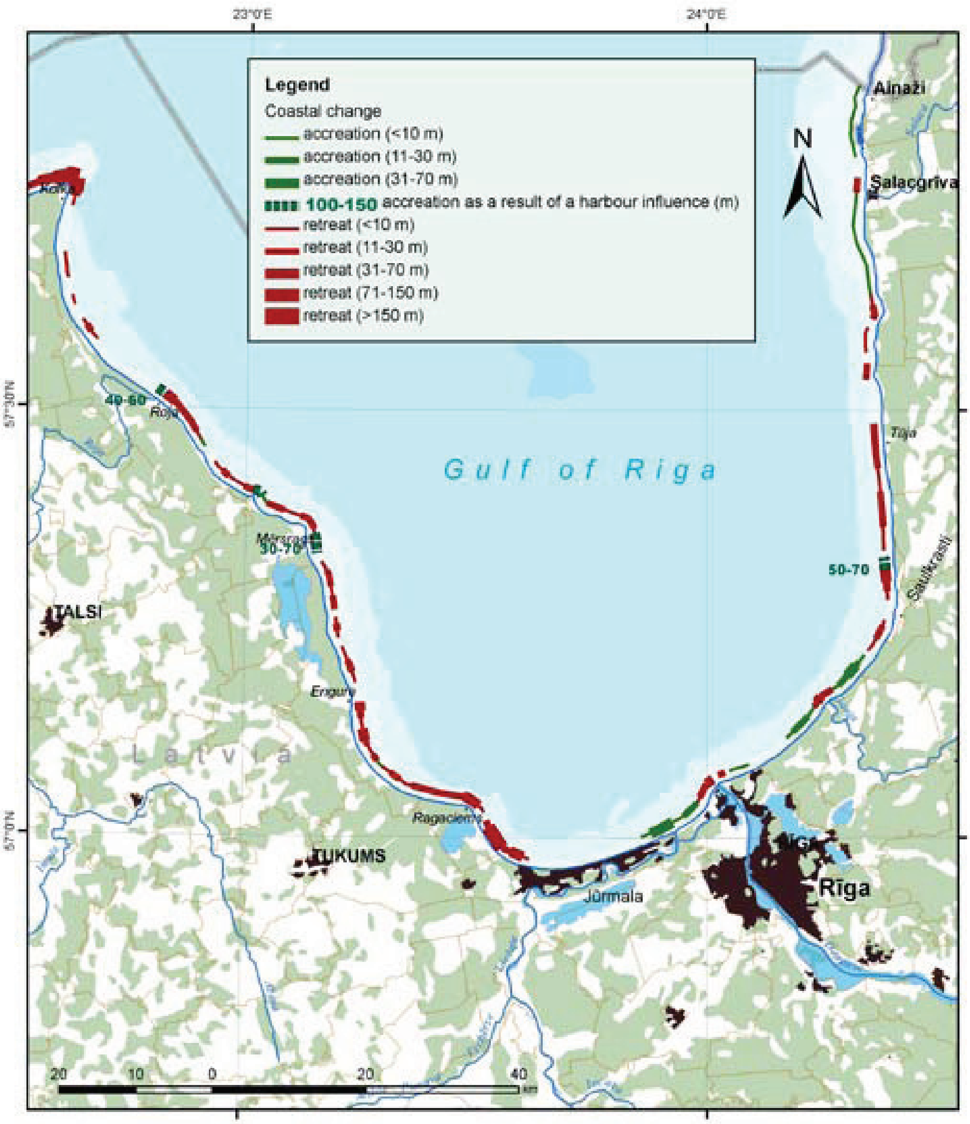

Fig. 3. Changes to the coast of the Gulf of Riga (1935–1990). Compiled by G. Eberhards and J. Lapinskis.

At the end of the 20th century (1995–1997), according to V. Ulsts' calculations (1998), the length of coastline exposed to active erosion (abrasion) reached 154 km (31% of the total coastline), with 73 km along the open Baltic Sea and 81 km along the Gulf of Riga.

During the past century, the changes in the seacoast, the division of erosion sections, and the maximum and long-term average erosional speeds on the open

Baltic seacoast, as well as on the Gulf of Riga's coast, have been significantly different, compared to the activation of these processes during the past 15 years (1992–2007) (Figs. 2, 3, 4, and 5). These changes were primarily caused by the orientation of separate sections of coastline relative to wind directions during storms, the repetitiveness of storms, the direction of long-shore sediment drift, the strength and amount of sedimentary deposits in the shallow sea's lithodynamic zone, as well as the geological structure of the coast and the coastal valley resistance to wave erosion. In some locales, the significant role is played by ports. The differences of the influences of the sum of these conditions in a local cross-section are especially visible along the coast of the Gulf of Riga, where, unlike the open Baltic seacoast, the longshore sediment transport is 5 to 10 times lower (Knaps 1968). Changes along the western gulf coast (Kolka – Jūrmala) are associated only with NW and N winds during storms; along the southern coast (Jūmala – Skulte) with W, NW, and N winds, while the eastern coast is impacted by the entire spectrum of dominating sea winds (SW, W, NW) (Fig. 1). During strong NW storms (frequency: every 2 to 8 years), with maximum storm surge levels >1.4–1.6 m a heightened risk of erosion affects the Kurland coast, but during ordinary storms the least threat of erosion is along the gulf's Vidzeme coast (Skulte – Ainaži), which is relatively resistant to erosion due to geological structure (Devonian sandstone and clay, or glacial till), with a wide coastal zone of shallow water and a high concentration of boulders. A noteworthy degree of erosion along the entire Vidzeme coast is possible only during very severe, long-lasting storms (wind speeds >30 m/s, >10–20 hours) with storm surges surpassing a maximum of 1.8–2 m (once every 30–36 years).

The accumulative coast of the Gulf of Riga (Jurmala – Skulte), with its predominant sediment accumulation since the time of the Littorina Sea, is ensured by the direction of sediment transport towards the edges of the gulf along both coasts (Knaps 1966), as well as by the long-term inflow of sediments from the three main rivers

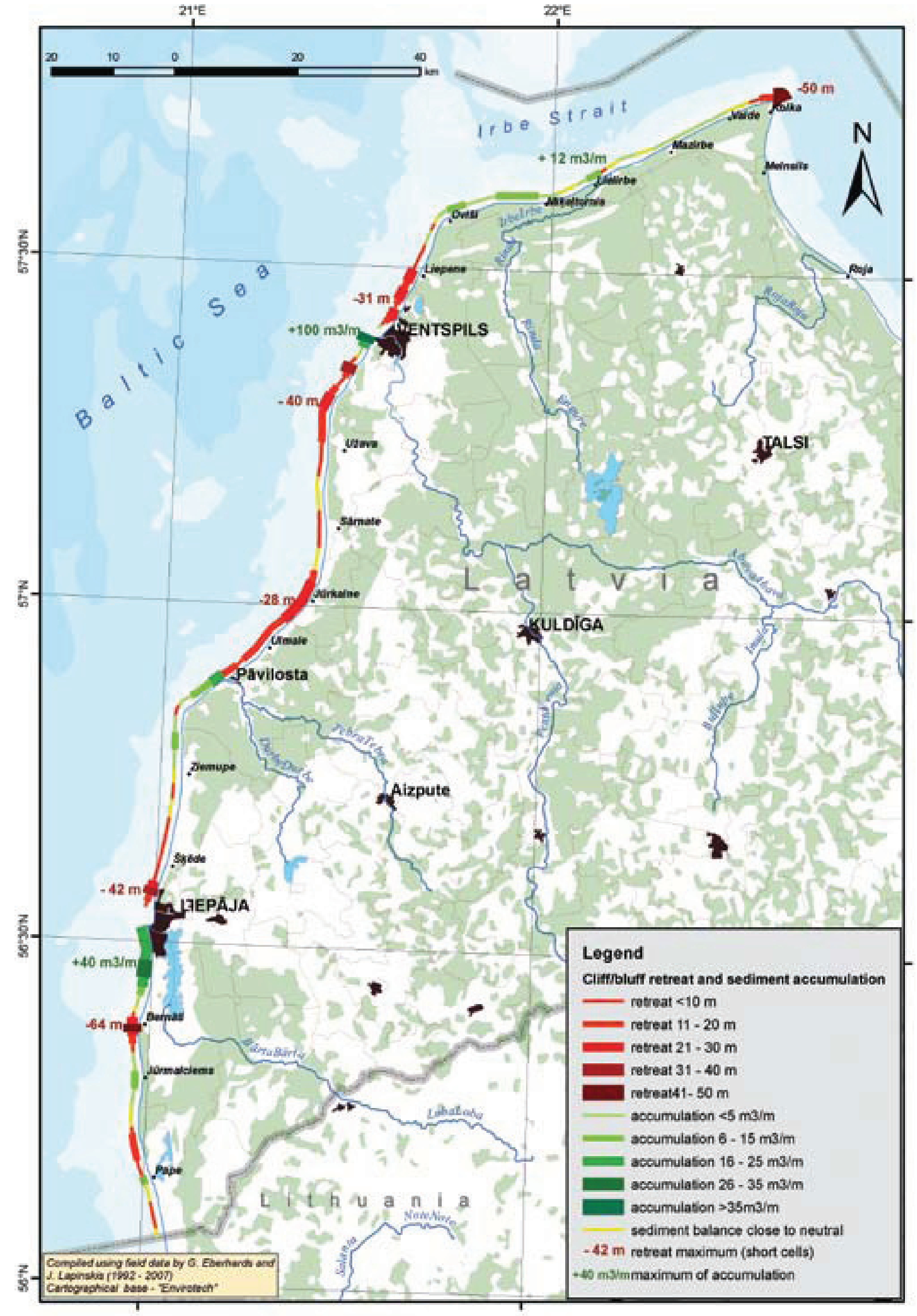

Fig. 4. Changes to the Kurzeme coast of the Baltic Proper during the past 15 years (1992–2007). Compiled by G. Eberhards and J. Lapinskis.

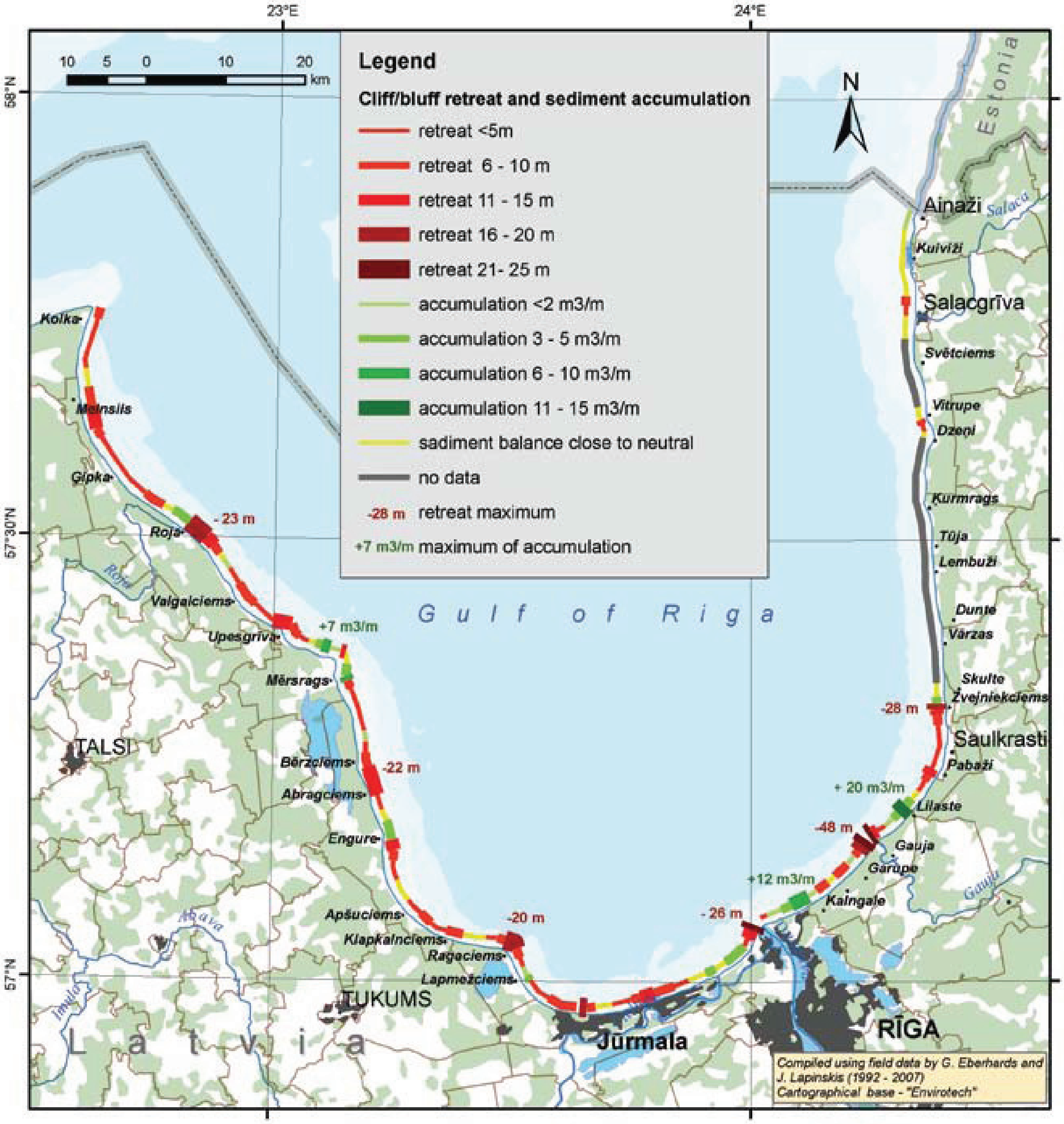

Fig. 5. Changes to the coast of the Gulf of Riga during the past 15 years. Compiled by G. Eberhards and J. Lapinskis.

(Gauja, Daugava, Lielupe). It is subject to noticeable erosion only during W and NW storms, when the maximum wind-driven surges exceed 1.5–1.6 m.

During the last 50-60 years of the 20th century, from Kolka to the city Jūrmala changes have predominately been a mosaic-style washing away of the coast in many small coastal sections, along with a few locations of accumulation (Fig. 5). Washed away are primarily the low-lying (2–5 m above sea level) coastal zones with average rates of 0.3–0.5 m per year. A pronounced accumulation and growth of the coastal zone up to 50–200 m is found only up drift of the ports of Roja, Kaltene, Mersrags, and Engure in 0.5–1 km stretches. The process of coastal erosion was activated by the devastating storm of 1969. During 1980–1982, according to the unpublished data of R. Knaps, from Kolka to Jūrmala the coasts were typically in equilibrium, with weak erosion and accumulation in local areas and with influence of ports.

During the last 15 years (1992–2007), with at least four southwesterly or westerly wind storms; the erosion rate has extended beyond that of the most severe storms before. Along the entire coastal zone from Kolka to Jūrmala, as a result of the storms of the last few years (2001–2007), the accumulative beach terraces and undeveloped fore-dunes that formed after 1969 were washed away.

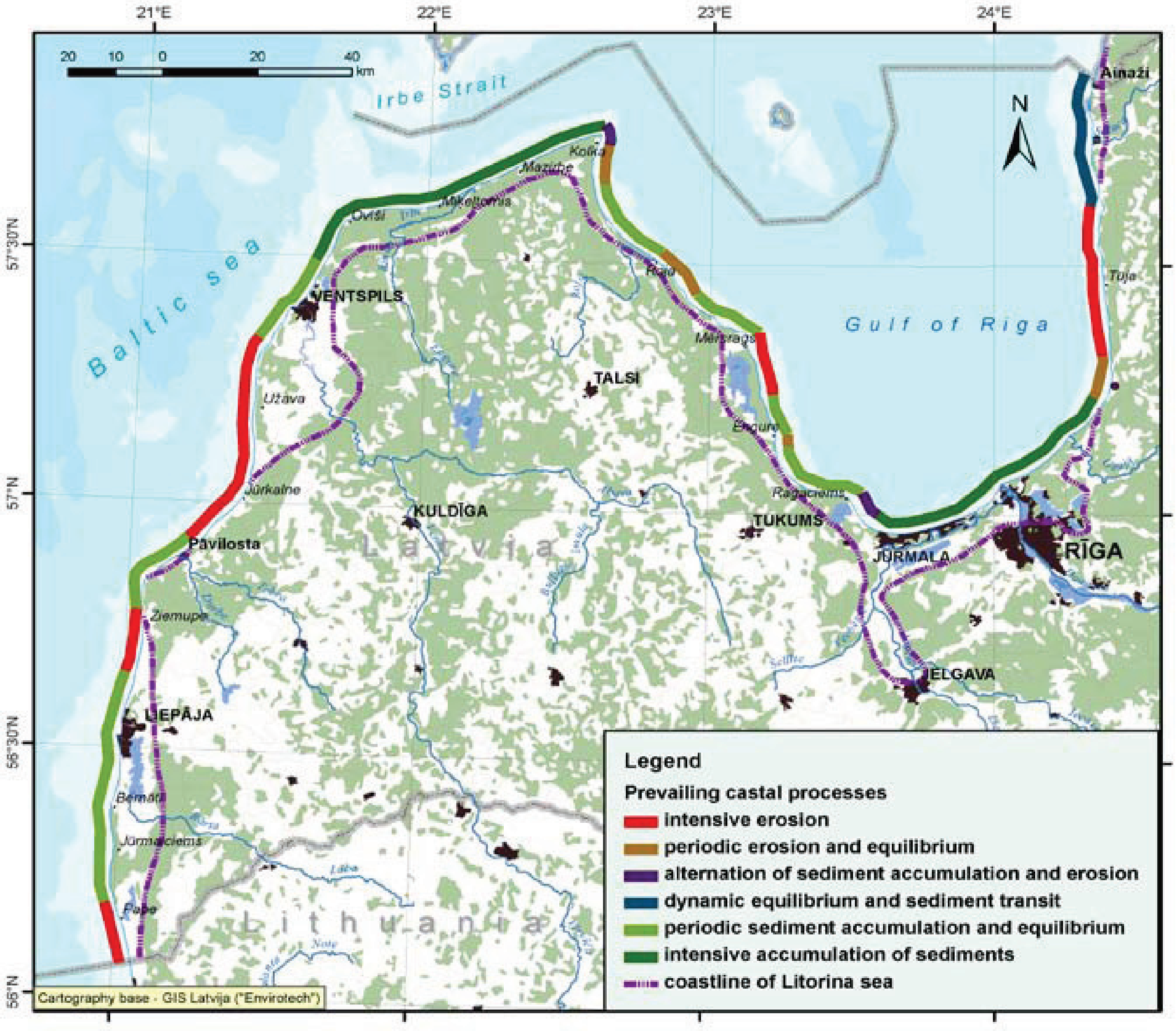

Fig. 6. Coastal processes along Latvia's coastal areas during Post–Litorina time (2500–2000 years). Compiled by G. Eberhards and J. Lapinskis.

Typical coastal erosion sections, usually 100–200 and up to 500 m in length retreated 20–25 m, but along the southern coast near certain ports (Skulte, Riga) and near the mouth of the Gauja, 30–50 m (Fig. 5). Furthermore, the average rate of coastal erosion reached 1–3 m/year. Compared with the rate of erosion for a 40–50 year period in the 20th century, the present rate has increased. Considered transit-type coasts with weak accumulation and erosion 20–25 years ago (according to R. Knaps), at the beginning of the 21st century they can be classified as transit-type coasts with sediment deficit and weak or average erosion.

After the storm of 1969, along the southern coast of the Gulf of Riga (Jūrmala – Skulte) the accumulative renewal of dunes and foredunes continued, ensured by sediment transit along the Kurland coast and input brought by the river Gauja along a coastal stretch reaching. The erosion of dunes and the widening of the zone of erosion continued only at the eastern end of the island Daugavgrīva, on both sides of the mouth of the Gauja and at Saulkrasti.

During the 1980's the Gulf of Riga's Vidzeme coast was considered a transit–type of coast with a deficit of sediments, weak abrasion, and stable against erosion in the section stretching from Vitrupe to Ainaži. During the last 15 years, only during the especially severe and persistent storm of January 2005 was there significant washing away of the coast, but in a section from Salacgrīva to Ainaži there was accumulation in the wide, low-lying terrace with field vegetation above the beach (*Randu pļavas*) (Eberhards *et al.* 2006; Eberhards & Saltupe 2006).

According to analytical data from carthographic material, along the open Baltic seacoast, during 50–60 years of the last century, the erosion of coastline has been predominant both along the high cliffs (10–18 m) (Pāvilsosta – Lībciems) as well as the accumulative–type barrier dunes of the Litorina Sea and Post–Litorina lagoon plains. In the erosional sections, coastal retreat

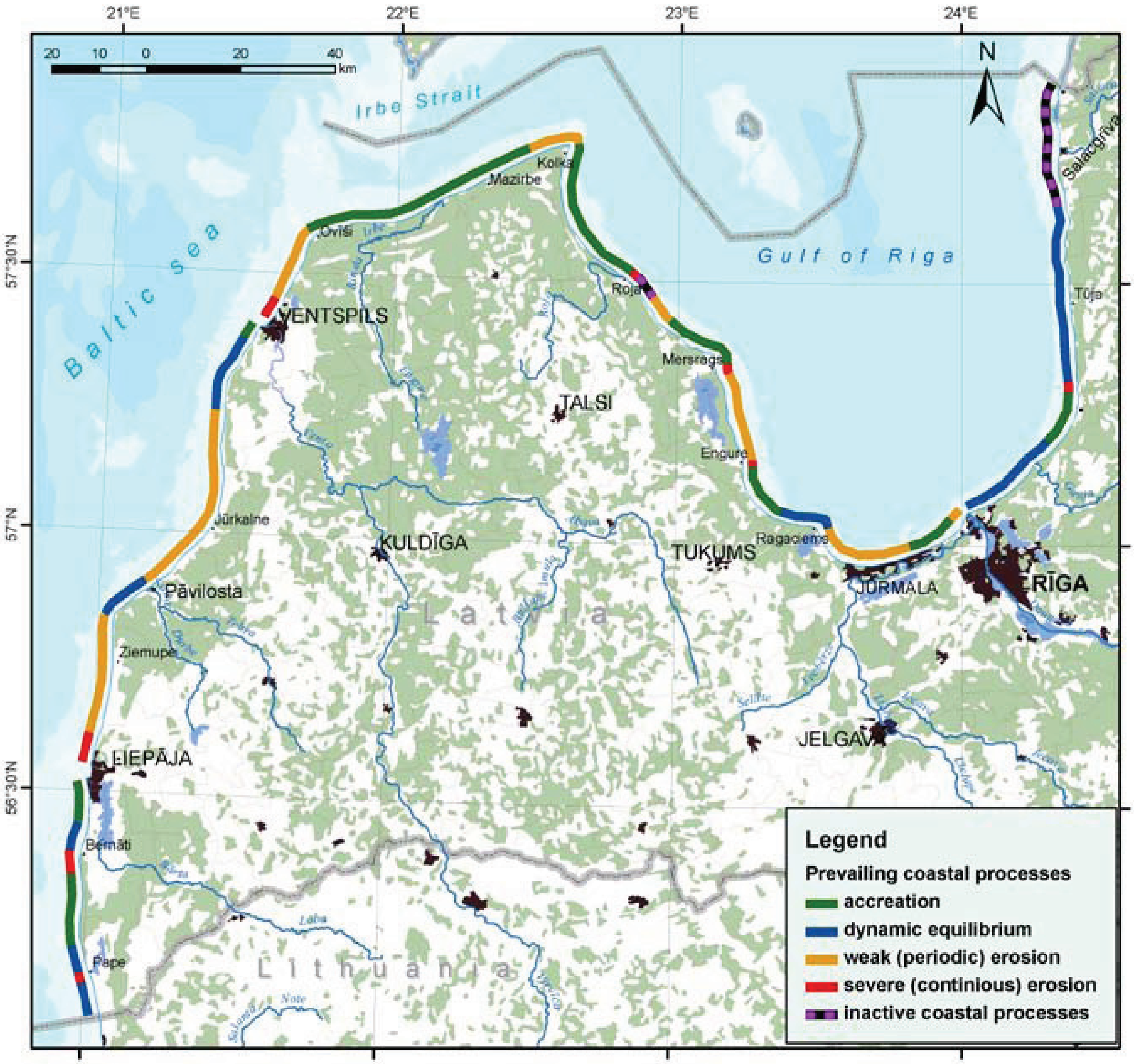

Fig. 7. Coastal processes during the 1980's (map drawn according to unpublished data by R. Knaps). Compiled by G. Eberhards and J. Lapinskis.

reached more than 50 m (0.5–0.7 m/year), reaching a maximum of 100–200 m (1.4–2.8 m/year) at the Cape of Bernāti, Jūrkalne, and to the north of the ports of Liepāja and Ventspils (Fig. 2). Only in certain separate local zones (Pape, Jūrmalciems, Akmeņrags) is there dynamic equilibrium or accumulation with development of foredunes.

Significant accumulation and growth of land averaging 250–350 m and intense formation of foredunes is found before the southern jetties of the ports of Liepāja and Ventspils (Fig. 2). Before the southern jetty of the port of Ventspils has the increase in coastal area reached 600–900 m (Eberhards 2003).

During the last 50–60 years of the 20th century, along a section of the Irbe Strait (approx. 60 km) from Ovīšu rags to Vaide, the beaches and fore-dunes have increased by 50–100 m (0.7–1.4 m/year) due to the flow of sediments along the eastern Baltic coast. This growth of coastal territory has been a tendency for the entire Post–Litorina time. Only in the region around the Cape of Kolka (a zone approx. 5 km in length) has there been a catastrophic washing away of coastal dunes during storms, reaching 200-300 m at the Cape of Kolka (2.8–4 m/year). According to R. Knaps' data, this tendency has been observed since 1850.

Systematic measurements at the Baltic seacoast erosion monitoring stations give evidence that there has been a rapid increase in the rate of erosion in recent times (Eberhards 2003; Eberhards *et al.* 2006). Because of the effects of five major storms (1993, 1999, 2001, 2005, 2007), the maximum width of washed away coastline reached 30–64 m (Figs. 4, 5). The sites of maximum erosion are mainly at the cliffed coast from Pāvilosta to Jūrkalne, at the largest capes (Mietrags,

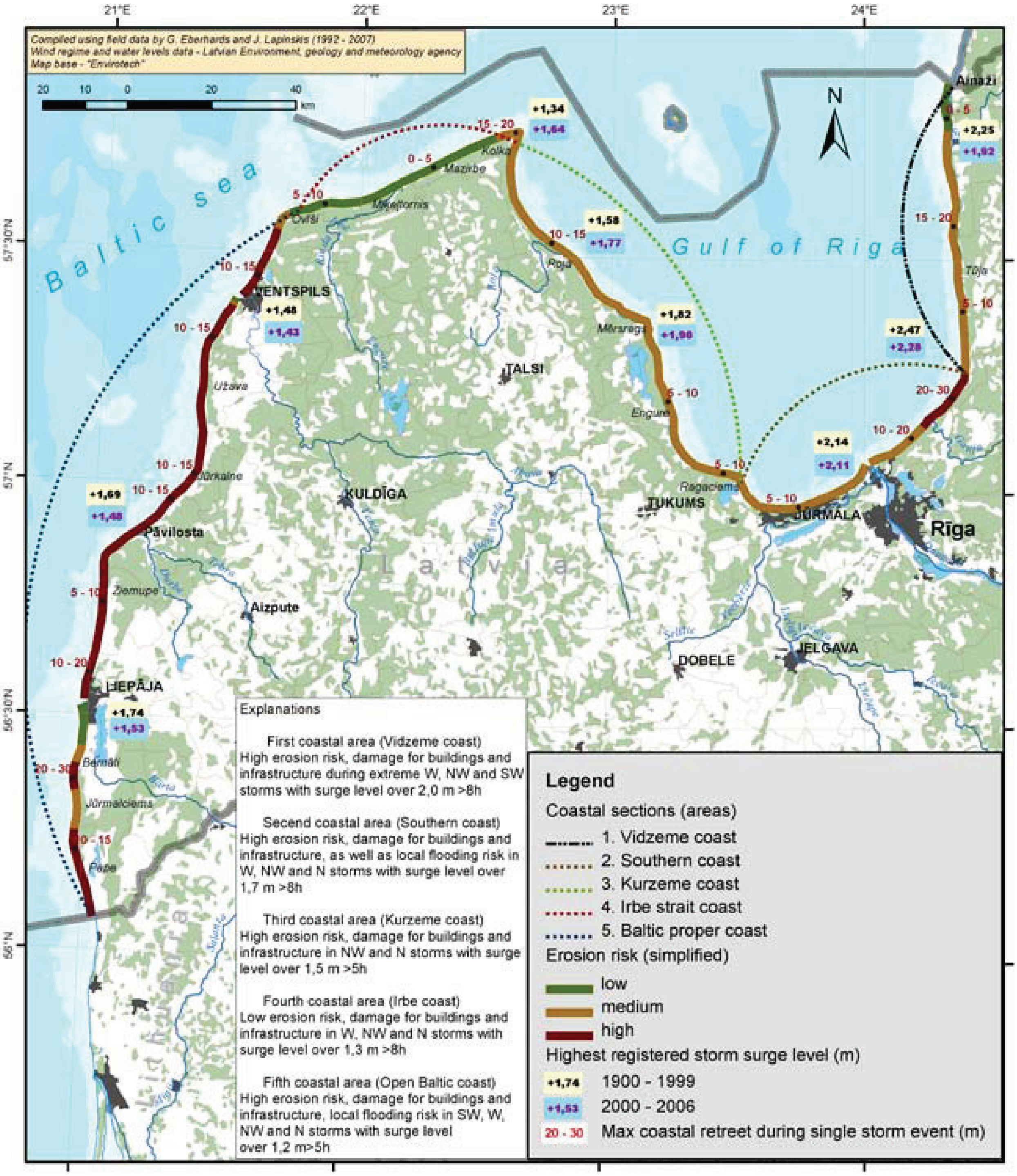

Fig. 8. Latvia's sea-coast zones with different erosional risk. Compiled by G. Eberhards and J. Lapinskis.

Bernāti, Melnrags), as well as down drift the ports of Liepāja and Ventspils (Fig. 4). The erosion at the Cape of Kolka during the storms of 2001 and 2005 was especially catastrophic due to predominant W and NW winds (Eberhards 2003; Lapinskis 2006).

Significant coastal erosion along the open Baltic seacoast was due to influential natural conditions: the location along the eastern edge of the Baltic Sea, the high frequency of storms with wind speeds at a maximum of 30 or more m/sec, storm surges along the coast above 1.0 to 1.2 m, the widespread coastal composition of unconsolidated material, as well as the lack of a coastal ice coating during autumn and winter storms. The retreat of the high cliff along Pāvilosta – Jūrkalne, Melnrags, and Bušenieki – Liepene, with their complex geological structure, was noticeably accelerated by slope processes (Eberhards 2003).

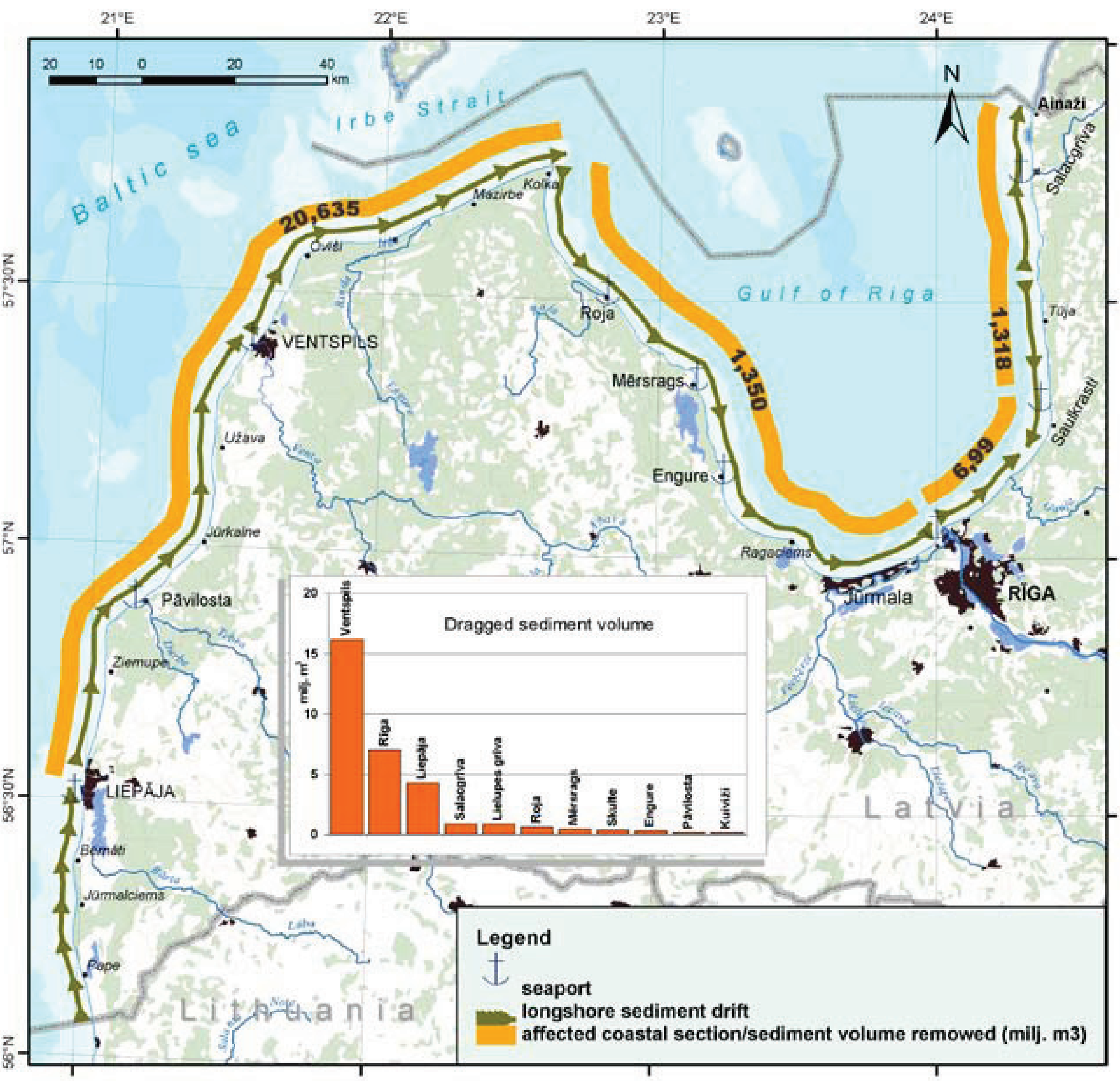

Fig. 9. Sand dredged from Latvia's port shipping channels and dumped at sea far offshore or on inland (1990–2004). Compiled by G. Eberhards and J. Lapinskis.

During the storm of 2005, when almost half of Latvia's coastline was subject to regional erosion, locations of intensive coastal erosion independent of their coastal type alternated with locations where only beach erosion and negligible coastal, fore-dune, and above-beach terrace erosion took place. These "zero-points" (0.3–0.5 to 1.5-2 km long coastal zones) usually last with negligible changes for 10 to 15 years (Eberhards *et al.* 2006). The coast of the Gulf of Riga saw erosion along 40% of the total coastline (except for the Kurland coast). During the more typical storms of the last few years, depending on wind direction, speed, and level of storm surges, a shorter stretch of coastline was subject to significant erosion (15–30%).

A map of the increased coastal erosion conditions was made based on the mapping of coast erosion, measurements of erosional intensity, and hydro-meteorological information during severe storms of the past ten years. According to the aforementioned factors, the Latvian coast was divided into five different coastal zones (Fig. 8). For NW storms, the most sensitive area threatened by damage to structures and infrastructure, high coastal erosion, and local flooding is the Kurzeme coast of the Gulf of Riga (Kolka – Jūrmala); the threat of damage to built-up residential areas is greatest along the open Baltic seacoast (Nida – Ovīšu cape); the greatest threat by coastal erosion and flooding is along the Gulf's southern coast (Jūrmala – Saulkrasti). Stable and little threatened by erosion is the coast along the Irbe Strait, with the exception of the Cape of Kolka (from Vaide to Kolka). The eastern shore of the Gulf of Riga and the buildings along it are seriously threatened only during rare, extreme storms.

CONCLUSIONS

There have been severe storms along the open Baltic seacoast with SW, W, and NW winds recurring every 2 to 6 years. Sea water levels have increased during storm surges (Liepāja, Pāvilosta, Kolka, Daugavgrīva), while the average sea level increase has been negligible. The severe storm season has increased (from October—November to February or even March). Especially characteristic are January storms with positive air temperatures and a lack of ground freezing and coastal ice formations (Eberhards & Purgalis 2008).

The rate of coastal erosion during any single storm has increased, averaging 3–6 m with maximum reaching 20 m. These tendencies directly coincide with comparable results over the last century obtained from research in Poland (Zawadzka & Kahlan 1993, 1995).

There has been a gradual but well-defined lengthening of the coastal erosional zones along accumulative coastal capes and cliffs, and a gradual straightening of the coastline along the open Baltic seacoast and the Gulf of Riga.

An increasing deficit of sediments is occurring in the coastal underwater slope. Sand dredged from ports and shipping channels is dumped at sea far from the coast (at depths of 10-20 m) or is transported on land. The volume of dredged sediment surpassed a total of 29 million m^3 in the last 14 years (Fig. 9). As well during the last ten years (1993–2003) there has been a well-defined deficit of sediments along the northern Lithuanian coast, and an increase of erosion from Būtingė to Nida near the Latvian border (Žilinskas & Jarmalavičius 2003; Bitinas 2005).

As a result of coastal erosion, the threat of loss of inhabited areas and infrastructure has increased significantly, encouraged by the rapid expansion of coastal land development (mainly along the Gulf coast from Roja to Jūrmala and Saulkrasti at the gulf's southeastern end, and also along the Vidzeme coast). Inadequate and usually ineffective coastal reinforcements have been made in some areas.

As a cumulative result of activity in the ports, located at the mouths of Latvia's largest rivers (except Liepāja), the dredging of shipping channels, as well as the construction of the hydroelectric stations on the Daugava river, the transport of alluvial deposits into the sea has been interrupted. This is felt most negatively along the southern coast of the Gulf of Riga, where according to the calculations of V. Ulsts, the total input of sediments from rivers Lielupe, Daugava and Gauja was reaching 10000-15000 m^3 per year. Now only the Gauja "feeds" the coastal beaches from its mouth to the east to Pabaži (approx. 8 km). The positive effect is observable only as far as Lilaste (approx. 5 km), where the accumulation of sediments is evident along the beach and the fore-dunes.

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