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Hurricane *Erwin* 2005 coastal erosion in Latvia

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Abstract The article represents the first experience and assessment of coastal changes during the severe storm that occurred in Latvia 2005. This study shows that during the violent wind, the wave regime and high storm surges changing in time and space, the Latvian coastal retreat was greatly varying. More than 190 km of coastline were affected by the attack of storm waves; the retreat was mostly 3–6 m, with a maximum of 15–27 m. Severe soft cliff erosion and retreat were located along the open Baltic Sea coast north from Cape Melnrags up to Ventspils and Cape Oviši, Cape Kolkasrags area, southern and eastern coast of the Gulf of Riga. The total volume of material washed out from the sub-marine part of the coastal zone (upper beach, foredune, coastal cliffs) of Latvia was approximately over three million m3 of sediments, and about 0.9 km^2 of land was lost.

Keywords *Latvian coast, wind regime, water level fluctuations, coastal erosion foredune, beach, sediments.*

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INTRODUCTION

Similarly to other coastal areas worldwide, the Latvian Baltic Sea coastal zone during the last decades has been subjected to notable changes, presumably due to global warming, anthropogenic factors, and increasing damage of storms during the last several decades (Eberhards, Saltupe 1995). This paper is the first review of identifiable short term erosional and accretion processes in numerous sectors along the Latvian coastline occurring during the hurricane *Erwin* in 8–9 January 2005. The main objective was to access coastal retreat, calculate wash-out sediment volumes according to coast exposure and geological structure, wind regime and relative sea-level fluctuations, identify new risk zones and calculate losses of land and infrastructure.

The total length of the Latvian Baltic Sea coast is about 496 km, 254 km of which is the eastern coast of the Baltic Sea between Nida (boundary with Lithuania) and the Cape Kolkasrags (Fig. 1). The coastline has been markedly straightened by prolonged marine erosion and deposition (Gudelis 1967; Ulsts 1998). In terms of geological structure, the lithology of the deposits composing the coast and height of the coast, in view of the character of present-day coastal geological processes during the past 30–50 years, the Latvian coast can be divided into two main types: cliffed,

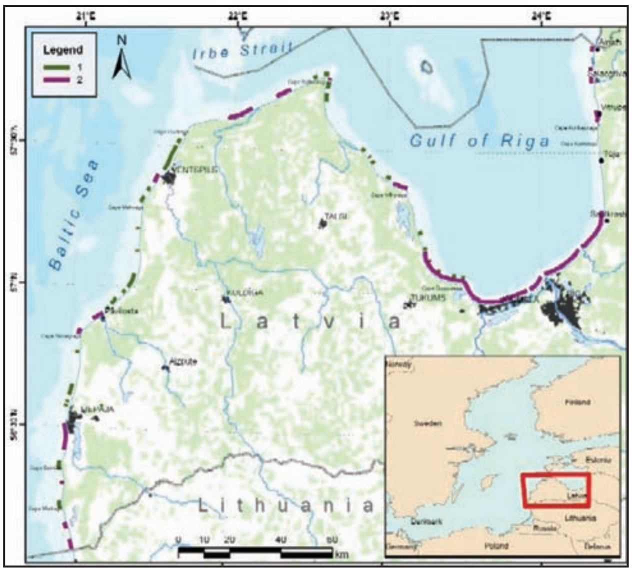

Fig. 1. Sketch map of the Latvian coast. 1 – cliffed coast retreat monitoring stations; 2 – accumulative coast monitoring stations.

abrasional or wash-out, and gently sloping, generally advancing and depositional.

In the section from Nida to Cape Oviši stretch of a gently-sloping, outcurving sandy depositional coast with the forelands—capes (Mietrags, Bernāti, Akmeņrags, Melnrags, Oviši) alternate with shallow embayment that usually have 10–20 m high soft cliffs, partly with complete geological structure, subjected to storm erosion (Eberhards 2003). Only the advancing depositional dune coast, about 70 km in a length along the Irbe Strait, of clear northeastern and eastern orientation, is markedly straightened.

Along the Baltic Proper coast (Nida–Cape Oviši) and the western (Kurzeme) and southern coast of the Gulf of Riga, soft cliffs face is formed by various genesis Quaternary deposits (glacial till, glaciofluvial, marine, eolian, organic). Hard cliffs (a height 4–6 m), consisting of Middle Devonian sedimentary rock (sandstone, clay, siltstone) and covered by a thin layer of Quaternary sediments, occur only along the Vidzeme coast of the Gulf of Riga between villages Tūja and Vitrupe and partly the Kurzeme coast at the Kaltene village. Along the Latvian coastline in certain areas high and lower ranking forelands (capes) are common. These mark the places where erosion of resistant bedrock (sandstone, dolostone) or Quaternary deposits (clayey till) is exposed in the nearshore zone or at the coast. Certain part of the major shore faces (Cape Akmeņrags, Cape Oviši, Cape Kolkasrags, and Cape Ragaciems) represent partial barriers to longshore sediment drift, while harbours (Liepāja, Ventspils, Rīga) can be considered as artificial absolute barriers.

Soft cliffs (a height 10–15 m) along the Baltic Sea occur in a distance of 2–25 km and are common from Pāvilosta to the Užava lighthouse, at Ziemupe (north of Liepāja), south and north of Ventspils, and near Uši and the Melnsils village at the Kurzeme coast of the Gulf of Riga. Low and medium (2–10 m) high advancing depositional coasts occupy more than 50% of the total length of the Latvian coastline (Eberhards 2003). Coastal formation with sandy beaches (30–60 m in a width), foredune belt and beach dune ridges, shallow, sandy nearshore zone with up to 3–5 sand bars, is most characteristic of the Baltic Sea coast south of Liepāja, from Cape Akmeņrags to Pāvilosta, along the Irbe Strait and the southern end of the Gulf of Riga (Jūrmala—Daugava River—Gauja River).

The Latvian coast in terms of risk of erosion in the coming years and the future are 'very vulnerable' and 'vulnerable'. Such risk of erosion is most common along the Baltic Sea (69%) and the coast of the Gulf of Rīga (66%) (Eberhards 2003). During the last 50–60 years of the twentieth century, the long-term mean rate of the cliff retreat has been 0.5–0.6 m/year, reaching a maximum of 1–1.5 m/year along particular stretches of the cliffed coasts with a height 10–20 m (Jūrkalne area). Since 1980/1981, rates of the coastal retreat have increased by 2–5 times, reaching 1.5–4 m/year (Eberhards, Saltupe 1995). During heavy storms of 1993, 1999, and 2001 predominant rates of erosion throughout each single storm were 3–6 m, with a maximum of up to 20–30 m at the dune coast of Cape Bernāti (Eberhards 2003).

MATERIAL AND METHODS

Monitoring of coastal geological processes was established between 1987 and 1993, and covered the whole Latvian coastal belt. This system includes more than seventy coastal monitoring stations, which usually cover from 200–400 m up to 2000 m long cliffs of various geological structure and height (Eberhards, Saltupe 1999; Eberhards 2003). The measurements have been performed annually using a special methodology, similar to J.Hooke (1979) and H.Hadson (1982), applied for riverbank erosion measurement. Tested in Latvia since 1990, the method has been conducted at least twice a year and more often if severe storms have occurred. The number of measurement lines in monitoring stations is 10–40, and the measured dimensions are: (1) maximum and mean cliff retreat (m), (2) account of the lost areas (m^2), (3) volumes of sediment (m^3/m) within single measurement lines and total volume of sediments washed out from the monitoring site (m^3) (Fig. 2).

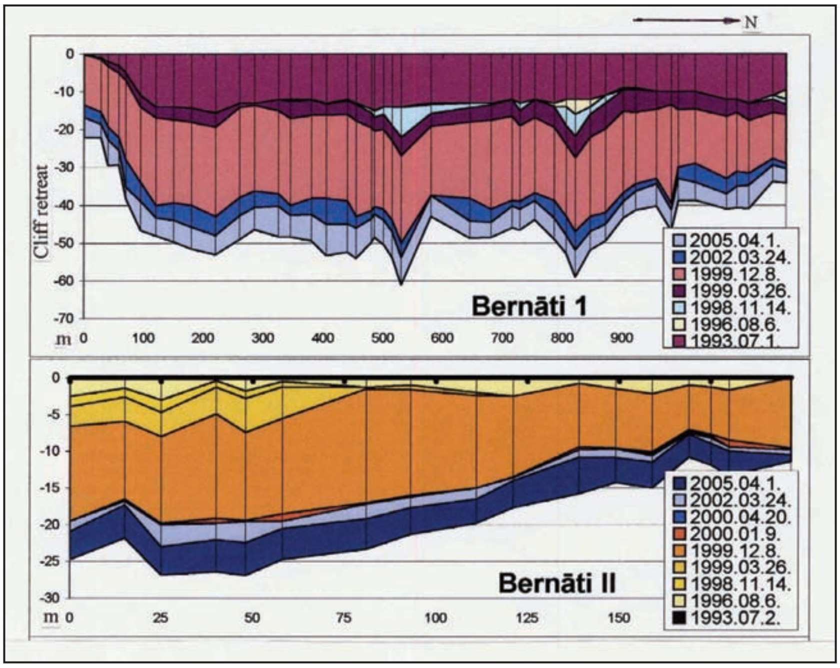

Fig. 2. Cliffed coast retreat measurements data at the monitoring station Bernati I and Bernati II.

Table 1. Soft cliff retreat during the hurricane 2005.

Monitoring site	Cliff geology	Cliff height, m	Length of cliff, km	Cliff retreat, m mean	maximum
Cape Mietrags	Dune coast	4-12	2	1.5-2	4-5
Cape Bernātu	Dune coast	2-8	3	3-5	7-8
Liepāja north	Dune coast	2-8	5	5-7	15
Ulmale—Užava					
Strante	Complicated	13-15	0.5	0-0.5	2-4
Ulmale 3	Complicated	13-15	0.35	1-2	4.5
Ulmale 1	Complicated	13-16	0.65	0.5-2	8
Ulmale 2	Complicated	13-15	0.5	0-0.5	3
Rīva	Complicated	14-16	0.46	0-1	2
Labrags	Complicated	13-15	0.42	0-0.5	5
Muiža	Complicated	13-15	0.5	1-2	4
Jūrkalne VII	Complicated	15	0.15	0.5-2	3
Jūrkalne II	Complicated	15-17	0.175	0.5-1	3
Jūrkalne I	Complicated	14-16	0.42	1-1.5	3
Jūrkalne III	Complicated	15	0.45	2-4	8
Jūrkalne V	Complicated	16	0.1	0.5-1	2
Jūrkalne VI	Complicated	15-17	0.35	-	0.5
Zaķi	Complicated	15-17	1	0.5-1	5
Sārnate	Sand, gravel	15-21	0.25	0.5-2	3-4
Ventspils area					
Cape Melnrags I	Complicated	7-18	2	5-7	10-12
Cape Melnrags II	Dune coast	5-20	2	5-8	14-17
Ventspils—Liepene	Complicated, dune coast	5-18	12	4-6	10-14
Vaide—Kolka					
Cape Kolkas	Dune coast	3-12	4	3-6	8-10

In total, three hundred fixed measurement lines have been established for assessing accretion/erosion along sandy stretches of the coast with pronounced sediment accretion on the beach and the foredune belt or with conditions of dynamic equilibrium. The stations cover from 0.5 up to 25 km long stretches of the

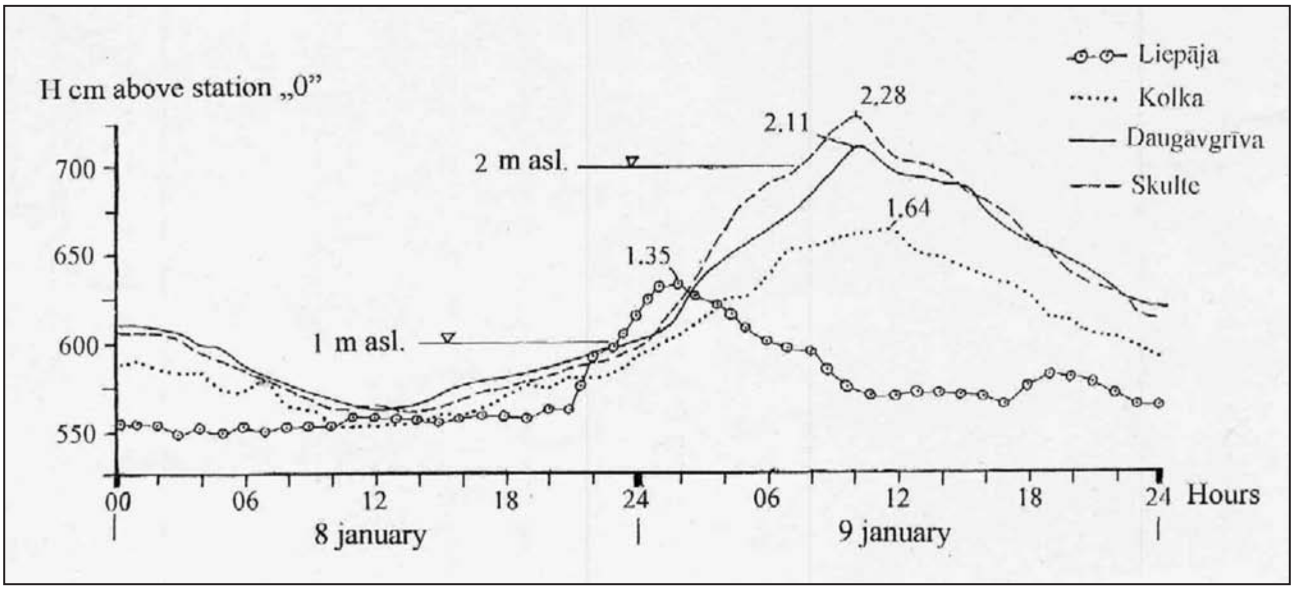

Fig. 3. Storm surges water levels during the hurricane 8–9 January 2005. Data of the Latvian Environmental, Geology and Meteorological Agency.

coast. For each site fixed location has from 5–10 up to 20–60 measurement lines. Measurements (levelling transects) are repeated once per year, and record the coast, foredune and beach changes above the mean water level. For each profile, using the MS Excel, the sediment budget (m^3/m) and total sediment budget on the monitoring station coastal segment (m^3) was counted with the formula:

$$V = (Q_i + Q_{i+1}).L_i / 2,$$

where: V = sediment budget at the coastal segment;
i = 1, 2, 3 … Nos. of transects;
Q = sediment budget at the separate coastal cross–section profile (m^3/m);
L_i = distance between levelling cross–section profile lines.

Both types of monitoring stations cover about 44% of the Latvian coastline: 70 coastal erosion sites in a 57 km length (over 2,000 measurement lines) and 160 km sites along the equilibrium and accretion sandy coast segments with 300 levelling transects.

RESULTS AND DISCUSSION

Wind regime and water level

Storms occur most frequently in autumn and winter, less commonly in spring. The violent wind-generated waves in the Baltic Sea reach a height of 13 m, with up to 4 m high waves at the coast (Pastors 1994). The longest fetch is along the eastern shore of the Baltic Sea and in the Irbe Strait with westerly wind, and in the Gulf of Riga with north-westerly wind, which typically causes the most significant maximum variations in water level related to non-periodic storm surges and coastal erosion. The highest storm surge levels at the Latvian part of the eastern Baltic Sea coast were recorded at Liepāja and Ventspils during the 1967 storm (174 and 148 cm above mean sea level), and at the south–south–eastern coast of the Gulf of Riga at Daugavgrīva (+214 cm) and the Skulte harbour (+247 cm) during the 1969 hurricane (Pastors 1969).

On 8–9 01 2005 several unusual meteorological conditions combined to produce a devastating south-west–west storm that caused extensive damage, flooding and erosion along the Latvian coast. The storm gradually increased in a magnitude, reaching its greatest intensity during the night of January 8, and the day of January 9. Most of the exposed Latvian coast was highly vulnerable to the storm due e to the wave battering and the resulting erosion produced by the hurricane. The storm has been classified as only a thirty to forty year recurrence event based on high water level data, the duration of the storm, its large wave heights, and resulting damage, which have led to comparison with the November 1969 hurricane, the strongest storm for this region.

Wind regime and sea water level characteristics during the January 8–9 storm illustrate data from coastal hydrological and meteorological stations (Liepāja, Kolka, Mērsrags, Rīga, Skulte, Salacgrīva), compiled by the Environmental, Geology and Meteorology Agency of Latvia. We have a full scale of measurement results only from the Skulte, Rīga and Liepāja stations, and only fragmentary data from other stations, as the strong wind interrupted the supply of electricity. Relative water level fluctuations were fixed every fifteen minutes, but wind speed and direction hourly. Maximum wind speed 28–31 m/s is recorded in all stations, and approximately 40 m/s in Ventspils. Significant coastal erosion started when the water level rose more than one meter above the normal sea level. During the storm high surges in water level at the coastal zone of Latvia is illustrated in Fig. 3. Along the Baltic Sea coast high surges in water level lasted only 4–6 hours and were associated with very strong wind (20–30 m/s). Along the southern and eastern coast of the Gulf of Riga devastating wind and high water level occurred for 20–24 hours (Fig. 3). The southwest, episodically south wind at the beginning of the storm was dominant during the night of January 8, and early

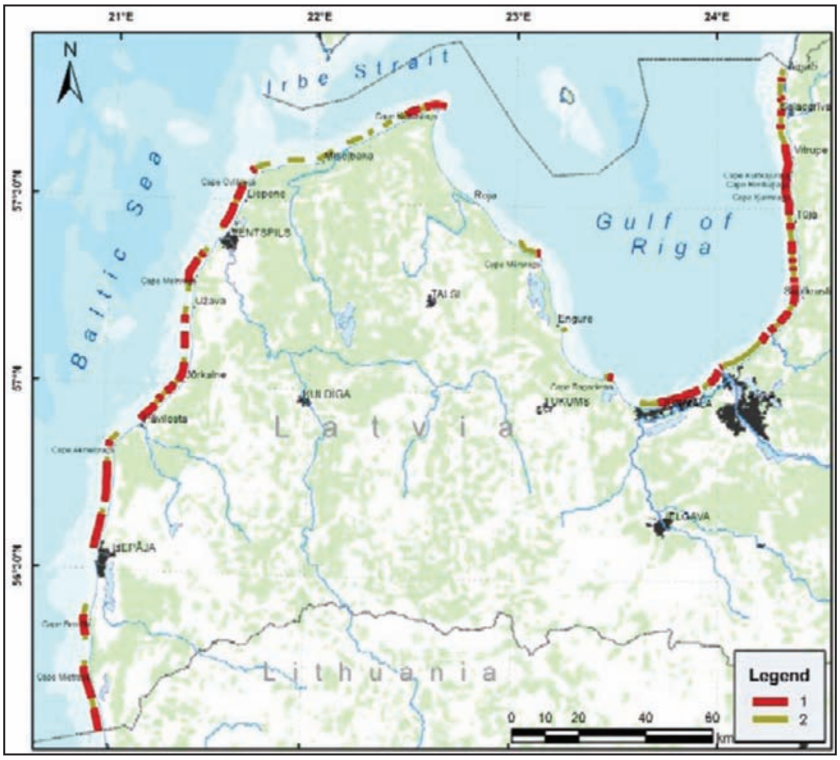

Fig. 4. Coastal erosion. 1 – strong–middle erosion, 2 – middle–mild erosion.

Table 2. Accumulative sandy coast retreat.

Coastal segment	Length of research area, km	Coastal retreat, m	Sand volume washed out, m^3/m mean	maximum
Irbe Strait				
Mazirbe	6	10-16	5-12	20-30
Gulf of Riga				
Jūrmala town	20	4-6-16	15-20	32-39
Riga City: Daugavgrīvas Island	6	5-23	10-12	38
Daugava—Gauja	18	6-16	6-10	20-35
Gauja—Saulkrasti	18	5-20	5-15	20-35
Vidzeme coast: Vitrupe	4	10-16	5-10	20-28

morning of January 9, but in the afternoon western winds prevailed. Only in the south-eastern part of the Gulf of Riga near Saulkrasti (Skulte station) southwest wind dominated the entire time.

Coastal erosion

During the first days after the storm we forecasted that the coastline must be affected by erosion approximately on 200 km or 40% of the total length of the Latvian coastline. In reality, according to the coastal zone post-storm mapping at springtime 2005 we recognized significant coastal retreat with cliff erosion, foredune and upper beach washout that took up about 190 km (Fig. 4). According to the Latvian coastline configuration, wind regime and the energy of storms destroyed more significantly coastal zone stretching along the southern and eastern coast of the Gulf of Riga, from the Jūrmala town up to Saulkrasti and the Vidzeme coast from Tūja to Vitrupe. Selective cliff retreat of the Baltic Sea coast occurred at capes of Mietrags, Bernāti, Akmeņrags, Melnrags and Kolkasrags, as well as cliffed downdrift coast north from Liepāja and Ventspils harbours, from Pāvilosta up to Užava lighthouse.

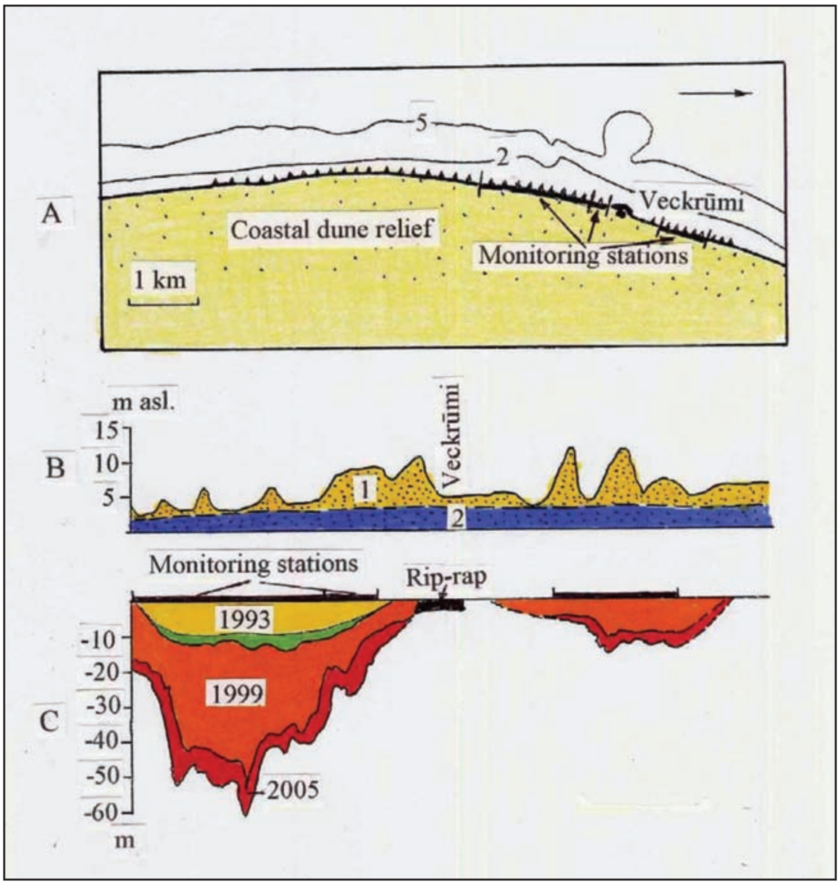

Fig. 5. The dune coast erosion rate at Cape Bernātu. A – study area; B – coastal geology: 1 – fine aeolian sand, 2 – fine marine sand; C – sandy coast retreat during the storms of 1993, 1999 and 2005.

During the severe storm conditions and high water levels, the Baltic Sea sandy cliffs retreat was less in the last 1992, 1993 and 1999 storms. Soft cliffs were reduced 2–7 m, with a maximum 8–15 m in local cells (Table 1, Fig. 5). The storm endangered Latvia's longest 10–20 m high cliffed coast from Pāvilosta up to Užava lighthouse insignificantly. Only in local segments the cliff maximum retreat was 3–8 m (Table 1).

Remarkable coastal erosion affected the north Kurzeme coast from Cape Melnrags up to Cape Oviši, including a 14-km long cliffed dune coast north from the Ventspils harbour when the storm conditions were more severe. Wave erosion and slope processes favour noteworthy soft cliff reduction, average 5–8 m, and maximum to 10–17 m (Table 1).

Along the accretional sandy Irbe Strait coastline with a 30–50-m wide beach and increasing foredune belt coastal segments up to 5–10 km long (lighthouse Miķeļbāka—River Irbe, Mazirbe area) with partly, or in local cells absolutely washed out foredune and back beach with embryonic aeolian forms appeared. Between them were stretches of coastal segments in dynamic equilibrium or with mild sand accretion. The cliffed dune coast, approximately 6 km long, stretches from Vaide up to Cape Kolkasrags, which since the severe storms of 1967 and 1969 was overgrown with pines, during the hurricane 2005 was severely affected by erosion. The dune cliff mean retreat was 3–6 m, with a maximum of 8–10 m. The eastern side of the Cape Kolkasrags direct to the Gulf of Riga was retreated a maximum of 20–27 m (Table 1, Fig. 6).

On the western (Kurzeme) coast of the Gulf for a distance of more than 120 km, where inland wind was dominant during the storm, the coast left more or less stable with insignificant changes of sand budget in the beach and foredune belt. Locally, on some low coast cells a little sand deposition was recorded (see Fig. 4). Only along the two biggest capes (Mērsrags, Ragaciema rags) along the northwest wings there was a mild–moderate sandy cliff retreat.

Significant coastal erosion started from the Jūrmala town and went up to Saulkrasti and Skulte harbour. Opposite to Kurzeme, the coast of the Gulf of Riga with northwest–southeast exposure, the eastern–north–eastern oriented coast was washed out by more than twenty-four hours of direct waves' attack. Wave contact time is also one of the major marine criteria with respect to the erosion processes (Williams, Morgan, Davies 1991). According to measurement data and calculations, the width of the upper beach, foredune and coast zone retreat, as well as the volume of sand washed out, increased in oscillating manner to the northeast, reaching a maximum before the mouth of the largest rivers (Lielupe, Daugava, Gauja) with shallow coastline headlands and accumulative nearshore shoals (Table 2, Fig. 7). Maximum width of coastal retreat increased up to 16–23 m and volumes of washout material to 20–39 m^3/m.

The total volume of sediments washed out along the southern part of the Gulf of Riga was amounted 732,000 m^3, divided into different local morphodynamical coastal subsystems (Fig. 8). Along the Saulkrasti sandy cliff retreat up to 10–15 m, waves ruined some houses and endangered the road *Via Baltica*.

Remarkable erosion affected the Jūrmala town coastal zone, up to 20 km long. Total volume of sand washed out from the upper beach and foredune belt was 387,000 m^3, the largest since 1987, when the coastal monitoring started. In comparison, removed sand volume during the northwest windstorm in 1992 reached only 250,000 m^3. The severe storm of January 8–9, 2005, washed out foredune at a distance of 6 km, which had been renewed with planting of osier after the hurricane of 1969. Waves damaged foundations of some houses and coastal protective structures.

It should be especially noted the sub-meridional eastern (Vidzeme) coast of the Gulf of Riga, straightened and cliffed during the long-term erosion from Skulte harbour up to Vitrupe. In hurricane 2005 this straightened cliffed coast (3–7 m high) with changing geological structure was influenced by direct wave attacks for more than twenty-four hours. At Vidzeme coast we can estimate the vulnerability and stability of cliffs with frequently varying geological structure and sediment layers against wave attack. Different levels of 'hard' cliffs (Devonian sandstone and clay) vulnerability and speed of retreat appeared opposite to normal storm conditions. Long-term research work in the world shows, that marine hard cliff erosion depends not only on the processes of wave attacks, but also on the composition and structure of the cliffs, which influence the nature of the mass movement (Komar, Shih 1993). Additionally, coastal erosion is influenced by such factors as a nature of bio–erosion, height of cliff,

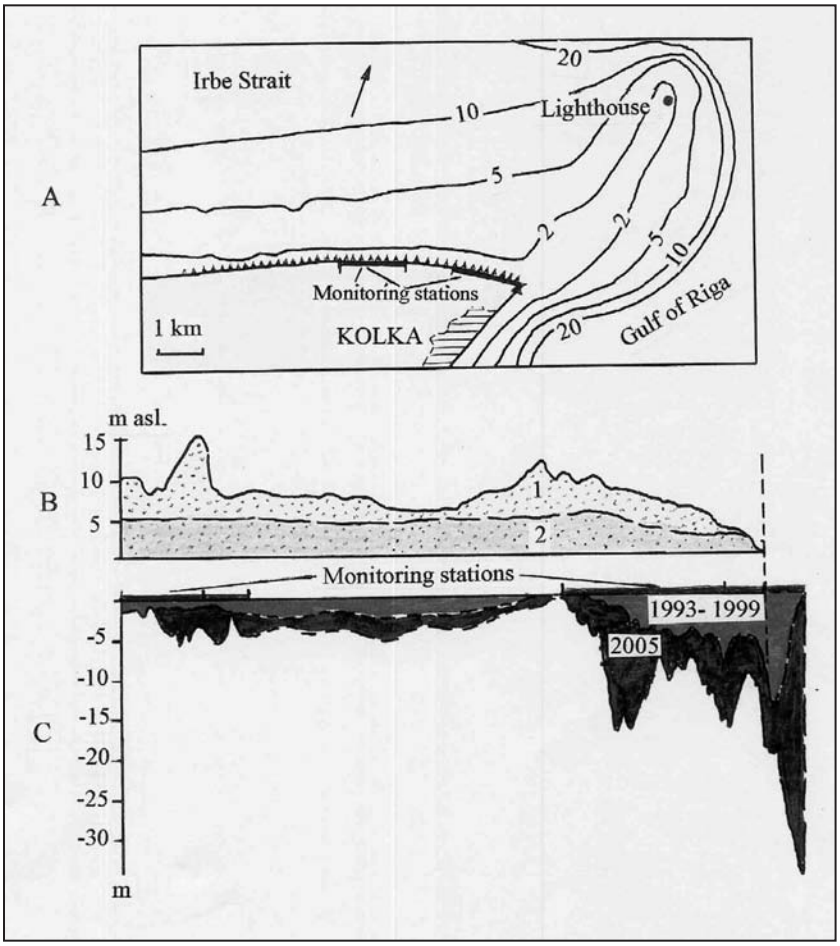

Fig. 6. The dune coast erosion at Cape Kolkasrags. A – study area; B – geology: 1 – fine aeolian sand, 2 – fine marine sand. C – bluff retreat.

nature of wave attack, and human activity (Pethick 1989). Sea wave undermining and scouring of cliff face faults, cracks and joints lead to development of caves that collapse over time and cause slumps of the unconsolidated overlying strata (Harker, Flich 1991).

In weathered sandstone/clay layered cliffs the significant waves attack and cliff retreat were enhanced in the specific case of stratified sedimentary rocks with continuous bedding planes and cross-joints, bedding planes angle and complicated by the presence of faults within the rocks, and water along discontinuity surfaces (Moon, Healy 1994). A collapse of jointed sandstone blocks is the most common form of instability of these cliffs, initially, if the sandstone beds are supported by the underlying siltstone but fault planes provide weak zones on the cliff face along which instability can occur. Two approximately perpendicular sets of fault planes occur in the Vidzeme coast cliffs. The single factor which is common to the various mechanisms of cliff retreat is that they are all exacerbated by water, which either induces increased cleft water pressures along joint and bedding planes, washes soft material out of fault planes, or causes subsurface piping along the soil rock surface (Moon, Healy 1994). Such cliff retreat is mainly determined by direct wave attacks and erosion, gravity processes, weathered and destroyed hard sediment block collapses, landslides, toppling, etc. (Van Rijn 1998).

Steep cliff faces, especially common along the Vidzeme shore, often encourage wave reflection rather than breaking. When the wave is particularly shallow, a pocket of air is trapped between the wave crest, mass of the wave and the cliff face, resulting in the generation of potentially destructive chock pressures (Williams, Morgan, Davies 1991).

Recognition of the Vidzeme coast during the storm and post-storm period and measurements show that cliffs with different geological structure but with common exposure to dominant wind and wave conditions during the severe storm 2005 can be grouped according to this vulnerability to erosion in succession:

* very vulnerable, very severe eroded sandy dune coast; mean retreat 5–8 m, maximum retreat 15–18 m;

* vulnerable, severe–middle eroded Devonian weakly cementing sandstone cliff with thin layers of clay and siltstone; mean retreat 2–5, maximum retreat 12 m;

* vulnerable, severe–middle eroded Devonian thick layered clay cliff with weakly cementing sandstone or sand inter-layers; mean retreat 2–4, maximum retreat 6 m;

* low vulnerable, mild eroded bulky layered Devonian clay or sandstone cliff; mean retreat 1–2, maximum retreat 4 m;

* low vulnerability, mild eroded glacial boulder till. Mean retreat 1-2, maximum retreat 3 m.

Fig. 9 shows zoning of the

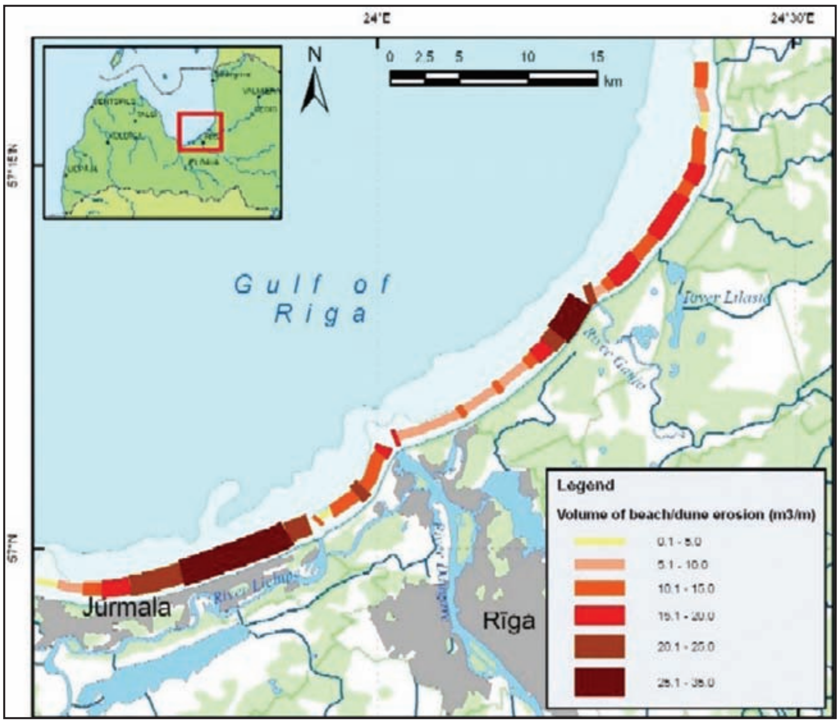

Fig. 7. Volumes of sediments washed out from upper beach, foredune and coast along the southern part of the Gulf of Riga, Jūrmala town—Saulkrasti.

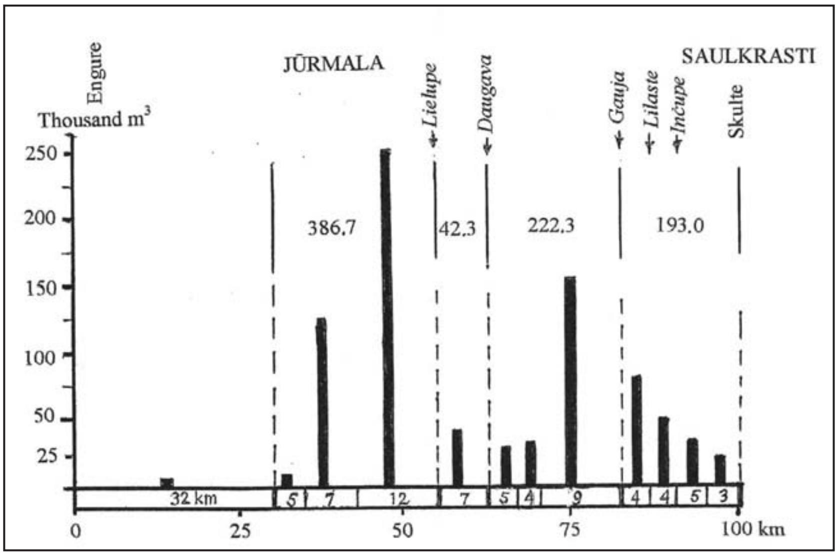

Fig. 8. Total volumes of sediments washed out from different coastal segments of the southern part of the Gulf of Riga.

Vidzeme coast into a relatively large number of small littoral cells differing in geological structure and cliff retreat.

It is sometimes difficult to distinguish natural erosion from downdrift erosion and to assess their relative magnitude, as in the effect of a littoral man–made barrier (harbour) on the downdrift shoreline. Examining the results from cases of barrier effects on downdrift erosion led to conclude that if the erosion increases downdrift of an established littoral drift barrier and the weather regime did not change and erosion increased, this is an indicator of an adverse effect of the littoral drift barrier, but if the weather regime improved while erosion increased, this is or may be taken as a proof of the adverse effect of the barrier (Bruun 1995, p. 1255).

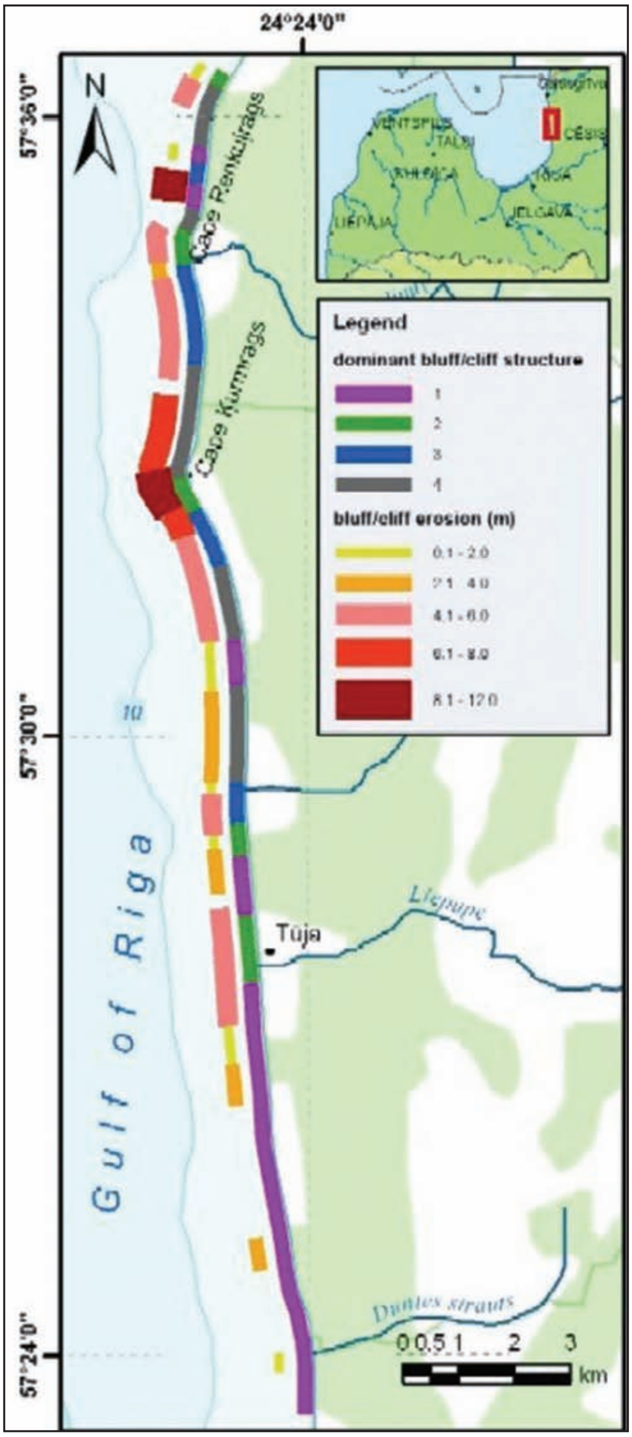

Fig. 9. Cliffed Vidzeme coast erosion. 1 – glacial till, 2 – aeolian and marine sand, 3 – Devonian sandstone, 4 – Devonian clay.

The Ventspils harbour effect on downdrift erosion research based on twelve years monitoring data at 14-km long coastline segments up drift and down drift of a man–made barrier was described (Eberhards 2003). We have tried to observe and calculate the effect of harbour jetties and shipping entrance channels as man–made barrier effects on coastal erosion during the hurricane 2005. Man–made littoral drift barriers that blocked the sediment long-shore drift enhance downdrift erosion, with S-curved cliff downdrift retreat with fixed 'zero' zones or areas with about zero–erosion. The peculiar 'zero-area' which sometimes appears downdrift at a short distance from the barrier is a coastal geomorphologic feature, which does not necessarily indicate the extreme limit of seaside erosion (Bruun 1995). We measured typical S-curved cliff retreat along the 12–14-km long coast north from the Ventspils harbour during the last thirteen years of monitoring, and very clean during the 2005 hurricane. Two stationary zero–zones

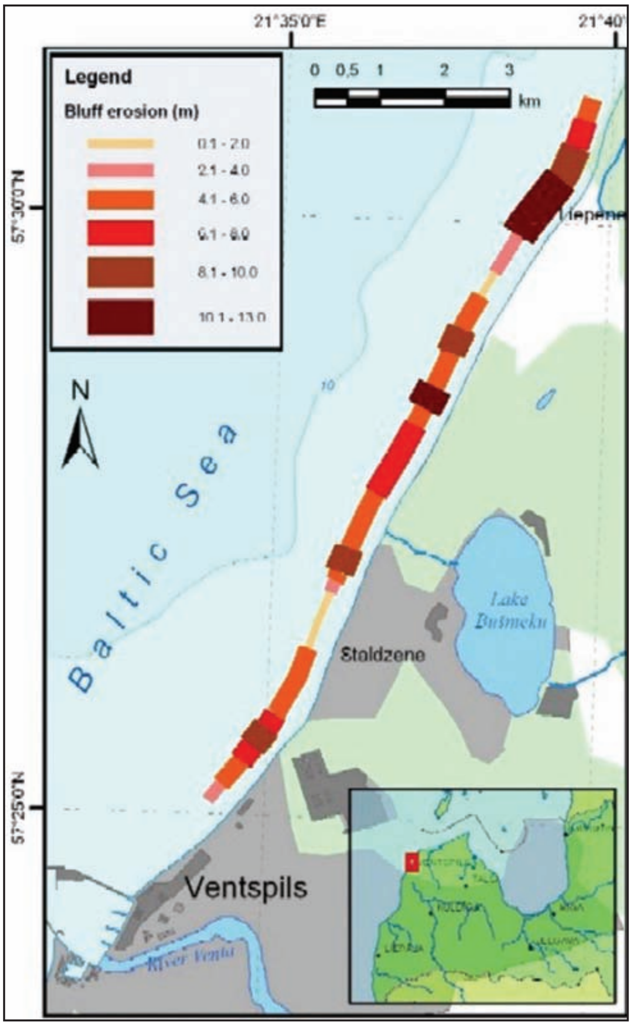

Fig. 10. Bluff erosion north from Ventspils harbour.

Table 3. Volumes of material washed out from separate zones of Latvian coastline.

Coastal segment	Volume of material, m^3
The open Baltic Sea coast	
Nida–Liepāja–Cape Akmeņrags	450,000
Pāvilosta–Jūrkalne–River Užava	387,000
Cape Melnrags–Ventspils–Liepene	864,000
Cape Oviši–Cape Kolka	220,000
The Gulf of Riga	
Jūrmala town	387,000
River Lielupe–Daugava–Gauja	264,000
River Gauja–Saulkrasti (harbour Skulte)	193,000
Vidzeme coast (Skulte–Vitrupe)	310,000
Total	3,075,000

(cell length about 0.5 km) coincide with positive glacial till elevations in the nearshore zone, beach or cliff (Fig. 10). As the rates of cliff retreat downdrift of the Ventspils harbour and 10–14 km south from the harbour in the Cape Melnrags area is similar (Fig. 11), it could be concluded that during the hurricane the harbour with jetties and ship entrance channel with a depth of 16–17 m essentially did not influence the downdrift cliff retreat. The erosion cut depends upon natural factors such as wind regime, waves, relative water levels and coastal zone geological structure. We recorded similar relative

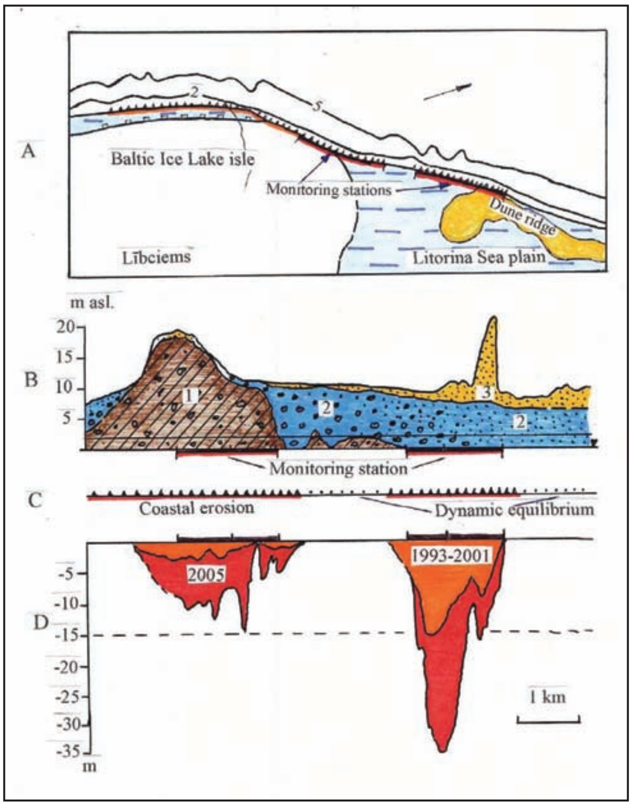

Fig. 11. Soft cliff erosion at the Cape Melnrags south from Ventspils. A – study area; B – geology: 1 – glacial till, 2 – marine sand and gravel, 3 – aeolian sand.

long-term (more than 10 of years) 'zero–zones' along the whole Latvian coastline in segments affected by erosion at the Baltic Sea cliffed coasts, as well as along the accumulative dune coast of the Gulf of Riga and Irbe Strait. Along the cliffed coast of the Baltic Sea with complicated geological structure 'zero–zones' usually coincide with boulder till elevations in the nearshore or in cliffs, and with long-shore sand-waves.

Summarised mapping, measurement and calculation data show that the severe January 8-9, 2005, storm impacted a large coastal zone, and Latvia loses approximately ninety hectares of land, mainly coastal dune forests, partly coastal villages and towns. Storm waves ruined some houses, in five stretches washed out local shore-side roads, damaged the highway *Via Baltica* at Saulkrasti, in some stretches partly destroyed coastal man–made structures, along the south-eastern and eastern coast of the Gulf of Riga there appeared new high risk zones (with more than thirty houses) very vulnerable to erosion. In total there were 30 km stretches of hurricane washed-out foredune along the Gulf of Riga. At the city of Riga in Daugavgrīva Island, hurricane produced waves washed out the foredune on a 0.5-km stretch and high surge waters flooded the low-lying Daugavgrīva nature reserve and, for a short time, divided the island into two parts. Seawater reached the line where the coastline stretched three hundred years ago (before the Daugava River dams and jetties were built). Calculated material volumes washed out from the upper beach, foredune belt and Latvia's coastline reached more than 3,000,000 m^3 (Table 3).

CONCLUSIONS

Hurricane 2005, the second strongest storm during the last hundred years, damaged 40% of the coastline of Latvia. The impact of hurricane *Erwin* was relatively minor on the western coast of the Gulf of Riga, as well as the Baltic Sea coast from Nida up to Užava lighthouse. Despite the various damage and disaster reports prevalent in the media, the long-term geological impact of the hurricane along the largest coastline of the Baltic Sea is likely to be minimal as a result of short-time high water level surges, severe wind speed, likely due to normal wind and wave front direction along the coastline. More significant coastal retreat was recorded here in previous storms of the last decades (1993, 1999).

Long-time dominant severe southwest and west winds and unusually high water level caused strong wave erosion along the southern sandy coast of the Gulf of Riga from the Jurmala town to Saulkrasti.

The severely damaged cliffed eastern coast of the Gulf with complex geological structure clearly shows that 'hard' Devonian weakly cemented sandstone and clay cliffs are very vulnerable to wave erosion, but less vulnerable are soft cliffs cut in till.

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