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Implications of Sea-Level Rise for Estonia

Are Kont†, Jaak Jaagus‡, Raivo Aunap‡, Urve Ratas†, and Reimo Rivis†

†Institute of Ecology
Tallinn University
Uus-Saadama 5, 10120 Tallinn, Estonia
are@tlu.ee

‡Institute of Geography
University of Tartu
Vanemuise 46
51014 Tartu, Estonia

ABSTRACT

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Estonia is a coastal country with a long coastline (3800 km) for which climate change and accelerated sea-level rise are key problems that need to be considered in any future impact assessment. Due to its flat, low-lying coastal zone, any rise in sea level places many coastal ecosystems and recreationally valuable sandy beaches at risk. Milder winters, combined with increased storminess and the absence of sea-ice cover, would exacerbate these impacts. However, isostatic uplift and the distance of coastal settlements from the present coastline could reduce these risks.

This paper presents the potential impact of a 1-m global sea-level rise by 2100 if no adaptation is undertaken. Seven representative study areas, characterising all shore types in Estonia, were selected for sea-level rise vulnerability and adaptation assessment. The diverse structure of Estonia's coasts, the rapidly migrating shorelines, and the abundance of small islands were found to complicate reliable predictions regarding climate warming and accelerated sea-level rise.

ADDITIONAL INDEX WORDS: *Climate change, coastal ecosystems, coastal areas at risk, Baltic Sea.*

INTRODUCTION

Sea-level rise due to thermal expansion of the ocean and melting of glaciers, ice caps, and ice sheets is both a global and a regional issue (MIMURA, 1999; NICHOLLS and MIMURA, 1998; PELTIER, 1999). For Estonia, accelerated sea-level rise (ASLR) is a particular concern as it would cause flooding of coastal areas, erosion of sandy beaches, and destruction of harbour facilities.

Estonia is located on the eastern coast of the Baltic Sea in the north-western section of the East European Plain. Its long coastline (3800 km) is strongly indented with characteristic peninsulas, bays, and islands. Its flat and low-lying bays contain many valuable coastal ecosystems that are at risk from both climate change and ASLR. Isostatic uplift has caused the coastal zone in Estonia to emerge throughout the Holocene (last 10,000 years), with current uplift rates ranging from 1.0 to 2.8 mm/y with maximum uplift located on the north-western coast (VALLNER, SILDVEE, and TORIM, 1988). Although hypothetically ASLR in Estonia would be partly mitigated by land uplift, it remains a serious potential hazard (KONT *et al.,* 1996a, 1996b). Historical sea-level data for the Estonian coast show frequent fluctuations due to changes in the precipitation/evaporation ratio, river discharge, and storms but no evidence of a long-term sea-level rise. However, extensive erosion and destruction of depositional coasts, such as sandy beaches, have been observed in recent years (ORVIKU, 1992; RAUKAS, BIRD, and ORVIKU, 1994). This would suggest that this beach erosion is the result of recent increased storminess in the eastern Baltic Sea, combined with a decline in sea-ice cover during the winter, a situation characteristic of some coastal areas in eastern Canada (SHAW *et al.,* 1998).

The main characteristics of the Estonian coast are as follows:

1. Although small in area (45,227 km²), Estonia is rich in geomorphic shore types. ORVIKU (1992) distinguished eight major shore types based on geology, slope of the primary relief, and prevailing shore processes: (i) cliff shore, (ii) rocky shore, (iii) scarp shore, (iv) till shore, (v) gravel–pebble shore, (vi) sandy shore, (vii) silty shore, and (viii) artificial shore.
2. Tidal sea-level fluctuations in the Baltic Sea are negligible (*ca.* 1 cm). Annual and seasonal changes in water level reflect mainly river discharge, precipitation/evaporation ratio throughout the drainage area, and rate of water exchange with the oceans (RAUDSEPP, 1998). Temporal west and south-west winds cause short-term positive sea-level fluctuations near the Estonian coast with maximum storm surges (2.53 m above the Kronstadt zero[1]) causing extensive flooding, whereas the highest water-level rise in the open sea rarely exceeds +2.0 m.

Coastal rural settlements in Estonia are very old, with many founded more than 5000 years ago, but although the first structures were probably erected near the coastline, isostatic uplift has resulted in former seaside villages being found inland today. Many coastal settlements in Estonia—with the exception of harbours and some low-lying districts

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[1] The local benchmark for the eastern Baltic Sea—in Pärnu and Matsalu Bay on 18 October, 1967.

of coastal cities—therefore appear to be in no direct danger of a moderate sea-level rise.

During the Soviet period, the entire Estonian coast—except that of cities—was a military frontier zone with highly restricted public access. Political and social changes since the last independence in 1991 have seen coastal areas serving multiple functions. Sandy beaches have high recreational value and are a popular summer vacation spot for both local people and tourists, and small harbours for yachting and trade are currently being built. The collapse of agriculture at the beginning of the 1990s led to a halt in previous mowing and grazing regimes, and an overgrowth of trees and shrubs now exists in coastal grasslands. For the same reason, a hiatus in reed cutting has left reed beds unmanaged. Although coastal areas have been monitored for many years, no plan for coastal zone management is currently in effect.

The aim of this study was to evaluate the impact of climate change and ASLR on natural ecosystems, as well as on human activity in Estonian coastal areas. Ecosystems and human settlements considered the most vulnerable to sea-level rise were therefore selected as study areas to assess the impacts of these changes. Using a Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), projected sea-level rise by 2100 will on average be 32–56 cm with a maximum of 95 cm (HULME, RAPER, and WIGLEY, 1995). For this study, a 1-m global sea-level rise scenario was chosen for analysis for two reasons: (1) to include the effect of possible bias in the model, and (2) to exclude the compensating effects of isostatic uplift. The prognosis of a 1-m ASLR during the next century was also recommended for vulnerability and adaptation assessment by the U.S. Country Studies Program in which Estonia participated (BENIOFF, GUILL, and LEE, 1996).

This paper contains an inventory of potential loss, values at risk, and possible adaptive measures and protection strategies.

STUDY SITES

Using similar guidelines to those in BENIOFF, GUILL, and LEE (1996), four study areas in various Estonian coastal areas were assessed during 1995 and 1996. These study areas were later analysed in more detail under the auspices of local climate change programs funded by the Estonian Ministry of Environment and the Estonian Science Foundation. Three sites were also added to better represent the variability of the Estonian coastal zone. As the additional study sites are smaller in area, the results were integrated and presented as a single study area (Figure 1, Table 1). The selected study areas represent all previously mentioned geomorphic shore types, as well as different types of coastal settlements (from the capital city to the smallest fishing villages). To achieve comparable results, the same methodology was applied to all study areas.

Hiiumaa Island (Figure 2-1) is located in the northern part of the west Estonian archipelago and is surrounded by nearly 200 small islands. It is a low island; most of the island is 1–10 m above sea level (ASL). The principal shore types are beaches with beach ridges and dunes behind. There are also gravel shores with beach ridges, abraded till shores with occasional boulders, silty shores surrounding shallow bays, and low limestone shores. The only city, Kärdla, and the harbours have constructed shores with protective structures. Because of its remoteness, small area, and low population (10,460 inhabitants in 2000), the island has no major economic significance. The principal industries are agriculture, fisheries, forestry, and tourism.

Tallinn (Figure 2-2), the capital, is the largest city (404,000 inhabitants in 1999) in Estonia. The coastline of the study area from the Tiskre brook mouth in the west to the Cape of Miiduranna in the north-east is 67 km long, is indented by numerous peninsulas and bays, and features mainly scarp, till, and sandy shores. Tallinn has Estonian's largest harbour, which has relatively long constructed shores with protective structures. A seawall was erected just before the Moscow Olympic Games yachting competitions at Pirita in 1980. To protect the main harbour area, groynes were built in the beginning of the 1900s.

Vulnerability assessment results for three relatively small study areas—Käsmu–Vergi, Toolse–Aseri, and Sillamäe–Narva-Jõesuu (Figures 2-3 through 2-5)—were integrated into the Käsmu–Narva-Jõesuu study area. These three study areas, which reflect minor differences in shore types along the northern coast of Estonia, are located in north-eastern Estonia where the coastline in the east (190 km) is straight and in the west is indented by peninsulas and bays. Most of the area consists of Baltic Glint, a limestone cliff up to 56 m ASL, which divides the north Estonian coastal plain from the Harju–Viru limestone plateau. The north Estonian coastal plain, which lies between the cliff and the sea, contains peninsulas and headlands stretching far offshore. Abraded till shores with boulders and sandy shores with beach ridges and dunes are characteristic where the coastal plain is wider.

The 200-km long Matsalu Bay (Figure 2-6) study area from Virtsu (in the south) to Haapsalu (in the north) typifies the most characteristic shore types of the west Estonian plain. The central part of the study area, which encompasses Matsalu Bay, is composed of a low-lying, varved clay plain with silty shores covered by reed beds, seashore, and floodplain meadows. It is one of the most important wetlands in Estonia and is a part of the Matsalu National Park. The southern and northern parts of the area feature mainly abraded till shores with erratic boulders, although some limited sections of the coast near Virtsu have rocky shores. Haapsalu is famous for curative mud and health resorts.

The Pärnu–Ikla (Figure 2-7) study area is located in south-western Estonia on the western coast of the Gulf of Riga. The area includes the inhabited island of Kihnu (16.4 km^2) and other smaller islands. The 150-km long coastline is fairly straight. Most of the area consists of sandy beaches with an extensive ridge of coastal formations covered by foredunes and dunes, the highest of which (40 m ASL) are situated in the southern part. This is one of the most popular recreational areas in Estonia, featuring famous health resorts in Pärnu and some motels between Rannametsa and Ikla.

METHODS

The Estonian vulnerability assessment considered a hypothetical 1-m sea-level rise from 1990 to 2100 with isostatic

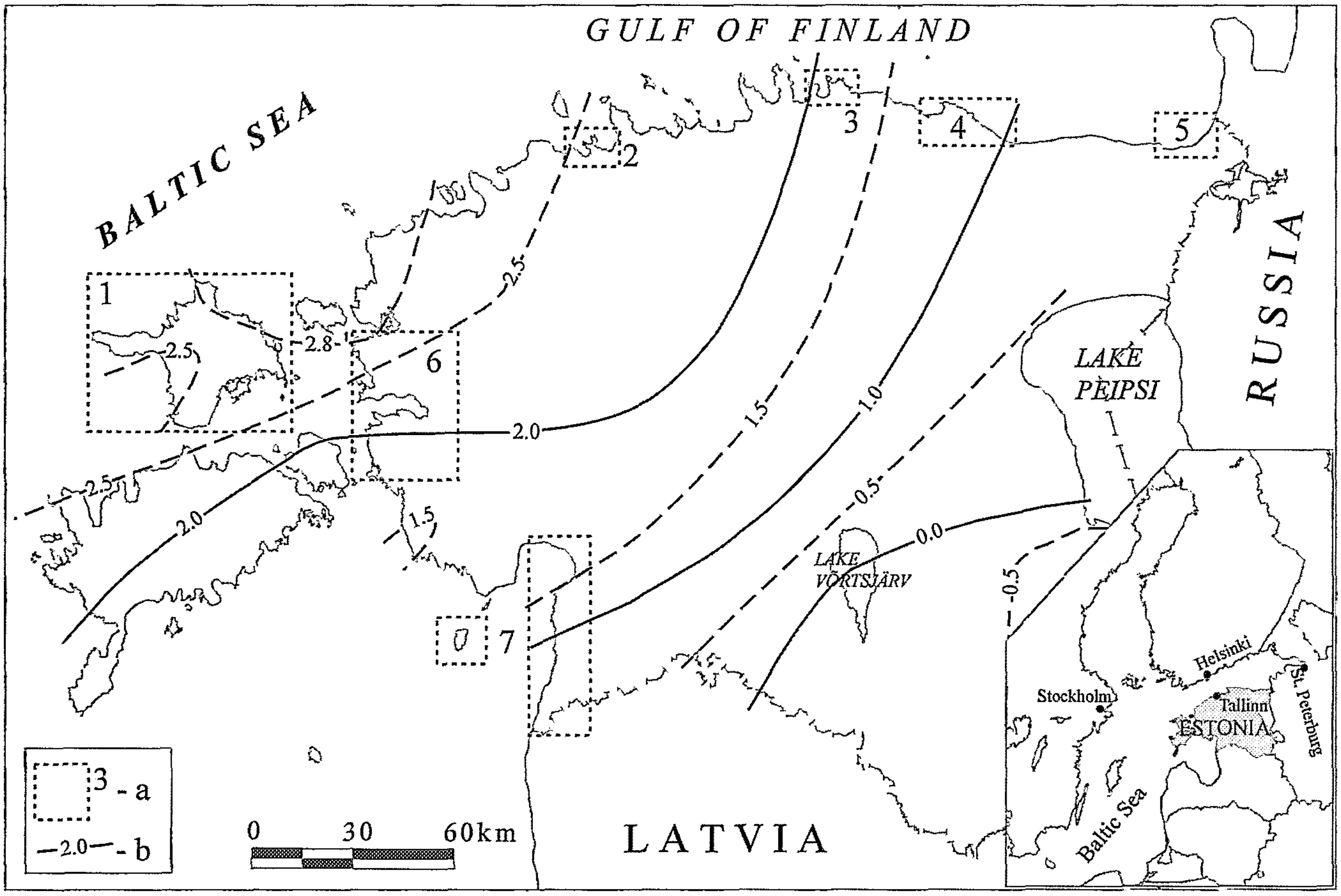

Figure 1. Estonia: Location of study areas (a) and isobases (b) of annual rates (millimetres per year) of vertical land movement (Vallner, Sildvee, and Torim, 1988). The seven study areas are (1) Hiiumaa, (2) Tallinn, (3) Käsmu–Vergi, (4) Toolse–Aseri, (5) Sillamäe–Narva-Jõesuu, (6) Matsalu Bay, and (7) Pärnu–Ikla.

uplift taken into account in land loss estimates for each study area. As can be seen in Table 1, different rates of uplift cause estimated sea-level rise to vary nationally, from 0.9 m (south-west Estonia) to 0.7 m (north-west Estonia), and locally, *e.g.,* the northern and southern coasts of Hiiumaa—69 cm and 73 cm per 110 years, respectively.

To assess the impacts of this sea-level rise, detailed measurements were initially made using large-scale (1:25,000) topographic and geomorphic maps and potential erosion calculated along the coastline at 200-m intervals using the Bruun Rule (BRUUN, 1962; HANDS, 1983). Application of the Bruun Rule was not without complications. First, the shoals off the Estonian coasts reduce wave energy and partly protect the shore against erosion. Second, the Bruun Rule is designed for calculating erosion on sandy beaches; as the U.S. Country Studies Program provides no alternative methods for non-sandy shores, the Bruun Rule was also used to calculate erosion on other depositional shore types (gravel, pebble, and till). However, the overfill ratio of 1.0 for sandy shores was modified for the other shore types (for sand to 1.0; for gravel and pebble to 0.7; for till (shingle-rich loam) to 0.4; and for limestone to 0.1). These coefficients were recommended by coastal geologists who have recorded rates of erosion on different shore types in Estonia for the last 30 years (K. ORVIKU and U. RATAS, personal communication). It is worth mentioning that till shores are erodable until the fine-grained fractions are entirely washed out. However, the remaining shingle ridges and boulder fields prove to be extremely resistant to further erosion. The results of calculations on rocky limestone shores are less reliable as erosional processes are aided by strong karstification. The Bruun Rule was inapplicable on very low and flat silty shores and in the coastal zone of the west Estonian plain, which consists of varved clay. The

Table 1. *Rates of land uplift and relative sea-level rise (through 2100).*

Study Areas	Land Uplift (mm/y)	Relative Sea-Level Rise (cm)
Hiiumaa	2.5 . . . 2.8	69 . . . 73
Tallinn	2.4	74
Käsmu–Narva-Jõesuu*	0.5 . . . 2.0	78 . . . 95
Matsalu Bay	1.8 . . . 2.6	72 . . . 80
Pärnu–Ikla	0.4 . . . 1.4	85 . . . 95

* Integrated results of three smaller study areas (Figure 1).

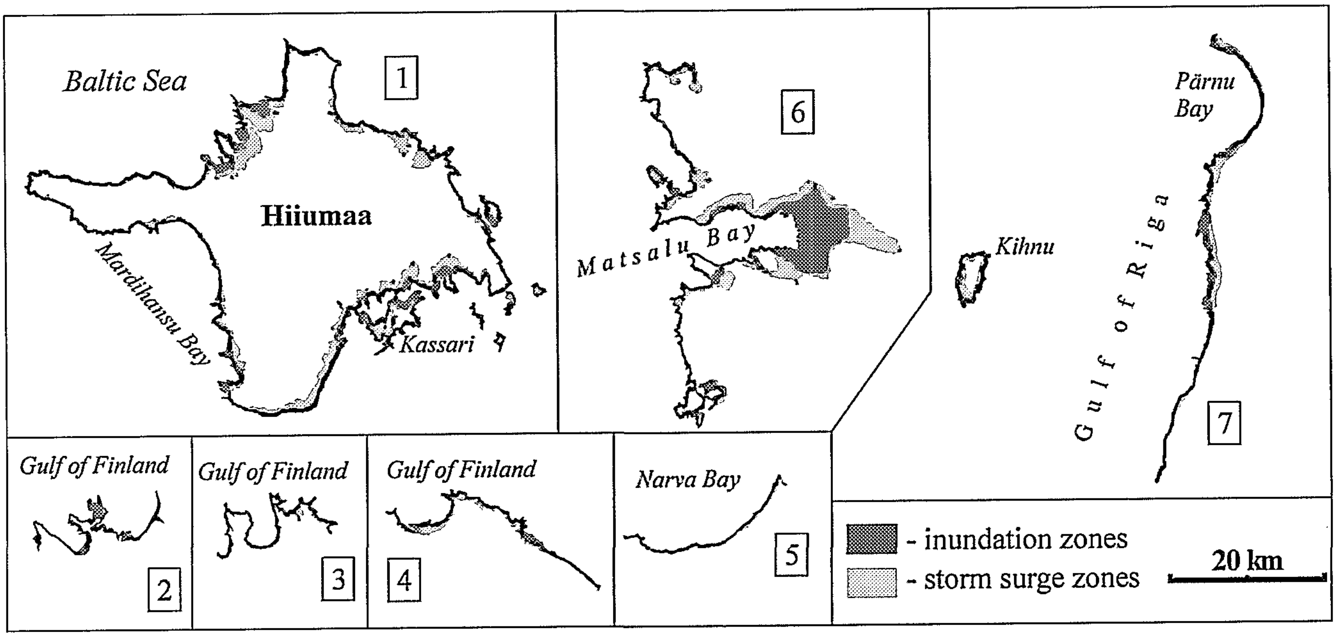

Figure 2. The inundation and storm surge (temporally flooded) zones of study areas. For location of study areas see Figure 1.

calculations of land loss in this region were based solely on the degree of inundation following a "bathtub" approach.

Based on these measurements and calculations, new coastline positions were drawn on topographic maps. Field observations and measurements from other current topographic and land use mapping were then used to compare possible coastline changes obtained by the Bruun Rule to actuality and to make corrections where necessary.

Data on water-level fluctuations and storm surges since the second half of the 1800s were obtained from the meteorological and sea-level observation stations located in the study areas (Table 2), and sea-level fluctuations were estimated with respect to the Kronstadt datum. Further coastline positions were then drawn for both typical weather conditions and potential storm surges based on the maximum observed event. Both zones were assessed for land loss and temporary damage.

Table 2. *Absolute maximum and minimum sea levels (in centimetres related to the Kronstadt datum) and potential coastline recession (CR, in metres) at 1-m sea-level rise in the study areas.*

Study Area	Station	Absolute Maximum Sea Level	Date	Mean Annual Maximum Sea Level	CR
Hiiumaa	Tahkuna	153	09.12.1951	117	1400
	Ristna	123	06.12.1961	87	100
	Sõru	87	22.01.1956	64	1000
	Heltermaa	93	16.01.1952	72	140
Tallinn	Tallinn, port	119	23.09.1924	80	1000
Käsmu–Narva-Jõesuu*	Loksa	123	14.12.1964	76	50
	Kunda	118	14.12.1964	96	140
	Narva–Jõesuu	202	23.09.1924	109	130
Matsalu bay	Rohuküla	108	16.01.1952	80	680
	Virtsu	119	09.1903	86	1000
Pärnu-Ikla	Pärnu	183	17.09.1923	130	560
	Kihnu	150	13.02.1962	103	800

* Integrated results of three smaller study areas (Figure 1).

The potential monetary loss from inundation and storm surge zones was calculated to reflect prices in Estonia in 1995 based on three criteria: value of submerged and temporarily damaged land, value of existing property in these two zones; and lost profit from damaged meadows and forests.

RESULTS

A hypothetical 1-m global sea-level rise, which translates into 69–73 cm of relative sea-level rise (Table 1), would result in the erosion and inundation of 38 km^2 of the coastal area of Hiiumaa, with the most extensive coastline recession (1400 m) on the silty shores near Kõrgessaare and Käina (Figure 2-1). Loss estimates indicate that all reed beds and 80% of coastal meadows (salt marshes), including the rare saline plant communities (*Salicornia europaea, Carex glareosa,* and *Glaux maritima–Juncus gerardii*; INGELÖG, ANDERSSON, and TJERNBERG, 1993)—which occur in all successional transitions—are at direct risk. The rare ecosystems of lagoons and orchid-rich calcareous meadows on the coast of Hiiumaa, the spawning grounds for trout and lavarets, and the breeding grounds for waterfowl and many other migrating birds would disappear. Table 3 shows the potential losses and their approximate monetary value (in U.S. dollars in 1995) with a 1-m sea-level rise for the test areas. However, the study areas on the western coast of Estonia and the archipelago would also suffer from wetland inundation. The loss of wetlands cannot be expressed in monetary terms.

The Tallinn study area (Figure 2-2, Table 4) would face a relative sea-level rise of 74 cm. Although seawall and groynes

Table 3. *Economical vulnerability of study areas to a 1-m global sea-level rise. All prices are counted as Estonia's average in thousands of 1995 U.S. dollars, assuming no adaptation.*

	Inundation Zone							
	Hiiumaa		Käsmu–Narva-Jõesuu*		Matsalu Bay		Pärnu–Ikla	
		Price		Price		Price		Price
Coastline length (km)	326		190		230		150	
Coastal meadows (km²)	7.8	116	0.9	22	31	714	19.7	411
Wetlands (km²)	13.7	204	3.3	85	38	875	0.8	17
Forests (km²)	8.3	123	1.5	40	7.5	173	0.3	6
Beaches (km²)	5.6	83	2.9	75	0.15	3	1.4	29
Settlements (km²)	2.6	39	0.11	118	0	0	0	0
Total area (km²)	38	565	9.8	340	76.6	1765	22.2	463
Timber (m³)	126,990	4535	23,562	842	114,750	4098	4590	164
Hay (100 kg/century)	561,600	3009	133,920	717	2,232,000	11,957	1,418,400	7600
Dwellings	20	83	120	471	27	108	30	122
Harbours†	7		5		2		0	
Beacons†	8		5		1		0	
Roads (km)	9.7	414	8.5	364	12	514	0	0
Overhead lines (km)	15.5	78	11.8	59	7.3	37	0	0
TOTAL		8684		2793		18,479		8349

	Storm Surge Zone							
	Hiiumaa		Käsmu–Narva-Jõesuu*		Matsalu Bay		Pärnu–Ikla	
		Price		Price		Price		Price
Coastal meadows (km²)	30	446	0.7	17	23	530	20.2	422
Wetlands (km²)	0	0	3.7	92	15	345	0	0
Forests (km²)	44.2	6570	2.5	62	25.5	587	2.5	51
Arable lands (km²)	0	0	0.03	1	4.5	104	0	0
Settlements (km²)	1.1	943	0.2	300	0	0	0	0
Total area (km²)	75.3	7959	7.15	472	68	1566	22.7	473
Timber (m³)	676,260	24,152	382,500	13,661	390,150	13,934	37,485	1339
Hay (100 kg/century)	2,160,000	11,571	161,280	864	1,656,000	8871	1,454,400	7791
Dwellings	330	1296	415	1630	267	1049	304	1194
Roads (km)	44	1886	31.5	1346	40	1714	0.7	30
Overhead lines (km)	60	300	22.5	112	36	180	0	0
TOTAL		47,164		18,085		27,314		10,827

* Integrated results of three smaller study areas (Figure 1).

† Possible damages are not expressed in monetary values because they can be avoided by regular care.

protect one-third of the city's coastline, the potential damage would be greater than in the other study areas. As the Paljassaare Peninsula represents more than half of the potentially submerged area, most damage would be in the form of land loss rather than economic loss, as it is not presently a residential district.

The Bruun Rule indicates that the lack of vulnerable shore types in the Käsmu–Narva-Jõesuu study area would limit the land loss to 9.8 km² (Figures 2-3 through 2-5, Table 3). The area contains two vulnerable sites: (1) the easternmost part between Narva-Jõesuu and Meriküla, an important recreation site with sandy beaches, and (2) Sillamäe, an important industrial centre. The dump site of the defunct uranium enrichment plant remains the greatest environmental threat to the coastal plain and the Gulf of Finland (KONT *et al.,* 1996b).

Table 4. *Economical vulnerability (in millions of 1995 U.S. dollars) of Tallinn, the capital of Estonia, to a 1-m global sea-level rise, assuming no adaptation.*

	Inundation Zone		Storm Surge Zone	
		Price		Price
Territory (km²)	3.34	19.0	3.04	17.0
Housing stock (number)	57	2.5	162	22.5
Enterprises (number)	7	0.5	181	12.0
Streets (km)	7.7	0.6	16.1	1.5
TOTAL		22.6		53.0

The Matsalu Bay study area is the most vulnerable in terms of land loss and destruction of valuable ecosystems. Recession occurs along the longest coastline length (6.4 km) among the study areas (Figure 2-6). Virtsu, an important port connecting the mainland with Saaremaa and Muhu Island, would witness significant changes. The peninsula upon which Virtsu is situated would become many islets. Sea-level rise (varying from 72 cm in the north to 80 cm in the south) would inundate more than 76 km² of the territory (Table 3), including the entire reed bed and most of the flooded meadows. Several plant communities and biotopes of rare species—including unique orchid species—would disappear. Broad-leaved forests—uncommon in high latitudes—would also suffer from the sea advance, while elevated groundwater tables would result in new wetlands. In Estonia, the absence of hard

Table 5. *Aggregate economical vulnerability (in millions of 1995 U.S. dollars) of Estonia to a 1-m global sea-level rise and number of people displaced, assuming no adaptation.*

Study Area	Inundation Zone	Storm Surge Zone	Both Zones	People Displaced
Hiiumaa	8.7	47.1	55.8	300
Käsmu–Narva-Jõesuu	2.8	18.0	20.8	800
Matsalu Bay	18.5	27.3	45.8	1850
Pärnu–Ikla	8.3	10.8	19.1	5450
Tallinn	22.6	53.0	75.6	8800
Study areas in total	60.9	156.2	217.1	17,200
Estonia in total	243.6	624.8	868.4	42,400

defences on the coast will allow the plant communities to migrate inland where land use allows. This differs from many European seaside countries, where hard defences would prevent migration, causing a coastal squeeze (NICHOLLS, 2000).

The territories most vulnerable to sea-level rise in the Pärnu–Ikla study area are both located in the north, where silt shores dominate and, during the most recent powerful storms, waves reached dwellings 300-m inland (Figure 2-7, Table 3). The rate of isostatic uplift in this area is the lowest in Estonia (about 1 mm/y), resulting in a relative sea-level rise from 85 cm in Pärnu to 95 cm near the Latvian border. This would inundate more than 22 km^2 of coastal territory, including almost 2.5 km^2 of the territory of Pärnu, the largest city in this region, and 3.8 km^2 of the densely populated Isle of Kihnu. Although no rare or highly valuable natural ecosystems in the Pärnu–Ikla study area would need special protection, sea-level rise would have socioeconomic impacts, particularly on the protection of recreational areas.

The estimates of potential losses over the entire coastal territory of Estonia are based on the results of the study areas. As the study areas represent all major shore types (including vulnerable coastal cities) and include about a quarter of the total coastline length, extrapolation of the results over the whole coastal zone is assumed to be reasonable. Total value was therefore calculated by multiplying the losses of the study areas by four and adding those of the cities in the study areas. The number of people who would be displaced by land loss due to sea-level rise (based on the data in 2000) and assuming no adaptation is also estimated (Table 5).

DISCUSSION

The climatic trend projected by climate change scenarios—less continental and increasingly maritime—has been observed in Estonia for the last 100–130 years (JAAGUS, 1996). Global warming is likely to accelerate this change during the 21st century. Generally, climate change scenarios predict similar climatic conditions in Estonia as occurred during the Holocene climatic optimum. The Atlantic climatic stage (4800–7800 years ago), during which vast coastal areas of contemporary Estonia were submerged, can therefore be considered an analogue for future climate (KONT *et al.,* 1996a; PUNNING and KOFF, 1996), although it must be remembered that no future scenario can be extrapolated directly.

Winter is the season most vulnerable to climate warming; temporal variability of temperature in winter is more than twice that during the other seasons. The most probable consequences of climate warming are increased temperature and precipitation in winter. Mild winters are associated with increases in cyclonic activity and storm frequency which, added to the reduced range of sea ice, would enhance seashore erosion in Estonia. Therefore, climate change poses hazards even without ASLR. Mild winters are likely to be followed by earlier springs.

Figure 3. Varved clay shore partly covered with reed bed in western Estonia (study area 6; photo by A. Kont).

Despite isostatic uplift, erosion of sandy beaches has been prevalent throughout Estonia in recent decades, and in some places the sea is advancing inland. The lack of evidence for rising sea level suggests that the observed beach erosion is due largely to the recent increased storminess in the eastern Baltic Sea and the decline in the occurrence of sea ice. In autumn and winter, the westerly and south-westerly storm winds can raise the sea level to 2.6 m above the summer level. Estonia, particularly the western archipelago, has experienced at least 10 violent storms since 1954, which—according to historical probability—should occur once in a century (ORVIKU, 1992). Most beaches deteriorate due to storms; in only a few places (*e.g.,* Ruhnu Island) has recovery occurred.

A 1-m global rise of sea level would affect the coastline configuration and position, especially in areas with small islands, some of which would be submerged. The most significant changes would occur on the western coast, including Matsalu Bay, where the flooded meadows of the Kasari River and the Matsalu reed bed (about 3000 ha) are among the biggest and most important breeding grounds for birds in northern Europe (and are designated under the Ramsar convention). As this area is low lying and flat and consists of varved clay, the dominant processes would be inundation and temporal flooding (Figure 3). Under current conditions, ecosystems found on this study site, such as coastal meadows, flooded meadows, and reed beds, are only temporarily flooded. A 1-m global sea-level rise would reinstate approximately the same coastline position as found in the 1700s, and plant communities could migrate inland. However, unlike the situation in the 1700s, arable lands, secondary species-poor for-

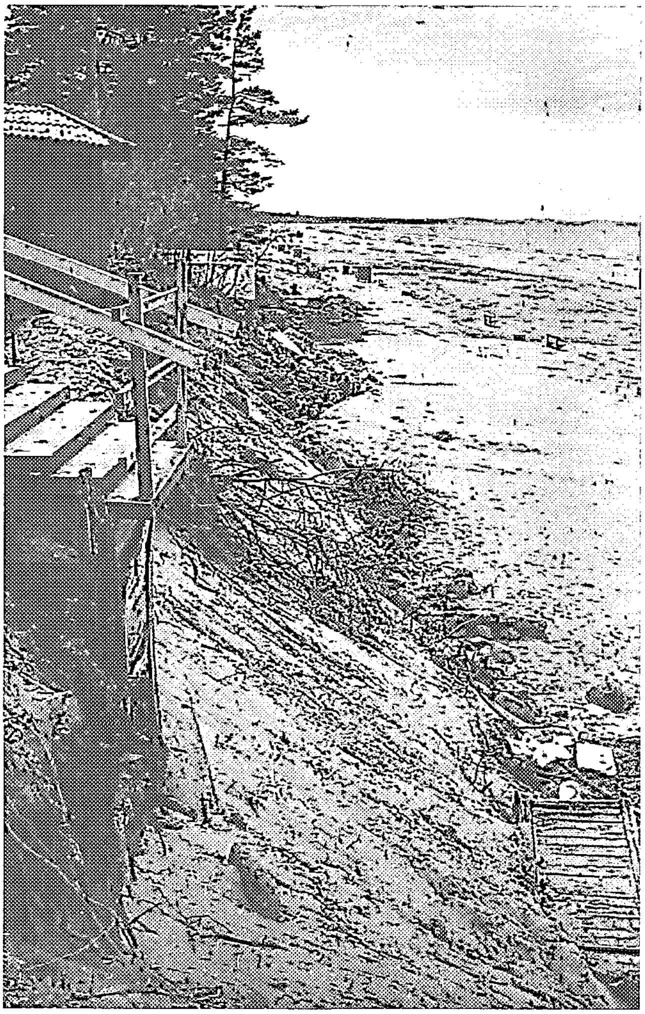

Figure 4. Sandy beach eroded after strong storm in Narva-Jõesuu (study area 5; photo by K. Orviku).

Figure 5. The dump site of the former uranium enrichment plant at Sillamäe (study area 5; photo by K. Orviku).

ests, and cultivated grasslands prohibit extensive migration of natural and seminatural communities. Although the ecosystems would survive, their species richness would be expected to diminish, as many rare species are unlikely to survive the gradual migration into these initially unfavourable conditions (KONT *et al.,* 1996a; KONT, RATAS, and PUURMANN, 1997). No effective response options could prevent deterioration in the species richness of these seminatural plant communities.

By contrast, the western coast of the mainland Estonia is sparsely populated and the few small villages are located at higher elevations, beyond the potentially flooded territory. This is a specific feature of Estonia compared to other parts of Europe, where the number of people at risk is usually much higher.

The area least vulnerable to ASLR is the eastern part of the north Estonian coastal plain, although relative sea-level rise would be among the highest in Estonia (up to 95 cm in Narva-Jõesuu). The study area is a narrow strip of land between the Baltic Glint and the sea, with two major sites at risk. Unfortunately, the excellent sandy beaches between Narva-Jõesuu and Meriküla (Figure 1) have suffered from strong storms in recent decades (Figure 4). One probable cause for this damage is the decline in runoff from the Narva River since 1956, when the river was dammed and a hydroelectric power plant was built. The high flow rate of the Narva River had previously curtailed the damaging effect of currents and waves on the beach. The river also carried larger amounts of sand to its mouth, which settled at the junction of the river flow and sea currents. As the accumulating and buffering effect of the Narva River has decreased, storms have carried coastal sediments eastwards (ORVIKU, 1987). Consequently, sea-level rise, combined with higher storm surges, would cause serious damage to the beaches and Narva-Jõesuu (a resort well known since the end of the 19th century) and exacerbate existing coastal problems.

Sillamäe, an important industrial centre, is also at high risk, particularly as it included the dumping site of the former uranium enrichment plant, which is separated from the sea by a narrow dam (Figure 5). Thousands of tonnes of radioactive substances containing ^{238}U, ^{232}Th, and ^{226}Ra leak annually from the site into the soil and sea. Sea-level rise and stronger storms would jeopardise the efficiency of the dam and could result in catastrophic pollution of the Gulf of Finland (KONT *et al.,* 1996b). In 1998, a Danish–Estonian 9-year joint project was initiated to seal the dumping site and eliminate the risk. Hopefully, this will take account of sea-level rise and climate change.

Of the well-recognised approaches to mitigating sea-level rise (NICHOLLS *et al.,* 1995), seawall construction and beach nourishment are two options that could prevent coastal land loss in Estonia. Coastal cities, such as Tallinn, Pärnu, Kuressaare, Haapsalu, Kärdla, Sillamäe, and Narva-Jõesuu, would need extended seawalls, dikes, and groynes to ensure effective protection and avoid socioeconomic damage. The most practical option to preserve unique and valuable natural ecosystems in the west Estonian archipelago and the west

Estonian plain would be to artificially reinforce the headlands. This would help to avoid straightening of the shoreline and protect the biotopes of rare plant species and communities but would also result in enhanced erosion of bays. In areas where this option is impractical, loss of unique ecosystems appears inevitable. Beach nourishment for Estonia's sandy beaches, a technique that has been practised at Narva-Jõesuu, would be needed on the western coast of Hiiumaa, the south-western coast of Saaremaa, the southern part of the Pärnu–Ikla study area, and in limited sections along the northern coast of Estonia. However, this is an expensive adaptation option and is most likely to be applied where highly developed and economically efficient recreational facilities exist.

Finally, although global climate change is unlikely to have a catastrophic effect on the Estonian economy (and may even be seen as advantageous—enhanced production, reduced heating requirements, *etc.*), loss attributable to ASLR would be significant, especially in the storm surge zone. A 1-m global sea-level rise would jeopardise the survival of several natural areas but would not cause widespread relocation of the population owing to the general sparsity of settlements and low population density in the coastal zone. About 3% of the country would be inundated or temporarily damaged, requiring relocation of about 40,000 inhabitants, notwithstanding seaside cities, some beaches of high recreational value, and some ethnographically valuable villages on the Isle of Kihnu.

This lack of economic impact has meant that, although global climate change and ASLR are recognised as threats among scientists, on a governmental level in Estonia no measures to protect the seashore are currently being considered. However, based on existing coastal problems and the results of this study, development of more comprehensive coastal management would seem prudent. One of the positive effects of the U.S. Country Studies Program for Estonia has been to set up the State Monitoring Program for Coastal Landscapes that is being carried out on nearly 30 different sites.

CONCLUSIONS

The relatively long coastline and the prevalence of low-lying coastal areas make the territory of Estonia vulnerable to ASLR. Although isostatic uplift partly mitigates the rising sea, the region is still threatened. A 1-m global sea-level rise would result in considerable change in coastal ecosystems and would lead to significant economic risk across the different regions of Estonia. Increasing erosion and changes in sedimentation would seriously unbalance sandy beaches and dunes, particularly in south-western and north-eastern Estonia, leading to a negative impact on recreation.

In the western part of Estonia (including the large islands), direct destruction of the coast would not be as great. Although seashore plant and animal communities could migrate inland, the interaction of changing water level and land use would result in the decrease of species variety. Here, the economic consequences would be greatest in urban areas, particularly in Tallinn and Pärnu, the most important summer resort, where roads and buildings are often close to the present shoreline and where the topography is low and flat.

Integrated coastal zone management should be based on trustworthy forecasts of coastal zone responses to the rising sea. This study has highlighted the limitations of existing methodologies for assessing the impact of climate warming and ASLR. The diverse structure of Estonia's coasts, including the rapidly changing position of shorelines and the abundance of small islands, causes difficulties for reliable assessments, and new methodologies—applicable to these conditions—must be developed and confirmed in study sites of different types of coasts.

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☐ SISUTUTVUSTUS ☐

Eesti on pika rannajoonega (3800 km) mereäärne maa. Seetõttu on võimalik meretaseme tõus üks võtmeküsimusi kliima muutuse mõju hindamisel Eesti jaoks. Kuna siinne rannik on valdavalt madal ja tasane, on paljud väärtuslikud rannikuökosüsteemid kliima muutuse ja meretaseme tõusu korral hävimisohus. Paljud kõrge rekreatiivse väärtusega liivarannad lakkaksid eksisteerimast. Kliima muutusega kaasnevate pehmete talvede, jääkatte puudumise ning sagedaste tormide koosmõju teravdaksid veelgi ülalmainitud protsesse. Ent isostaatiline maakerge ja rannikuäärsete asulate paiknemine tänapäeva rannajoonest eemal mõnevõrra leevendavad riski suurust. Käesolevas artiklis on esitatud analüüsi tulemused aastaks 2100 toimuva 1 meetrise globaalse meretaseme tõusu stsenaariumi järgi tingimusel, et mingeid kaitse- ega kohandamismeetmeid ei võeta eelnevalt tarvitusele. Meretaseme tõusuga kaasneva rannikualade haavatavuse ning selle tagajärgedele vastavate kaitse- ja kohandamismeetmete analüüsiks valiti seitse võtmeala, mis esindavad kõiki peamisi Eesti rannikutüüpe. Eesti rannikutüüpide vaheldusrikkus, kiiresti muutuv rannajoon ning saarte rohkus teevad kliima soojenemise ning meretaseme tõusu võimalike tagajärgede ennustamise väga keerukaks.

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