

The impact of two newly built port terminals in the Eastern Gulf of Finland on sedimentation processes and coastal zone dynamics

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Abstract. The natural coastal zone in the Luga Bay and Bjorkezund Strait are characterized by a positive sediment balance. Recent sediment extraction and significant depth increase within the dredging areas in the vicinity of the newly built oil and coal port terminals in Ust-Luga and Primorsk disturb the dynamic equilibrium and sediment balance in the coastal zone. This activity leads to a change in sediment flows, with a high rate of accumulation in ship channels and an increase of coastal erosion.

Key words: Eastern Gulf of Finland, port terminals, sedimentation processes, coastal erosion.

1. INTRODUCTION

Several big oil and coal port terminals and harbours have been constructed in the Russian part of the Gulf of Finland over last decade. The terminals near Ust-Luga town (Luga Bay southern coastal zone) and near Primorsk town (Bjorkezund Strait, northern coastal zone) are among the largest in the region (Fig. 1). The planned activities propose intense dredging and building of huge coastal engineering infrastructure, consequently there are significant transformations of on-land and submarine coastal landscapes. It is expected that the changes will affect the coastal zone litho-dynamics and result in bottom relief and shoreline transformation and a change in the sediment balance and wave regime alteration.

The newly built Ust-Luga port complex is planned to be one of the world's ten biggest ports (Fig. 2). According to the plan, its carrying capacity of general cargo will reach 120 million tonnes per year (50 million tonnes by 2010, www.ust-luga.ru).

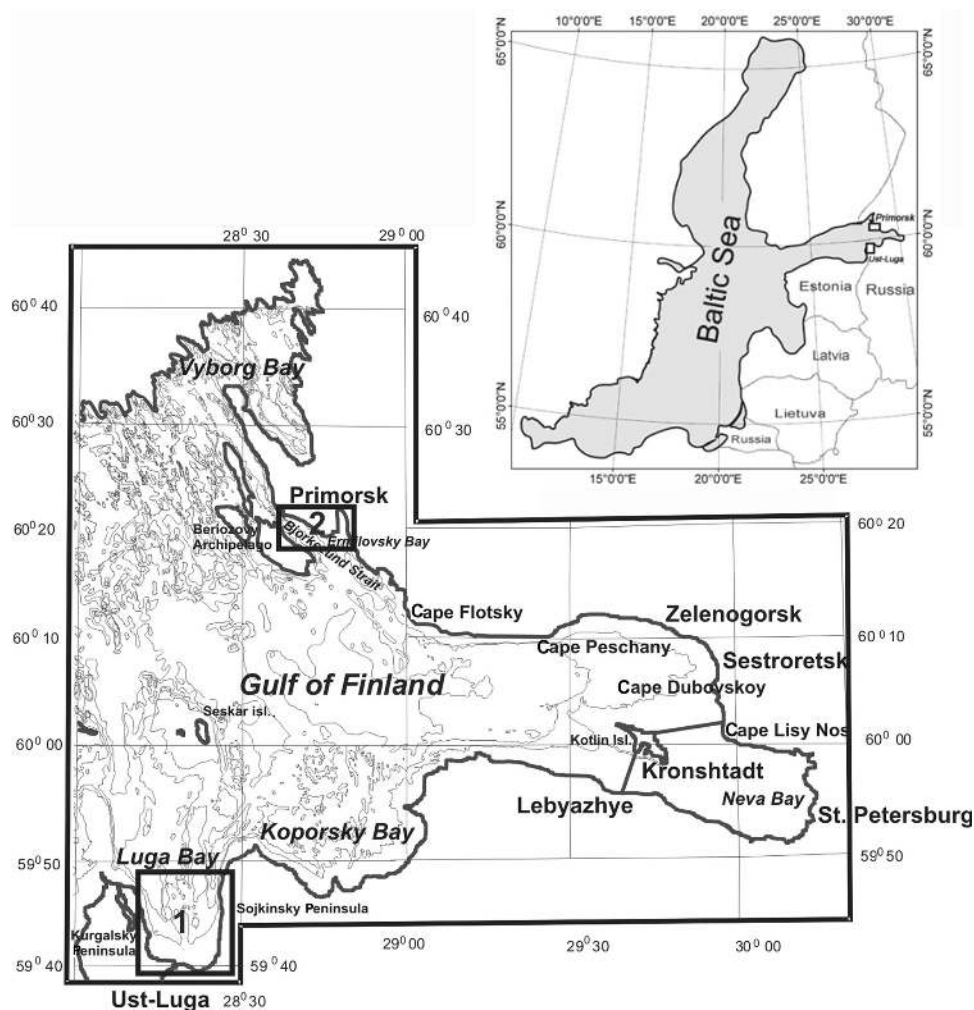


Fig. 1. Location of the Ust-Luga port complex (1) and the Primorsk oil terminal (2) in the Eastern Gulf of Finland.

The Primorsk oil terminal (part of the Baltic Pipeline System, the first segment of which has operated since 2001) is the biggest oil export port of Northwest Russia. The volume of oil shipped exceeds 57 million tonnes annually, and since 2006, 65 million tonnes annually (www.mtp-primorsk.ru). In the near future further expansion of the port area to the shores of Ermilovskiy* Bay is planned.

Navigation safety determines that the location of the terminals and port complexes is within bays, which are better protected from the wave impact. Both Ust-Luga and Primorsk terminals are located in such places.

* Transliteration of Russian names into Latin alphabet is given according to the manuscript, presented by the authors.

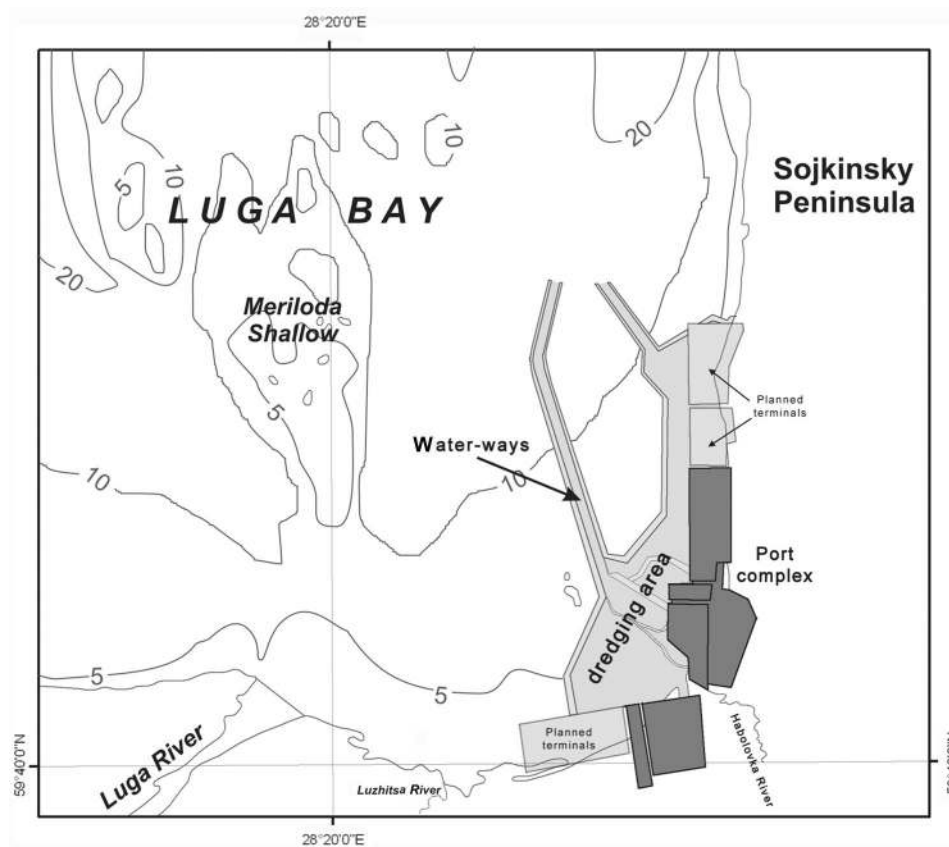


Fig. 2. The planned port constructions in Luga Bay (www.ust-luga.ru).

Both port complexes are very important for regional economic development. Among the main goals of both projects is the minimization of the anthropogenic impact on the natural environment (www.ust-luga.ru, www.mtp-primorsk.ru). Potential significant anthropogenic impact on the coastal zone makes detailed studies of the background natural characteristics of the litho- and morphodynamics and sedimentation processes very important.

Land-based geological research was started by Kropotkin [1] and Hyypä [2] on the Karelian Isthmus and Markov [3,4] in the coastal area of Luga Bay. Significant regional land-based research by Malakhovsky, Znamenskaya, Kvasov et al. [5-7] and a comprehensive marine geological survey, carried out by the A. P. Karpinsky Russian Research Geological Institute VSEGEI in 1987–2000 [8-11], enabled the analysis of long-term coastal zone change. Orviku studied and for the first time classified the coasts of the Eastern Gulf of Finland during his field expeditions in 1987–1990. The results of this work were published as a separate chapter of [12].

The resolution and quality of available geological data in this region were considerably improved as a result of the detailed VSEGEI coastal zone investigations in Bjorkezund Strait, carried out before 2000 and immediately after 2003 as a part of preparation for the first part of oil-terminal construction. In 2007–2008 the coastal zones of both areas were examined in the framework of the project “Up-to-date assessment of mineral-resource potential, control over geological hazards and establishment of prediction development models of geological environment in the Baltic Sea and its coastal zone”, funded by North-West Department of the Federal Agency on Mineral Resources. Additionally to studies on the coast, about 200 km of side-scan sonar profiling (CM2, C-MAX Ltd, UK) with search swath 100 m and a working acoustic frequency of 325 kHz and 85 surface sediment samples were taken in the nearshore zone.

Grain-size analyses of 32 samples were carried out in the laboratory of VSEGEI (Department of Regional Geoecology and Marine Geology) using an analytical sieve shaker (AS 200 Retsch).

The objective of this paper is to examine the coastal zone dynamics and the nearshore sedimentation processes in the vicinity of the newly built terminals as a background for the management of the geological environment under the growing anthropogenic impact.

2. STUDY AREA

Luga Bay (Figs. 1–3) is one of the two biggest southern bays in the Russian part of the Gulf of Finland. The bay extends 15 km in the north-south direction and is about 13 km wide between the Sojkinsky and Kurgalsky peninsulas.

The Meriloda and Temnaya Loda shallows are situated in the central part of the bay between two relatively deep (up to 32 m) and narrow sedimentation basins. The shape, size and bottom relief of Luga Bay generally prevent the development of high wind waves. Waves created by northern winds mostly affect the eastern (north and NW winds) and western (north and NE winds) coasts of the bay. Usually waves approach the coastal zone under an acute angle with respect to the coastline. The impact of the waves on the bayhead is insignificant because of the shallows located in the centre of the bay and the wide sandy shallows formed by the Luga River sediment input.

The northern coast of the Bjorkezund Strait, where the Primorsk oil terminal was built, is an example of a skerries (skären) type coast. It is very well protected from wind waves from all directions by the islands of the Beriozovy Archipelago (Fig. 1).

However, the commencement of the terminal activity induced wave regime change as a result of near-shore relief transformation and ship-wave impact [¹³].

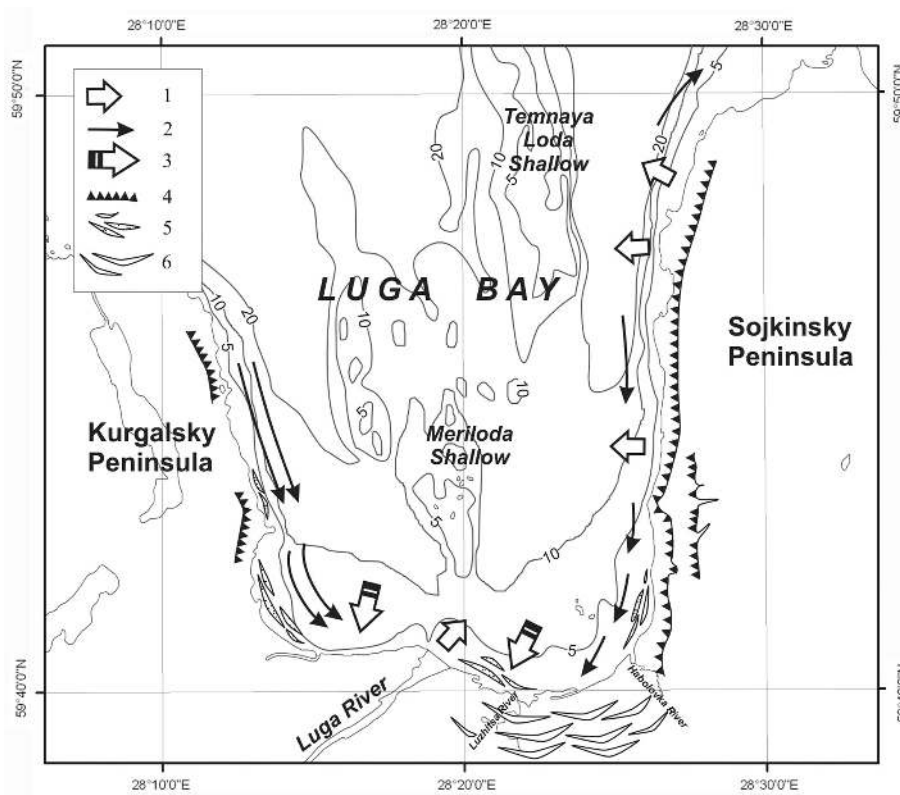


Fig. 3. Coastal zone dynamics of Luga Bay [13]: 1 – areas of sediment input; 2 – directions of sediment flows; 3 – sediment accretion areas; 4 – Litorina terrace scarp; 5 – modern longshore sandy bars; 6 – relict sandy bars.

3. RESULTS ON GEOLOGY, SEDIMENTATION PROCESSES AND COASTAL DYNAMICS

3.1. Luga Bay

The bedrocks of the study area comprise crystalline basement covered by Vendian argillites, siltstones, clays and sands, gently inclining in a southern direction. The coastal zone of Luga Bay is covered by Quaternary deposits (glacial till, glaciolacustrine, lacustrine and marine) from 20 to 70 m thick [9].

The onshore coastal areas of Luga Bay comprises a terraced plain with distinct relief levels resulting from their pre-Quaternary development, and late-Pleistocene and Holocene geological history. The uppermost level is the Sojkinskaya Upland of the eponymous peninsula, with the highest point at 135 m. The western border of the Sojkinskaya Upland is surrounded by the erosion escarpment of the Baltic Ice Lake (with an absolute height of 65–75 m), with very distinct relief that has partly levelled off by subaerial erosion. Unlike

the other parts of the coastal areas, the Sojkinskaya Upland had never been covered by water over the period of postglacial lakes or Litorina Sea [3,4].

There are two clearly distinguishable terrace levels between the contemporary coast and the Sojkinskaya Upland. The upper terrace was formed by the Baltic Ice Lake. It consists of the Kurgalovskoye plateau of Kurgalsky Peninsula (absolute height 25–30 m), Kurovitskoye plateau (absolute height 25–29 m), which is situated to the south of study area and the so-called “second terrace” of the Soykinsky Peninsula (absolute height 27–40 m). This relief level is limited by the Litorina Sea shoreline. Within the Kurgalsky Peninsula there are some beach ridges of Litorina time which have later been transformed into dunes. In the vicinity of the Ust-Luga port complex the width of the second terrace varies from 0.75 to 1.2 km.

The lower terrace was formed during the Litorina transgression. The Litorina Sea shoreline is characterized by a distinct erosion escarp (absolute height 10–25 m) parallel to the modern coast [14], while in the bayhead area the terrace surface is complicated by relict sandy bars. Along the eastern coast of Luga Bay (including the Ust-Luga port area) the lower terrace is just 250–650 m wide, slightly descending from the absolute height of 7–10 m towards the sea. In the bayhead, in the interfluves of the Luga and Habolovka rivers, the cross-shore width of the sand bars (about 4 km) is at a maximum. There are up to 20 sand bars (absolute height 4–6 m) with low peaty runnels between them [14] (Fig. 2).

The sediment transport on the western coast of Luga Bay is caused mainly by waves and is directed from north to south. The eastern coastal zone is characterized by the same direction of longshore sediment drift, but the volume of transported sediments is smaller. Before the Ust-Luga port construction began, the annual sediment input to the southern part of the bay from erosion of the coasts and near-shore bottom was about 110 000 m³ (about 100 000 m³ of sediments from the western coast and about 10 000 m³ of sediments from the eastern coast of Luga Bay) [15]. The Luga River discharge in the western part of the bayhead is the other important source of sediment. The volume of suspended load is about 40.8 thousand tonnes annually [14]. The relief of the catchment area is almost plain and the river bed is very gently sloping. The slow river flow, thus, supplies almost no coarser sediment to Luga Bay and suspended silty-clay material dominates in the river discharge. In the bayhead, eastward sediment transport dominates. The sediment flows from the north towards the bayhead form a vast accretion zone (Fig. 3). It is important to note that the location of areas of accretion, erosion and transition have been constant at least during the Holocene [3,4].

The grain-size compositions of eroded beaches of the eastern coast of Luga Bay and accretion areas of the bayhead differ considerably. Medium to coarse-grained sands and gravel from the areas of erosion are very poorly sorted (the sorting coefficient [16] $So > 2.0$). The nearshore zone is usually covered by a boulder-pebble bench, sometimes with areas of coarse or very coarse grained sands. In areas of sand accretion the bottom surface comprises well-sorted fine-

grained sands (mean size about 0.16 mm, the class 0.1–0.25 mm dominates with 80%–94% of the total occurrence, S_o varies from 1.0 to 1.2).

The bottom sediment distribution in Luga Bay is very complex and is primarily the result of the complicated relief. The sediments are represented by wide grain-size spectrum (Fig. 4).

The boulder-pebble and gravel sediments cover the bottom surface of the nearshore zone along eastern and western coasts, and on the Meriloda Shallow. Sands of different grain-size, which were observed at depths from 0 to 30 m, are the most widespread types of bottom sediments. Fine and very fine, well sorted (S_o about 1.0) sands form accretion bodies (bars) in the southern part of the bay. Between the bars there are areas of water plants growing, where the silty-clayey mud with high content of organic matter is observed on the sandy surface. The silty-clayey mud of the elongated sedimentation basin is enriched with sandy particles [9].

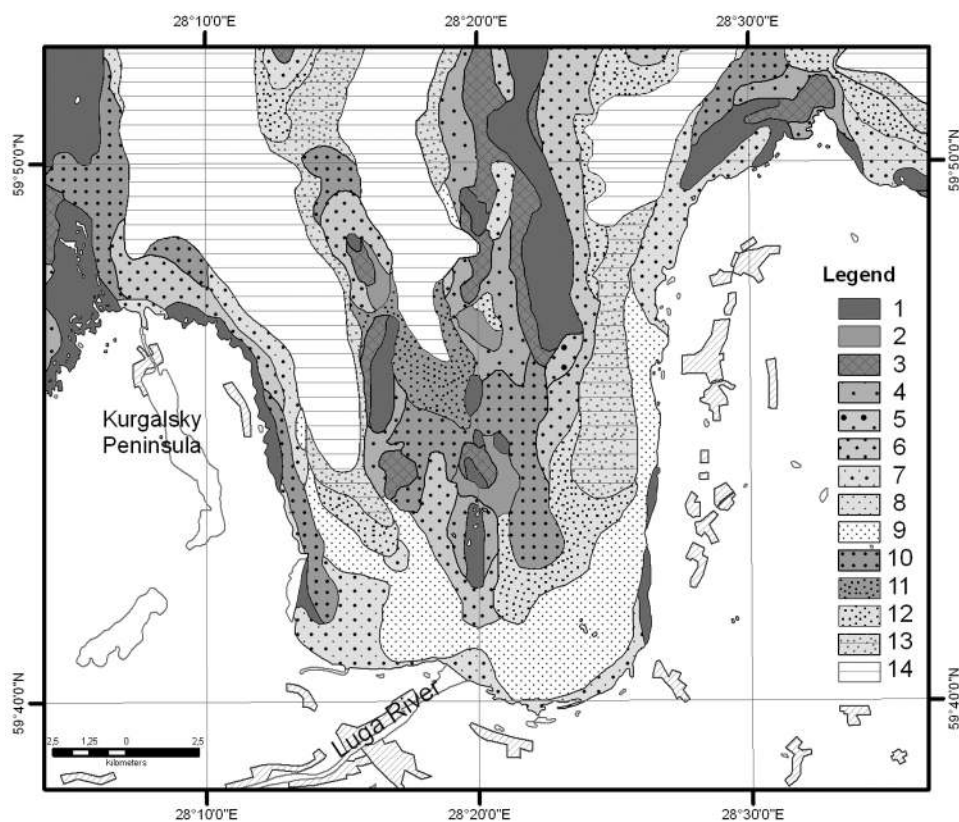


Fig. 4. Surface sediment map of Luga Bay: 1 – boulders, pebbles; 2 – unsorted (mixed) sediments; 3 – sands with gravel; 4 – poorly sorted sands; 5 – coarse-grained sands; 6 – medium to coarse-grained sands; 7 – medium-grained sands; 8 – fine to medium-grained sands; 9 – fine-grained sands; 10 – very fine-grained sands; 11 – clayey sands; 12 – sandy silts; 13 – clayey silts; 14 – silty-clays.

3.2. The Bjorkezund Strait coastal zone

The bedrock of the study area are metamorphic and intrusive rocks of the Baltic Crystalline Shield of the Archaean and Early Proterozoic. The Vendian sedimentary rocks (argillites and siltstones) covering the crystalline rock surface is observed only to the south of investigated area (the southern part of Bolshoy Beriozovy Island). The numerous tectonic faults within the bedrock have a north-western or northern direction. The Quaternary deposits completely cover both on-land and submarine parts of the coastal zone. Their thickness is highly variable, from a few meters to about 60 m. The on-land areas adjacent to the Bjorkezund Strait are represented by partly swampy lowlands.

The shoreline of Bjorkezund Strait is slightly embayed. The coastal zone of advanced segments of shoreline was formed as a result of glacial till erosion. Both the nearshore and the narrow beaches are covered by a protecting boulder and pebble pavement, which prevents further erosion. The erosion scarp is low (0.7–1.0 m) but is still active and situated at a distance of 10–15 m from the shoreline. Within the small bays, local pocket beaches are observed. The long-shore sand drift is directed to the north-west, unlike the eastern parts of the coastal zone of the Gulf of Finland [^{15,17}]. The pavement surface in the nearshore zone of the small and narrow Ermilovsky Bay is covered by vegetation.

The surficial bottom sediments of studied area are diverse (Fig. 5). The underwater coastal slope of the northern coast of the Bjorkezund Strait is relatively steep (the 15 m isobath is situated at the distance of 250–300 m from shoreline). The seabed up to water depths of 5–8 m is actively eroded by waves and is covered by coarse sediments (boulders, pebble, gravel) alternating with sands, formed on the erosion surface of glaciolacustrine clays. The upper boundary of the modern silty-clayey mud accumulation zone is at a water depth of 13–15 m. In the marginal areas of the sedimentation basin, the grain size composition of mud sediments is characterized by a high (up to 30%–32%) proportion of sandy particles suggesting that the properties of the accumulation process vary in time. In deeper water, pure silty-clayey mud is observed. Towards the east, the nearshore relief changes. Seaward of the mouth of the Bjorkezund Strait (capes Zarozshy and Toporok) there is a large shallow area elongated in the southern direction. The shallow is formed by a glacial till ridge and its top is situated in a zone of submarine erosion covered by boulders. The nearshore bottom of Ermilovsky Bay is composed of a boulder-pebble bench. The seabed of the central part of the small bay is covered by poorly sorted coarse grained sands. The large submarine accretion spit formed by fine-grained well sorted sands attaches to the eastern coast of Ermilovsky Bay (Fig. 5). The sand spit is a very important feature of the coastal zone dynamics, and its future development can be an indicator of changing coastal processes.

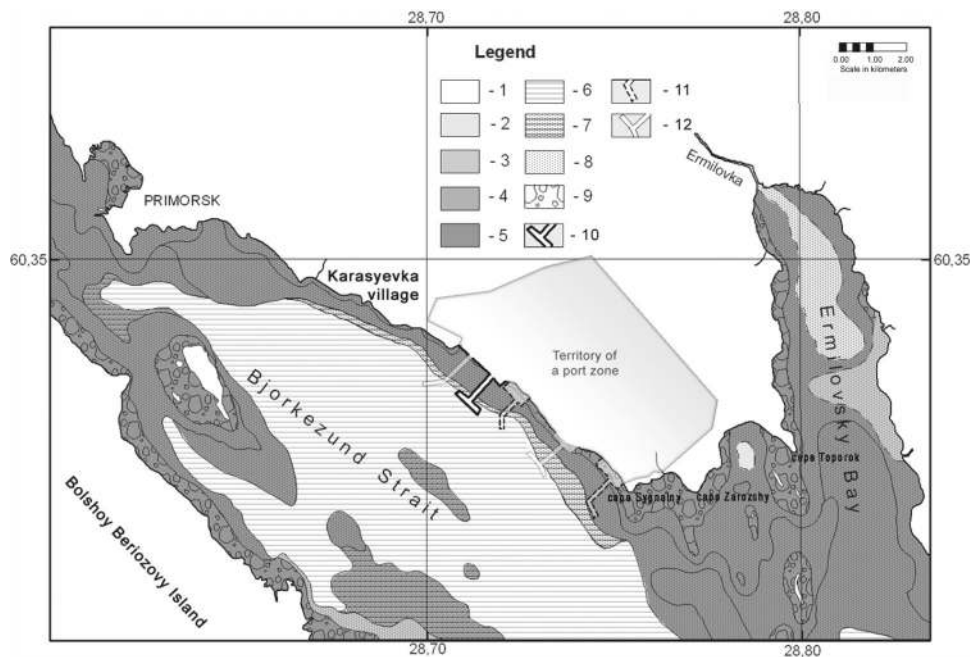


Fig. 5. Map of the bottom sediment distribution of BJORKEZUND STRAIT and ERMILOVSKY BAY: 1 – stable mud accumulation; 2 – occasional mud accumulation; 3 – accretion; 4 – submarine erosion; 5 – intense submarine erosion; 6 – silty-clayey mud; 7 – sandy silty-clayey mud; 8 – sands; 9 – boulders, pebbles; 10 – port constructions.

4. DISCUSSION

4.1. Geological environment impact assessment

4.1.1. Ust-Luga port complex

The coastal land in the vicinity of Ust-Luga is covered mainly by pine and mixed forests. The planned area of various port and coastal engineering constructions is 1.74 km² within the whole port complex area of 5.19 km² (www.ust-luga.ru). By 2003, the terminals were constructed on an area of 4.66 km², and about 0.78 km² of forest were cut.

The geomorphologic description of the Luga Bay coast, undertaken by Markov in 1926, described the southern part of shore (to the east of Luga River mouth) as being a low marshy plain up to 1.5 km wide, with a series of relict sand bars [3,4]. Analysis of topographic charts and air-photos from the 1950s to about 1990 has shown that active sandy accretion with the formation of river mouth bars and longshore sand ridges were the main processes in the bayhead of Luga Bay head. By 1990 a 4.5 km long bayhead sand bar, unique in the Eastern Gulf of Finland, was formed. The bar partly separated a shallow water area, covered by water plants, from the open part of Luga Bay. It has been growing and gradually shifting towards the central part of the bay.

Markov observed a narrow eroded sandy beach with an active low cliff (erosion scarp) up to 1.5 m high along the eastern coast of Luga Bay in 1926. Active erosion processes continue today. Remote sensing analysis of data since the end of 1970s shows that the shoreline has shifted landward up to 10 m (Fig. 6).

The maximum beach recession, derived from remote sensing analysis, (about 0.9 m/year) occurs to the north of the newly built port terminal Ust-Luga. Positions of boulders, which marked the beach level about 15–20 years ago, have shown that the height of the eroded beach was 1–1.5 m (Fig. 7). The maximum shoreline retreat rate is less than it is within some areas of the more eastern part of the gulf, where the maximum rates reach 2–2.5 m/yr [17]. To the north, the coastal erosion rate decreases.

Intense dredging of sand in the nearshore zone and the construction of the new terminal started in 2005. The dredging area is 6.63 km². As a result the sea depth within the parts of nearshore bottom, adjacent to the building terminal, increased from 2–5 m to 10–16 m (Fig. 2, dredging area). The maximum suspended sediment concentration in the water reached 90 mg/l [18]. The areas of dredging are easily seen on the side-scan sonar images (Fig. 8).

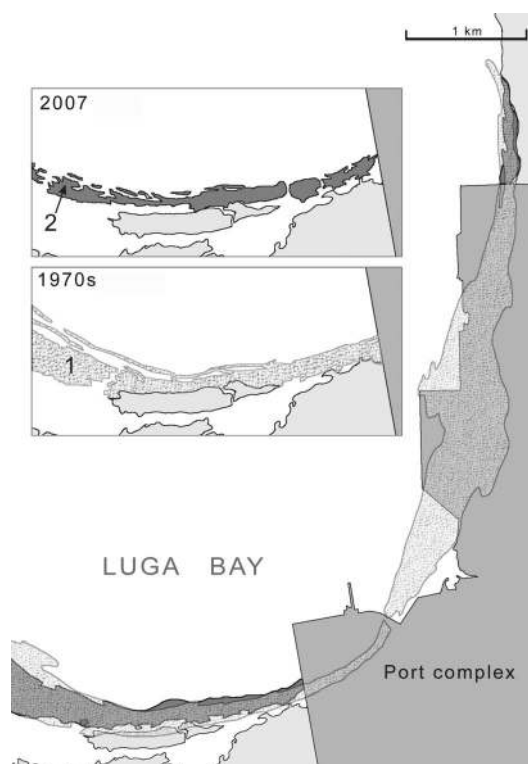


Fig. 6. Degradation of the sand bar in the southern part of Luga Bay: 1 – sand accretion bars derived from aerial photos from the late 1970s; 2 – sand accretion bars derived from a satellite image of 2007.



Fig. 7. Area of active erosion to the north of the Ust-Luga port terminal.

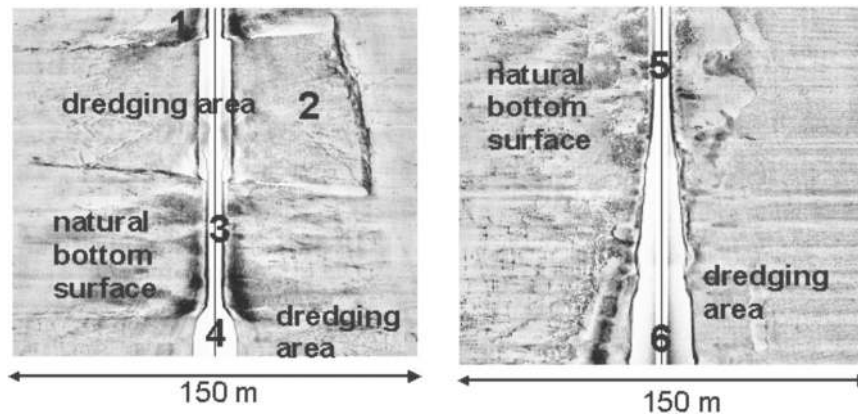


Fig. 8. Side-scan sonar images of the dredging area near the Ust-Luga terminal. Water depths: 1 – 2.9 m, 2 – 7.4 m, 3 – 2.6 m, 4 – 9.5 m, 5 – 3.1 m, 6 – 12.8 m.

Because of active dredging in the nearshore zone, destabilization of sediment transport, and significant reduction in sediment accumulation in the southern part of Luga Bay took place. By 2007, in the bayhead, the accretion processes had gradually reduced and the size of accretion bar had decreased. The coastal zone within the area of the port complex was naturally stable from a lithodynamic point of view.

As was mentioned above, accretion processes dominated in this area for a long period of time. However, in the near future, it is predicted that there will be increased erosion within this segment of the coastal zone. A large quantity of sediments (mostly sands) were removed from the coastal zone during the dredging and used for terminal construction. The new ship channels will interrupt sediment transport and act as large sediment traps. As a result, the natural sediment nourishment of the sand bars will be reduced (Fig. 6). In the late 1970s the area of sand accretion was 2.24 km², including 0.65 km² of the bayhead sand bar area between Luga and the future port. By 2003 the area of sand accretion

reduced up to 0.5 km². The size of the whole accretion zone decreased by about 80% whereas the area of bayhead sand bar decreased by about 30% to 0.42 km².

Before the commencement of construction, the sediment balance of the Luga Bay head was positive. The disturbance of natural processes, caused by dredging, leads to the formation of new accretion areas within the ship channels and stimulates erosion of the coasts and nearshore seabed. In addition, the wave regime in the coastal zone can significantly change because of relief transformation. The other problem is ship waves, which were unusual in the investigated area before the port complex construction. Planned increases and changes to ship traffic mean that the impact of ship waves on the shore could be significant.

Substantial dredging of the new waterways can completely change the sedimentation conditions in the vicinity of the port. The natural accumulation rate within the sedimentation basins of the Eastern Gulf of Finland varies from 3–5 to 8–9 mm/yr [19,20]. Artificial bottom depressions such as waterways and submarine carriers become “sediment traps” with abnormal accumulation rates. The rates could be up to 3–5 cm/yr as revealed during the side-scan sonar investigation of the Eastern Gulf of Finland bottom, where some 1–2 m deep water ways had been filled with sediment over a period of 7–10 years [21].

4.1.2. Primorsk oil terminal

The specialists of the Laboratory of Geography and Mapping of Vegetation of V. L. Komarov Botanic Institute [22] carried out an analysis of the vegetation prior to 1997–2000 and during the first years (2000–2002) of the oil terminal construction. According to investigations, prior to terminal construction the vegetation was disturbed on 8% of the area, partly destroyed on 19% (agricultural areas, glades etc.), 38% was characterized as “medium disturbed” and 31% as “non-disturbed”. By 2002 the area of natural vegetation within the terminal zone decreased for 20%, 26 types of phytocenosis were damaged. Forests were cut on 123 ha and swamps were destroyed on 4 ha [21]. Since 2003, vegetation monitoring has not been undertaken but it is known that landscape disturbance has continued. According to the construction plan, the land area of the oil terminal is going to be about 1000 ha (www.mtp-primorsk.ru).

Significant changes to the lithodynamic and sedimentation processes took place in the vicinity of Primorsk after the construction of the first oil terminal (2000–2003). A side-scan sonar survey accompanied by sediment sampling established the boundary between a submarine erosion zone (10–20 cm of sands on the glaciolacustrine clay surface) and silty-clayey mud of sedimentation basin. In 2000 this boundary was traced along the northern coast of Bjorkezund Strait (from Karasyevka village to Cape Signalny). A new survey carried out in 2003 showed that in some areas the surface sediment characteristics had changed. Directly seaward of the terminal, in 2000, the silty-clayey mud boundary was situated at a distance of 300–400 m. The 2003 study showed that it was shifted 100–200 m seaward (Fig. 9). A former zone of passive near-bottom dynamics and mud accumulation has obtained the nature of an erosion area under impact of anthropogenic processes such as dredging and ship waves.

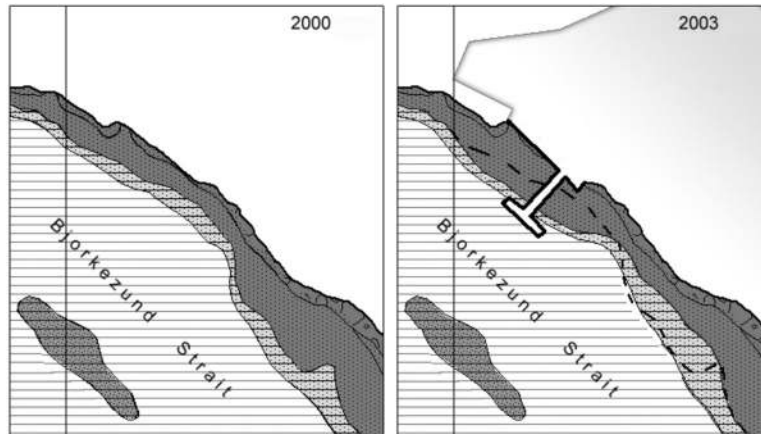


Fig. 9. Changes of surface sediment distribution around Primorsk oil terminal between 2000 and 2003. For explanations see Fig. 5.

To the east of the terminal, sedimentary processes were reversed. In 2000, sands and gravel were observed, while in 2003 the bottom surface was covered by 3–5 cm of silty-clayey mud.

As was the case for the Ust-Luga port terminal, the coasts of the Biorkezund Strait have not been subjected to a significant wave impact for a long time, and therefore the alteration of the wave regime, caused by bottom relief transformation and active navigation, can enhance the wave impact on the shores.

5. CONCLUSIONS

The above analysis reveals that most significant impacts of the newly built port terminals on the geological environment of the coastal zones are:

- landscape degradation within the terminal areas;
- transformation of the near-shore bottom relief;
- disturbance of the coastal zone sediment balance, a decrease in the areas of accretion and intensification of coastal and bottom erosion;
- mechanical destruction of the upper sediment layer, changes to the surface sediment distribution, caused by a change to the sedimentary processes, and marine landscape degradation;
- an increase in the suspended sediment concentration during dredging.

Both discussed Primorsk and Ust-Luga port complexes are very important for national and regional economic development. Unfortunately, irreversible transformation of some parts of the natural environment in the case of such large-scale constructions is inevitable. The development of wide-ranging infrastructure of these ports demands cutting of forest, reclamation of marshlands, earth handling, dredging of harbour basins and fairways, etc. As a result of these activities, the most significant human impact is evident within the coastal zone areas where the

natural equilibrium of sedimentation processes was disturbed and the usual course of coastal processes was even reversed at places. A former sand accretion area near the eastern coast of Luga Bay has been destroyed and the area of the bayhead sand bar has considerably decreased. In the vicinity of the Primorsk oil terminal the mud accumulation area has been shifted essentially, by several hundreds metres seaward.

As the intensity of coastal processes in the vicinity of the discussed complexes is relatively low, the transformation of the sedimentation processes apparently is in the initial phase and more changes eventually will occur. Therefore, minimization of the long-term impact of these human interventions on the natural environment calls for further studies into the changes to the litho- and morphodynamics and sedimentation processes, the results of which may essentially contribute towards mitigation of the adverse effects.

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Uute sadamaterminalide mõju Soome lahe idaosa setete liikumisele ja rannikuvööndi dünaamikale

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Luuga lahe ja Björkesundi väina randades toimub looduslikes tingimustes üldiselt setete akumulatsioon. On näidatud, et hiljuti ehitatud nafta- ja söeterminalide lähistel tehtud süvendamistöödega kaasnenud vee sügavuse märgatav suurenemine on viinud rannavööndi setete dünaamika tasakaalust välja. Erosiooni- ja kuhjepiirkondade asukohad on muutunud ning toimub laevateede intensiivne täiskandumine ja ranniku kiire erosioon.