SATELLITE REMOTE SENSING APPROACHES AND FIELD MEASUREMENTS TO TRACKING COASTLINE CHANGES OF THE SAMBIA PENINSULA AT THE BALTIC SEA

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ABSTRACT

The work is aimed at the accuracy assessment of coastline extraction from optical imagery in studying the short period dynamics and development trends of the coastal zone of the Sambia Peninsula using high- and ultra-high resolution satellite imagery. The paper presents the methodological issues relating to the studies of the Sambia Peninsula coastal dynamics using field data and optical images. It gives the error estimates for satellite remote sensing data based on comparison of those data with the data of field measurements of the shoreline coordinates. It has been established that the accuracy of shoreline extraction from optical image could be that of only several metres. It is shown how the Change Detection algorithm can be used to detect spatio-temporal coastline changes on multi-temporal images. The analysis of the quantitative assessment of changes in the area of erosion and accretion on the Sambia Peninsula coast during the research period of 2010-2017 showed the prevalence of abrasive processes over accumulative ones, which has also been confirmed by field observations during coastal zone surveys conducted after storms in 2012-2017. The prevailing trend on the greater part of the peninsula over the last five years has been established as coastal retreat of 6-36 m on the average.

KEYWORDS:

Coastline; coastal dynamics, remote methods, exogenous processes.

INTRODUCTION

In recent decades, the Baltic Sea of the Kaliningrad region has seen an increased coastal erosion and changes in the shoreline position leading to increase or decrease of beach areas, as well as substantial economic or environmental damage. In most cases, the disturbance of the natural course of the seacoast and the consecutive changes in the shoreline shape are associated with technogenic impact. The construction of hydrotechnical structures of any kind, building material excavation, recreational areas, etc. have mostly negative impact on the coastal dynamics.

The primary focus is on the coastal zone of the Sambia Peninsula with its resort towns and settlements, industrial and agricultural facilities. The coast of the peninsula is characterized by active shoreline abrasion, almost complete absence of stable cliff sections, poor beach development, absence of foredunes, and wide spread boulder-pebble bench on the coastline. The coastal erosion here is intensified by extreme storms repeating in the Baltic Sea every 5-7 years. They bring raised sea level (known as storm surge) and extreme winds. Their highly energetic waves cause severe damage breaking on the shore.

The most significant coastal erosion is observed on the northern coast of the Sambian Peninsula in the coves from village Filino to Svetlogorsk, to the west and to the east of Cape Gvardeisky and on the western outskirts of Zelenogradsk. According to the data, (1) the total deficit of sand deposits in the coastal zone of the northern coast reaches 40 million m³ in the area from Cape Taran to 20 km of the Curonian Spit.

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As the Baltic Sea coast stretches far, most remote sensing surveys employ multi-temporal satellite imagery. Due to their high cost, aerial photography and laser scanning are used only in individual cases requiring detailed studies of coastal and underwater processes. The advantage of using modern high-resolution satellite imagery is that it provides larger spatial coverage with the resolution comparable to that of aerial photographs. Moreover, in recent years, thanks to the information and space technologies development, the spatial resolution of images has increased significantly enabling detailed surveys of coastal processes. Such data include space images with an average spatial resolution of 10 m and images with a high spatial resolution of less than 10 m. Images with high spatial resolution (0.5-0.8 m) can be obtained from Ikonos satellites since 1999, QuickBird since 2001, WorldView-1 since 2007, and from Russian satellites Resurs-P No. 1 and Resurs-P No. 2 since 2013 and 2014.

The high-resolution space images archive is small in terms of timeliness. In addition, the images have high cost, thus this method is not available for studies of long-term coastal zone dynamics. Images with an average spatial resolution are obtained from such satellites as Canopus-B, BKA, Sentinel-2A. The use of Canopus-B and BKA images in most cases is limited due to their incorrect geographic location in local coordinate systems or the absence of others. Sentinel-2A images are now available in open access. For this reason, the images mainly used in coastal remote sensing surveys are those from the Landsat satellite archive that reaches back more than 35 years. The results of these studies are reflected in a number of publications of Russian (2,3) and foreign scientists (4,5,6). One of the studies (2) reveals a retreat of the shoreline by 0.5-1.5 m/year on the northern coast of the Sambia Peninsula and by 1-13 m/year on its western coast over five years (2002-2007). The only exception is the area of Sinyavino where the average annual retreat ranged from 100 to 200 m over the same 5-year period. Another paper (3) reports on the results of a remote sensing survey on long-term dynamics of the Baltic coastal zone based on Landsat imagery from 1979 to 2010 and German topographic maps from the 1940ies. Using quantitative estimates of changes in the area and rates of shore abrasion (accumulation), this paper demonstrates the prevalence of abrasion processes over accumulative. For instance, the most significant change of the shoreline position during the study period 1939-2010 occurred on the west coast of the Sambia Peninsula. It was a retreat by 580 m in Pokrovskoe-Novoye area and by almost 300 m in Sinyavino area.

However, coastal zone dynamics studies using remote sensing do not address the issue of the accuracy of coastline measurements based on optical images to estimate measurement errors in the study period. The long-term dynamics studies also ignore local short-term shoreline dynamics, which is mainly associated with interstorm periods and does not serve as an indication of erosion or accretion processes. Therefore, the main objective of this study was to assess the accuracy of coastline extraction from optical images in studying the short period dynamics and development trends of Sambia coastal zone using high- and ultra-high resolution satellite imagery.

RFESEARCH OBJECTIVE

The Sambia Peninsula is a horst uplift of glaciotectonic origin. The absolute elevation of its highest point (m. Goltgarben) is 111 m. The steep coastal cliffs of the peninsula rising up to 40-55 m fall to 8-10 m at the bases of the Curonian and Baltic Spits. Geologically the coastal slopes consist of sedimentary strata of middle-upper Paleogene and Neogene overlain by Quaternary glacial deposits (Figure 1).

The lithological composition of the Paleogene-Neogene rocks is dominated by poorly consolidated sandy-aleuritic-clayey sediments easily eroded by sea waves, surface and groundwater, and precipitation (Figure 2). Theses Neogene-Paleogene bedrocks are subhorizontal (Figure 1), but in many areas they are subject to glacial denudation and deformations. The total apparent thickness of the bedrocks is up to 40-50 m.

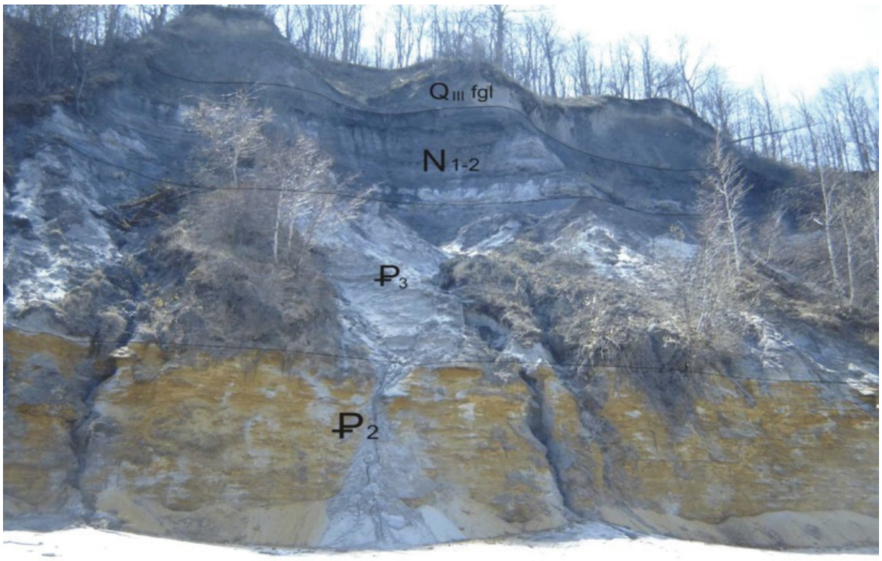

Figure 1: Composition of coastal bedrock in Primorye area.

a) *b)*

Figure 2: Slope denudation by ground and surface waters. a) v. Kulikovo area; b) v. Primorye area.

a) *b)*

Figure 3: Coastal slopes composed of glacial and fluvioglacial deposits. Area of a) v. Donskoe and b) v. Kulikovo.

The Quaternary deposits of the Sambia Peninsula are of glacial (boulder-pebble sandy loam and clay loam) and glaciofluvial (loam clays with horizons and lenses of pebbles and sand and gravel deposits) origin. The thickness of the Quaternary deposits of the coastal slopes varies from several metres to several tens of metres. The characteristic feature of the coastal Quaternary deposits is their compact structure and inclusions of boulders and pebbles. In the process of coastal erosion, argillaceous and partially sand fractions of moraines are carried to the sea, while the remaining boulders, pebbles and gravel fractions form natural stone revetment at the slope base and on the beaches protecting the coast against active abrasion (Figure 3).

Poorly consolidated sandy-aleuritic-clayey Neogene and Paleogene sediments are more susceptible to abrasion-denudation processes and are easily eroded. At the same time, the slope denudation in the bedrock areas actively replenishes beaches with sand material (Figure 4).

Figure 4: Poorly consolidated ferruginated Oligocene sand (v. Primorye area).

RESULTS OF FIELD SURVEYS

Extreme storms conditions pose a considerable danger both to geological environment and to people living and involved in economic activities in the coastal zone. One of the recent extreme storm events occurred on January 14, 2012. A survey of the storm impact on the coastal zone was conducted on the territory from v. Donskoe in the west to v. Roshchino in the east comprising a shoreline stretch of approximately 30 km, as shown in Figure 5.

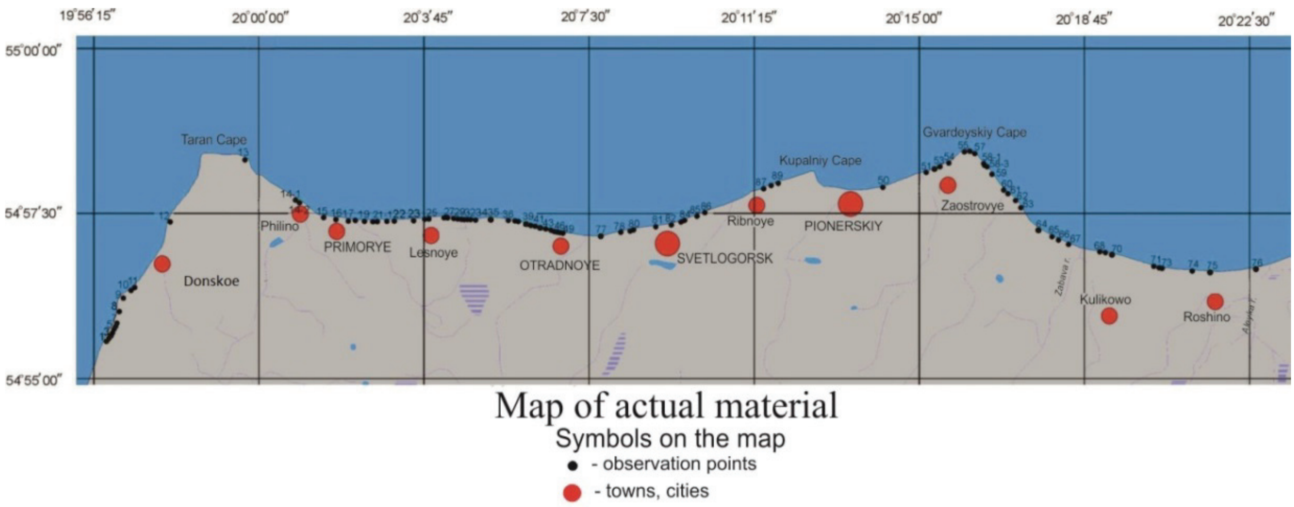

Figure 5: Index map of the northern coast of the Sambia Peninsula.

The survey revealed abrasion and denudation actively developing along the entire coast of the peninsula. The evidence of these geological processes is numerous landslides, gullies, slope failures and beach area reduction.

Repeated surveys of the coastal zone from v. Filino area to Svetlogorsk were conducted in 2017. A comparative analysis of images in Figures 6 and 7 clearly indicates the high dynamics of coastal exogenous processes associated with beach area reduction and coastal slope erosion.

a) *b)*

Figure 6: Fragments of the images of coastal zone changes in the Filinskaya Bay area in 2012 (a) and 2017 (b).

a) *b)*

Figure 7: Fragments of the images of coastal zone changes in the Svetlogorsk area in summer 2012 (a) and 2017 (b).

REMOTE SURVEY METHODS AND DATA

The short-term coastal dynamics study is based on the images from the US satellite Landsat-8 from 2010-2015 and the images from the Russian satellite Resurs-P from 2015-2017. The images used in the study were taken mostly during summer time, as that is the season of the relative shoreline configuration stability. Table 1 lists the satellite images for two dates.

Table 1: The dates of satellite images.

Study period:	Capture dates	
	1st year	2nd year
2010-2015	L5189022_02220101009	LC81890222015184LGN00
2015–2017	ResP_Geoton_PAN_10904_20150606_123557	ResP_Geoton_PAN_21819_20170519_121930

Landsat images obtained from the Global Land Cover Facility (7) are of Level 1T processing with radiometric and geometric correction using digital terrain models. The Landsat-8 OLI (Operational Land Imager) instrument collects data from 9 spectral bands, 7 of which are consistent with TM (Thematic Mapper) of Landsat-5 ensuring data continuity. TM scanner and OLI images of the earth surface have a spatial resolution of 30 m in the visible and infrared spectrum and 15 m in the panchromatic mode on Landsat 8. Landsat images are available in UTM projection (zone 34 N, WGS-84).

In 2013-2014 the Russian polar-orbiting satellites Resurs-P No. 1 (2013) and Resurs-P No. 2 (2014) were launched. Their images have 0.9 m panchromatic-spectral spatial resolutions along a 38 km wide swath. The geometrical correction of Resurs-P No.1 and Resurs-P No.2 multi-temporal images was made with ENVI 4.7 software using Ground Control Points (GCP).

Currently, complex processing and decoding of images is carried out using various software tools: Image Analyst, Er Mapper, Easi / Pace, Erdas Imagine, Envi, ArcGIS etc. For example, the ability to automatically recognize objects in pictures in the ENVI software package contains a large set of methods and algorithms (8). One of the methods for converting multi-temporal images is color synthesis (RGB-synthesis), based on combining three different-time images. A more complex variant of this method is the classification of objects from the synthesized image from multi-temporal images. Pre-shots should be radiometrically and geometrically corrected to avoid false changes caused by differences in shooting conditions, seasons of photos, etc. One example of such image processing for detecting changes in the coastal boundaries of lakes is shown in (9). Using Erdas Imagine software, different pairs of classified images were combined, which allowed to distinguish three groups of objects: the water surface, appeared and disappeared lakes.

In our work the coastal zones space-time changes were analyzed applying the Change Detection algorithm on ENVI 4.7 software. This algorithm is based on subtraction of multi-temporal images of the same or similar survey systems after geometric correction with a single spatial resolution. The Landsat imagery used for change detection were in spectral band 3 (Landsat-5) and 4 (Landsat-8) providing the strongest land-water contrast (3). The Change Detection algorithm was applied to determine alterations on the multi-temporal Resurs-P panchromatic images with 0.9 m spatial resolution. During Vectorization, the boundaries of the coastal zone were determined automatically. Data processing and analysis were performed using the ArcGIS 9.3 software. The sites erosion rate during the study period was determined using a point layer created on the nodes of linear shapefiles. The distance between the points was calculated using the Near tool in ArcGIS 9.3. The rates of erosion and accumulation areas were then calculated in a point attribute table.

During the studies, the preliminary accuracy analysis of the shoreline extraction from Resurs-P No. 2 imagery was conducted by means of comparison of the images with the field measurements of the shoreline coordinates. In June 2017, a field survey of the outer shoreline using a portable GNSS receiver (GPS and GLONASS) was conducted in the area from Filino to Lesnoy. The surveyed stretch was 2.7 km long. Figure 8 provides an example of the results obtained from the field survey (red) compared to the coastline extracted from Resurs-P No.2 images (blue). The points in Figure 8 indicate the distance between the shorelines at 100 m increments.

The median distance between Resurs-P-derived shoreline and field data was calculated at increments of 100 m. As Figure 8 shows, the amplitude of the obtained measurements in the Resource-P image relative to ground-based the shoreline measurements range from 1 to 13 m. The comparison of the control points measurements on the satellite images and in the field data showed a mean net shoreline movement (NSM) of 6.6 m for the entire area.

Thus, the shoreline variability error is an average of about 7 m, but it can be reduced due to the measurement accuracy of a GNSS receiver. The above analysis of the data shows that the accuracy of coastline extraction from optical imagery could be that of only several metres.

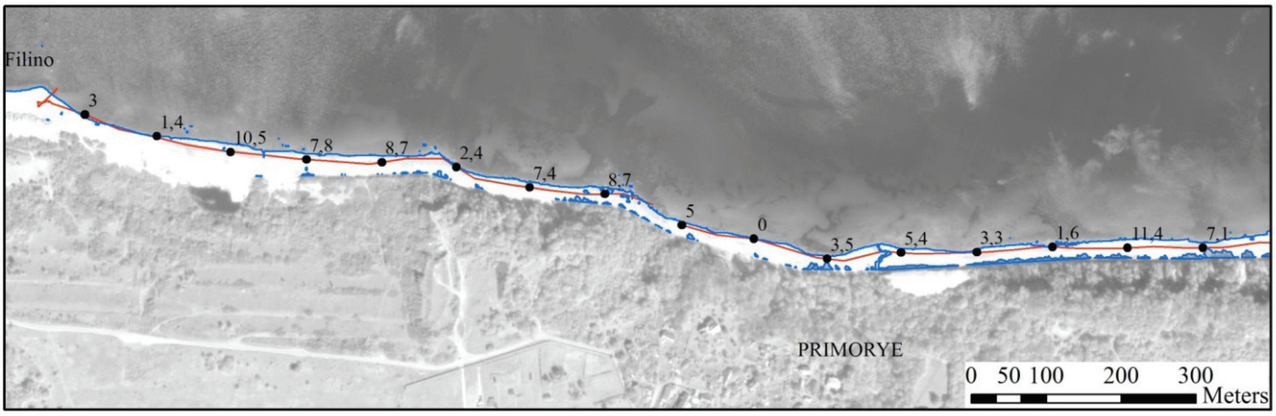

Figure 8: Fragment of the Resurs-P images (19.05.2017) with the coastlines marked. Field survey results are shown as red line, Resurs-P No.2 extraction is shown as blue line.

THE RESULTS OF REMOTE SENSING AND THEIR ANALYSIS

Figure 9 shows a fragment of a Landsat-5 image with the coastal line marked according to the data obtained on 10.07.2010 (black line) and 03.07.2015 (red line). The most obvious coastline change on Figure 9 is in the areas near Pokrovskoe-Novoye, Yantarnoye, Sinyavino, Primorye, Lesnoye and Svetlogorsk.

Figure 9: Fragment of the Landsat image obtained on 03.07.2015 with the coastal lines marked according to the images from 2010 and 2015.

The spatial-temporal changes on the multi-temporal images were analyzed on ENVI 4.7 software using Change Detection algorithm following the described procedure. Figure 10 showing the coastal area dynamics is a result of the application of Change Detection algorithm and estimation of the changes in the shore abrasion (accumulation) rate in the control points during the period 2010-2015 using multi-temporal Landsat images.

Figure 10 shows the alternation of erosion and accumulation areas on the west coast of the Sambia Peninsula. Their formation is associated with the longshore drift, internal wave dynamics and technogenic impact of the industrial areas. Thus, the largest changes in the areas of coastal erosion and accretion during the study period 2010-2015 are observed near the industrial regions of

Sinyavino and Yantarny. The retreat rates here ranged from 20 to 36 m/year, the accumulation rate in some areas was up to 48.1 m/year. The 5-year mean net retreat along the entire stretch from Cape Taran to Baltiysk was 17.7 m.

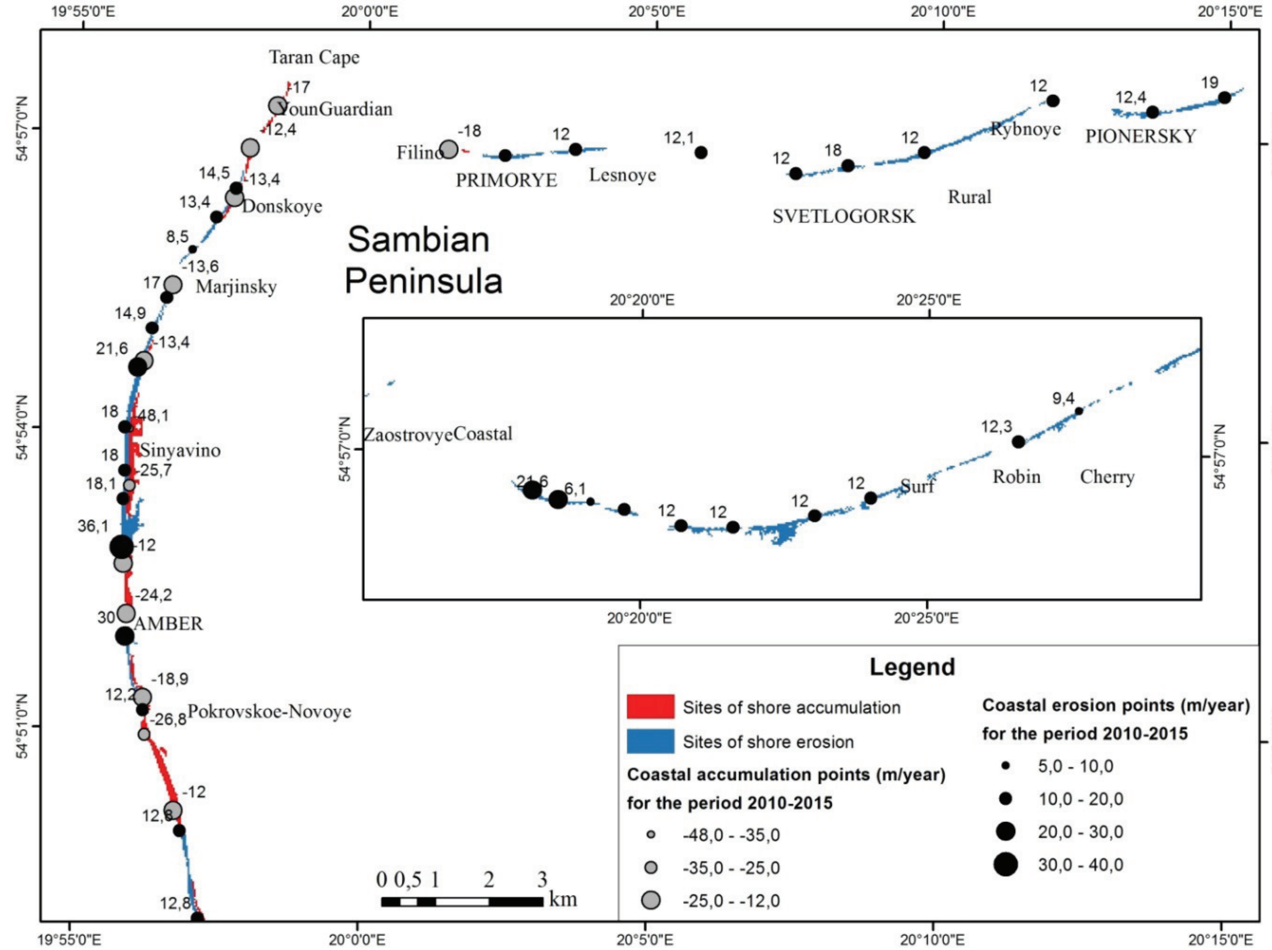

Figure 10: Coastal dynamics of the Sambia Peninsula during the period 2010-2015.

As Figure 10 shows, shore erosion is the dominating process on the northern coast of the Sambia Peninsula due to longshore sand transport from west to east resulting in general sand deficit on the coast. The only exception is the site in the Filinskaya bay area with accretion of up to 18 m/year, as beach nourishment was repeatedly applied there (1). The 5-year mean net shoreline retreatment on the stretch from the village of Filino to the town of Zelenogradsk was 15.6 m. The total area of erosion and accretion sites on of the coastal zone of the Sambia Peninsula during the period of the survey 2010-2015 is 311.2 hectares, where the total eroded area is 213.4 hectares, and total accretion is 97.2 hectares. Figure 11 is the fragments of maps showing the changes in the eroded areas of the coastal zone of the Sambia Peninsula over the period 2015-2017 on Resurs-P images.

According to the results of measuring the eroded area, the mean net retreat on the stretch from Baltiysk to Pribrezhnoye was 6.4 m over the period of 2 years, which is comparable to the measurement error associated with local changes in the shoreline position. However, Figure 11B shows a slight increase in the coastal erosion from 7 to 11 m/year to the south of the village of Pokrovskoe-Novoye. The value exceeded the possible measurement error, signifying the presence of coastal erosion areas. This trend is observed in Svetlogorsk area, with erosion of about 8 m over two years (Figure 11C), which is also confirmed by photo illustrations in Figures 7a and b for the compared years of 2012 and 2017 showing the reduction of beach areas after the severe storm in 2012. The base of the Sambia Peninsula is relatively stable, the size of the eroded area here falls within the measurement error associated with the local short-period dynamics of constructive and destructive waves. The total eroded area of the coastal zone of the Sambia Peninsula over the period 2015-2017 was 21.3 hectares.

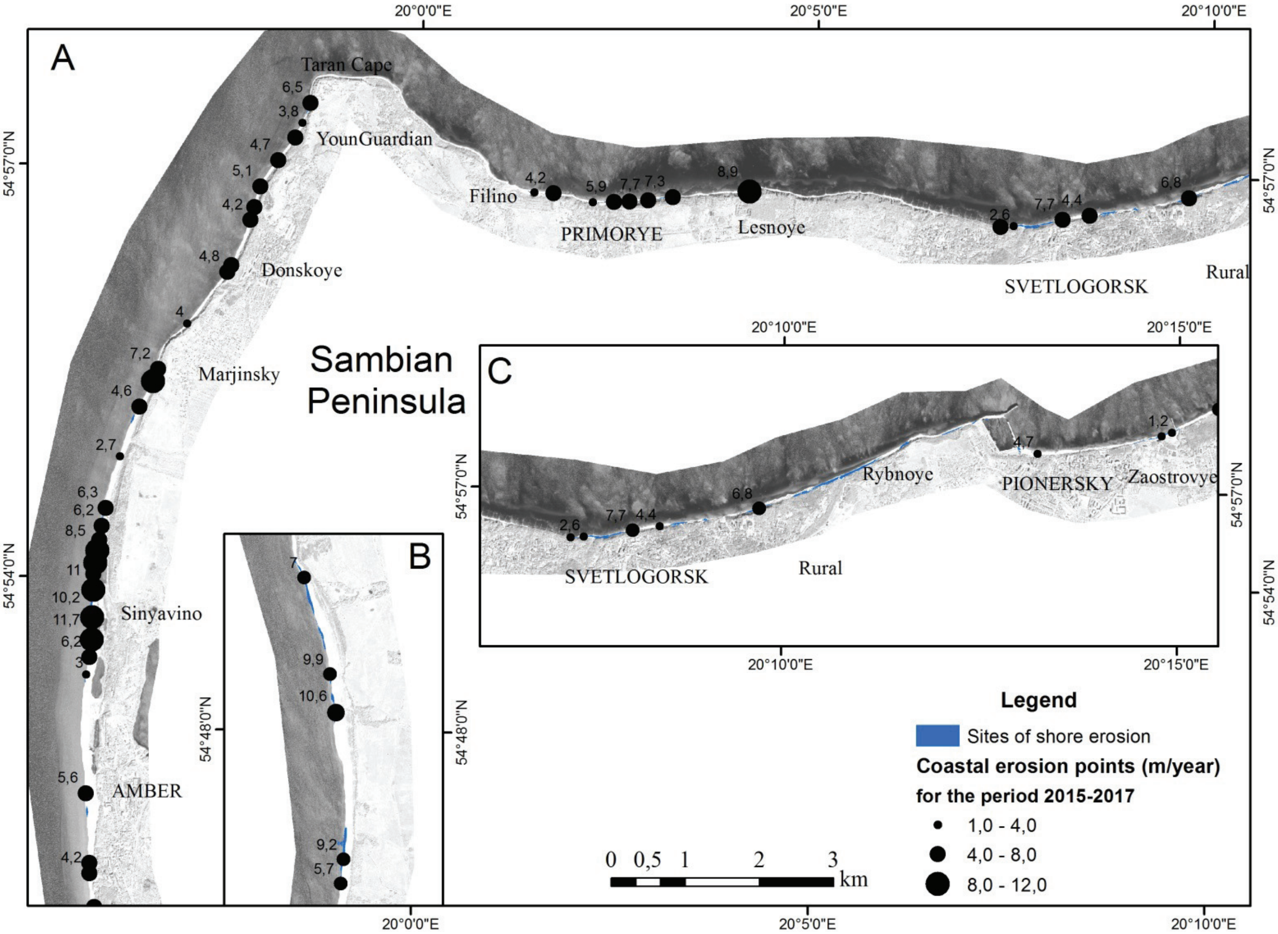

Figure 11: Fragment of a map of the coastal erosion area dynamics on the Sambia Peninsula over the study period 2015-2017.

CONCLUSIONS

The analysis of remote sensing surveys on the short-period Sambia coastal dynamics provides valuable information on a possible change in coastal dynamics rate after 2015. For instance, the coastal retreat in 2015-2017 was only iobserved in some areas of the coast of the Sambia Peninsula and, on average, it ranged from 1 to 12 m, which in most cases falls within the measurement error. In 2010-2015 erosion trend dominated on most of the peninsula, the average erosion rate exceeded 35 m/year, which is almost 2 times lower than the values for this region presented in (2) for the period 2002-2007.

The analysis of the quantitative assessment of changes in erosion and accumulation areas on the Sambia Peninsula coast during the research period has showed the prevalence of abrasive processes over accumulative, which has also been confirmed by the field observations during the coastal zone survey in 2012-2017. During the study period 2010-2015 the total eroded area was 213.4 hectares, the total accretion was 97.2 hectares. The greatest deficit of sandy sediments is noted on the west coast of the Sambia peninsula in the area from Cape Bakalinsky to Cape Taran (1). Numerous violations of the stability of slopes are recorded here: landslides, collapses of blocks, caving. The annual volume of destruction of this area is about 70 thousand m³ (10).

Other essential results of the field survey are the conclusions that the coastal configuration (including erosion dynamics) depends on the geological structure and lithological composition of the coastal slopes. Collapsing coastline capes and cliffs composed of compact glacial deposits form boulder-pebble stone debris that protect the shore from active abrasion. The coves and concave shores are normally composed of loose sandy-clayey bedrock Neogene and Paleogene deposits actively eroded by sea waves, surface and groundwater.

REFERENCES

1 Boldyrev V L, 1992. Formation, development and modern dynamics of the Kaliningrad coast of the Baltic Sea. In: Main regularities and tendencies of the Baltic Sea shoreline migration during the past 100 years, edited by C. Orwick (Publishing House of the Estonian Academy of Sciences, Tallinn) 25-33

2 Spiridonov M A, V L Boldyrev, V A Zhamoyda, D V Ryabchuk & V V Sivkov, 2010. Dangerous endogenous and exogenous geodynamics in the coastal zone of the Russian States Baltic. Exploration and Protection of Mineral Resources, 6: 53-60

3 Bryksina N A, 2014. Study of the dynamics of the Baltic Sea coastal zone using space images. Bulletin of BFU, 1: 50-59 (in Russian language)

4 Alesheikh A A, A Ghorbanali & N Nouri, 2007. Coastline change detection using remote sensing. International Journal of Environmental Science and Technology, 4(1): 61-66

5 El-Asmar H M & M E Hereher, 2011. Change detection of the coastal zone of the Nile Delta using remote sensing. Environmental Earth Sciences, 62(4): 769-777

6 Marfai M A, L King, H Almohammad, S Dey & B Susanto, 2008. Coastal dynamic and shoreline mapping: multi-sources spatial data analysis in Semarang Indonesia. Environmental Monitoring Assessment Journal, 142(1-3): 297-308

7 United States Geological Survey: Landsat Data Access (last date accessed: 22 Dec 2017)

8 ENVI Application Help (in Russian language)

9 Kravtsova V I & AG Bystrova, 2009. Study of dynamics of thermokarst lakes of Russia. Geoinformatics. 1: 44-51 (in Russian language)

10 Boldyrev V L & O I Ryabkova, 2001. Dynamics of coastal processes on the Kaliningrad coast of the Baltic Sea. Izvestia of the Russian Geographical Society, 133(5): 41-48