climate

MDPI

Article

Sea Coast of the Western Part of the Russian Arctic under Climate Change: Dynamics, Technogenic Influence and Potential Economic Damage

Stanislav Ogorodov [1], Svetlana Badina [1,2,*] and Daria Bogatova [1]

[1] Faculty of Geography, Lomonosov Moscow State University, GSP-1, Leninskie Gory, 119991 Moscow, Russia; ogorodov@geogr.msu.ru (S.O.); aleksyutina@geogr.msu.ru (D.B.)
[2] Laboratory of Regional Policy and Regional Investment Processes, Plekhanov Russian University of Economics, Stremyanny Lane 36, 117997 Moscow, Russia
* Correspondence: badina@geogr.msu.ru; Tel.: +7-977-257-12-93

Abstract: The Arctic coast dynamics has been an urgent problem over the last years, from both a practical and a fundamental point of view. In this research, for the first time for the Russian Arctic coast, we assessed the damage from the loss of territories in the western part of the Russian Arctic, where the active production and transportation of hydrocarbon material are carried out. Most of the studied coastline is composed of frozen unlithified soils with inclusions of underground ice. In this regard, the coastal zone is highly sensitive to climate change and its economic consequences. According to our investigation and literature data, the erosion rates could rich up to 2–3 m/year in some part of the coastline. Having estimated the cadastral cost of land and the area of the possible loss of territory, as well as the cost of transport infrastructure in the risk zone, we tried to predict the damage from changes in the total structure of the area under consideration. In particular, the economic damages from coastal permafrost processes were estimated. The assessment was conducted for the middle of the 21st century, taking into account the current climatic trend, erosion rate and probable maximum warming in this region.

Keywords: coastal dynamics; climate change; potential economic damage; Russian Arctic

Citation: Ogorodov, S.; Badina, S.; Bogatova, D. Sea Coast of the Western Part of the Russian Arctic under Climate Change: Dynamics, Technogenic Influence and Potential Economic Damage. *Climate* **2023**, *11*, 143. https://doi.org/10.3390/cli11070143

Academic Editor: Alessandro Pezzoli

Received: 1 June 2023
Revised: 4 July 2023
Accepted: 5 July 2023
Published: 10 July 2023

1. Introduction

The problem of global climate change, including those changes caused by human activity, is a rather relevant topic of research. This topic was the subject of numerous studies [1–4]. Many environmental, climatic, geologic, biologic and anthropogenic factors influence the coastal erosion rates (soils erodibility, fractures, adjacent bathymetry, cliff lithology, waves, wind, vegetation, etc.). In the Arctic region, additional factors relate directly to the presence of permafrost. The coasts composed of unlithified permafrost deposits, whose state and stability depend on the temperature regime [5], are very sensitive to the climatic change. Accordingly, this has implications for coastal infrastructure and land use. The combination of hydrometeorological factors determines the conditions for soil thawing and the discarding of thawed material in the sea [6]. The hydrometeorological factors of the Arctic coastal retreat include first of all the thermal regime of the territory (air temperature, sea water temperature, surface temperature), which determines the thermodenudation intensity, and the energy (wind–wave) regime that determines the thermal abrasion intensity and the removal of thawed material from the beach. The wind–wave regime depends on the frequency and intensity of storms directing to the coast from the seaside and on the duration of the ice-free period [6]. For different key coast sites of the Kara Sea, the long-term (30–50 years) average annual retreat rates range from 0.3 to 1.7 m/year [7–9]. The morphological features of the territory and the permafrost characteristics of the coast influence the coastal retreat rate only on the local scale for short time periods of observation [10,11]. Currently, there are many models [12,13] trying to predict the arctic coastal dynamics. Due to the climate change, there is a tendency of increased coastal erosion rates [6], which can lead to economic damage in the Arctic regions.

The issue of assessing and forecasting the economic consequences of natural disasters, including those that are climate change-related, is very relevant today. Many industrial and regional studies have been devoted to this topic. Works related to the assessment of the economic risks from coastal abrasion occupy a special position.

For instance, in their research [14,15], authors estimated the economic efficiency of coastal protection measures for residential real estate and predicted the damages associated with the loss of infrastructure and undeveloped land from coastal erosion (in the case of the UK). The loss of gross value added (GVA) from the loss of economic objects due to coastal erosion, as well as the adaptive capacity to coastal erosion for various types of economic activities, were estimated in another work [16]. A study [17] analyzed the economic benefits of a Korea's coastal erosion control project (in monetary terms). A research article [18] proposed an empirical benefit estimation for coastal property owners and beach visitors in the USA (including economic value estimates for the loss of beach sites and economic value estimates for changes in site characteristics, as well as the economic costs of erosion management).

There are much fewer works devoted to the study of the Russian Arctic coasts in this context. We highlight a study [19] that reviewed the anthropogenic changes in the coastal zone of the Russian Arctic seas from the 17th century to the present day. Estimates of economic damage from hazardous coastal processes based on information on the cadastral value of coastal areas were presented in [20]. However, the authors explored the coast of the Sea of Azov, which was developed intensively and evenly and where the land market is well developed; so, the problem of lack of information is not so acute. Indeed, the Russian Arctic within the framework of this problem has a number of specific features.

As known, the circumpolar regions of the Earth are the most susceptible to climate change [21]; therefore, the transformations associated with them, including those related to coastal processes, are also most active there. At the same time, plans for the active economic development of these territories suggest an increase in the anthropogenic impact and feedback and, thus, an increase in the level of vulnerability of this territory to natural and man-caused hazards [22]. Summarizing all of the above, it should be noted that in addition to the results of previous studies, it is important to address the issue of the physical disappearance of a significant part of the land, which occurs in the Russian Arctic due to coastal thermal abrasion and shows an increasing trend, taking into account the future climate warming.

Despite the fact that on a national scale, the losses of this relatively underdeveloped territory are insignificant, over a long period they may become very significant for individual Arctic regions, especially municipalities. In addition, due to the fact that the highest density of economic development in the Russian Arctic is characteristic of coastal areas (primarily due to the lack of alternatives to sea transport for their general supply and reliance on marine logistics for most new resource development projects [23]), coastal stability is of particular importance.

The purpose of this study was to assess the probable economic damage from thermal abrasion of the coastline of the Kara and Pechora Seas until 2050. Damage refers to the direct future loss of land value, as well as to that to the infrastructure facilities located within their boundaries. This paper proposes an estimate of the minimum amount of probable damage derived from two causes. First, the loss of infrastructure can have economic consequences away from the coast, such as when a gas pipeline fails. Accordingly, the multiplier effects would be quite significant. Secondly, due to the lack of open information about the market value of land plots in poorly developed Arctic territories, only the cadastral value can serve as an accessible criterion for their value, which in itself is usually greatly underestimated in Russia for various reasons.

It is important to state in advance the limitations of this study. Since it is a pioneer study for the Russian Arctic, it cannot claim to fully account for all possible economic consequences of the processes under consideration. For instance, the study took into account only the existing infrastructure without considering promising investment projects, since the economic instability in modern Russia does not allow making such long-term forecasts.

2. Study Area

Our research was carried out on the Western Russian Arctic coasts from Cape Sengeisky in Pechora Sea to Cape Skuratov in Kara Sea (Figure 1). A specific feature of the western sector of the Russian Arctic is the presence of numerous regional forms and complexes of glacial and fluvio–glacial sediments left from several glaciations [24]. The rock outcrops at the coastal cliffs, occupying about 20% of the coastline, and the accumulative and thermoabrasion shores covering approximately 80% [25,26] are typical for the western sector. The study area is composed mainly of unlithified rocks, except for the north of the Yugra Peninsula (150 north from Amderma town).

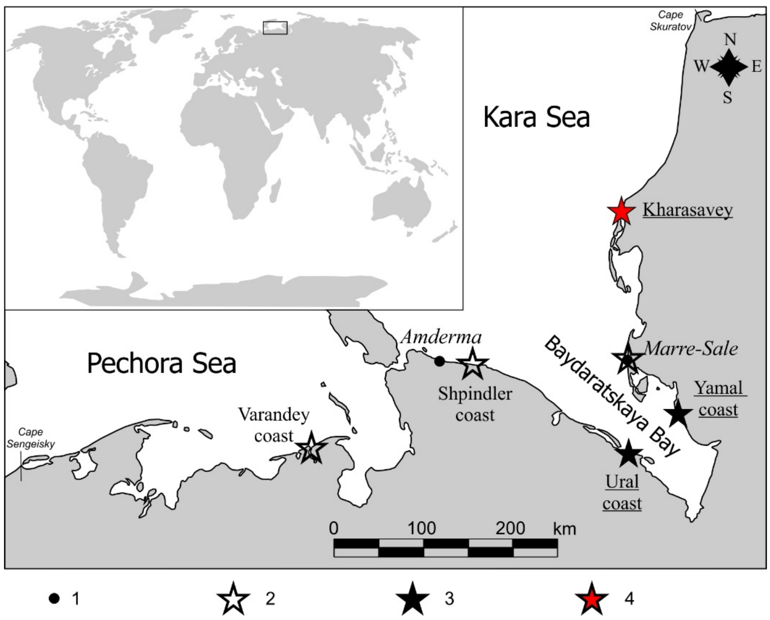
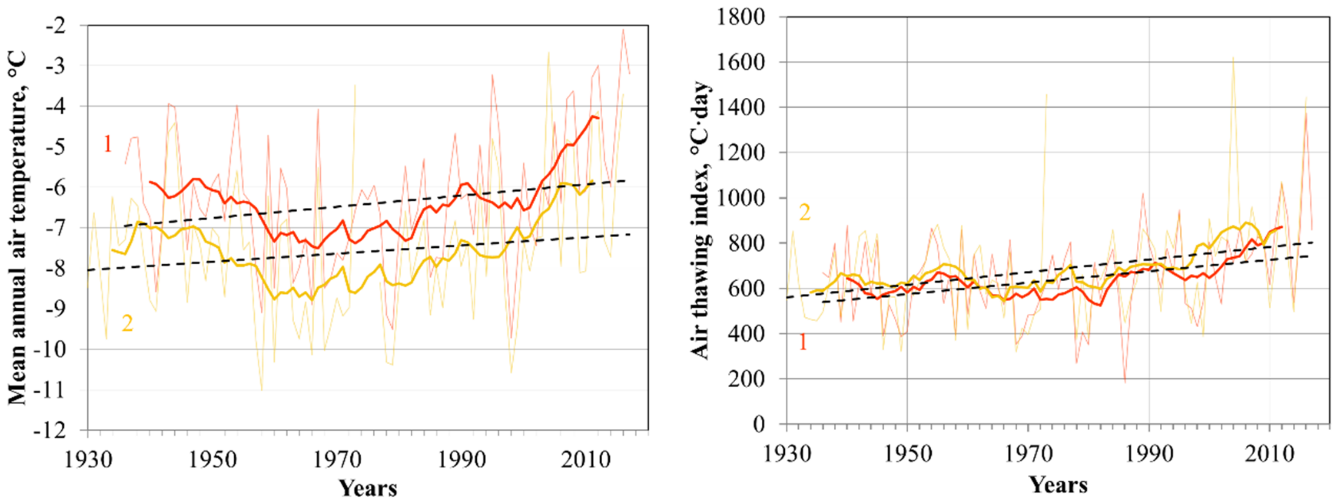


Figure 1. Study area: 1—weather station, 2—key sites (based on published data), 3—key sites (based on our investigation and historical data), 4—detailed key area.

The Pechora Sea coast is located in the zone of sporadic permafrost. The Kara Sea coast is characterized by continuous permafrost [27]. According to publish data, region coastal dynamics was monitored at the six key sites (stars on Figure 1) [28,29]. The Ural and Yamal coasts and the coasts near the Kharasavey gas condensate field have been research plots of the Faculty of Geography of the Lomonosov Moscow State University since the 1980s [30]. The coastal slope is composed of frozen unlithified rocks, and the cliff height is mainly from 1–2 to 25–30 m [31–33]. The lithological composition of the cliff sediments varies from loamy clays to gravel sands. Saline soils are widely present in the geological sections of the western part of the Russian Arctic. Since the cliffs are composed of saline soils with different grain size distribution, the freezing temperature of the sediments is much lower than 0 °C, and in the permafrost section, cooled unfrozen in interchange with frozen ones [5,34]. The beaches (accumulative forms) are widespread at the numerous thermal abrasive coastal areas [28]. Tabular ice is widely developed and forms one or two layers in some sections [8,26]. The ice beds, typically, are up to few meters in thickness and spread laterally up to few tens of meters. The composition of tabular ice includes mainly clean ice. Ice wedges are widespread on low absolute levels, especially up to 15 m and on laidas [8]. The ice wedges are usually epigenetic, up to 2 m in width and several meters in depth.

In this region, the coastal erosion rates are 0.3 to 4.5 m/year [8,9,29,35,36]. At some points where massive ice beds open up on high cliffs and on low cliffs after great storm events, the erosion rates may rich 7–14 m/year [32,37–39]. There are two meteorological stations located in the study area (bold points on Figure 1).

The air temperature data were averaged monthly for the observation period of 1973–2017 [40]. The mean annual air temperature at the Amderma weather station was higher than that at Marre-Sale, but the value of the air thawing index (the sum of the positive air temperatures in one warm period of the year) was a bit lower (Figure 2). In Amderma, the average long-term value of the air thawing index was 650 °C·day/year, from the beginning of the 1980s and increased to 900 °C·day/year. According to the Marre-Sale weather station, the average long-term value was 680 °C·day/year and has increased from 600 to 820 °C·day/year since the early 1980s.



(**a**) (**b**)

Figure 2. Mean annual air temperature (**a**) and air thawing index (**b**) at two meteorological stations: 1—Amderma; 2—Marre-Sale [30].

In economic terms, this territory belongs to the regions that are some of the key centers for the production of Russia's main export raw material—hydrocarbons. The Yamalo-Nenets and Nenets Autonomous Okrugs account for about 48% and 7% of the total indusotrial production in the Arctic zone of the Russian Federation, respectively. The Yamal-Nenets Autonomous Okrug produced 617.5 billion cubic meters of gas and 36.1 million tons of oil in 2021, and the Nenets Autonomous Okrug produced about 11.5 million tons of oil in 2021 (including at the Prirazlomnoye field, the only one currently on the Arctic shelf of Russia, where oil has been produced since 2013).

3. Materials and Methods

3.1. Estimation of the Coastal Dynamics

Monitoring of the coast dynamics was carried out with the help of field work (geodetic survey) and remote sensing methods. The database for Russian Arctic coast and their dynamics was used to estimate the coastal erosion rates for the study area [35]. This database was supplemented by published data [6–9,36,37] which were collected, sorted and classified. In addition, we analyzed data on lithology composition, permafrost structure [41], ice content [32], and morphological features including the presence of beaches [29,33]. For the study area, the coastal dynamics was investigated in six key sites (segments). These areas are shown in Figure 1 (objects 2 and 3). For each key area, the retreat rates were estimated based on the literature data and our data obtained during the research. The distribution of the current coastal erosion was determined through the construction of occurrence histograms of one or another value. In addition, the average, median, maximum and minimum values of coastal erosion were estimated for each key site. We found no data for the retreat rates of the coasts and estimated them based on coasts' morphology, lithological composition, and permafrost features by analogy with similar areas for which data from observations were available. This approach made it possible to divide the coasts into different types (accumulative, abrasion, rocky stable), and data on the retreat rates in key areas were used to fill in the missing data on the coast dynamics of unexplored areas to cover the entire study coastline. In addition, sections of the unexplored coast were characterized taking into account various summarized published data about the Russian Arctic coasts [42–44].

3.2. Coastal Dynamics Prediction

For selected key sites of the Kara Sea, the reaction of the coastal retreat rate to environmental forcing changes was assessed in two respects: current trends in climate change [4,35] and maximum possible warming CMIP6 data models with the climate change scenario SSP5-8.5 [45,46]. It is the extreme scenario of climate change that is always considered in the design of infrastructure facilities on the Arctic coast of Russia. Calculations of the hydrometeorological factor were carried out, including wind–wave energy and thermal impact. The calculation of the interannual variability of hydrometeorological factors, including the assessment of wind–wave and thermal energy, was carried out according to the method of Popov–Sovershaev based on data from weather stations, as well as according to CFSR reanalysis [3]. To estimate the duration of the ice-free period (necessary for calculating the wind–wave energy), modern arrays of satellite data on ice concentration (OSI SAF and NSIDC) were used [47]. The normalized values of wind–wave energy and the normalized values of the thermal factor were calculated [3,4] for all key sites of the chosen territory. The thermal and wave energy factors of coast dynamics act simultaneously. With their equal contribution to the retreat of the coast, they can both strengthen and weaken each other's action. For different observation periods in each of the five key sites of the Kara Sea coast, the correlations of the normalized values of the coastal retreat rates from wind–wave energy and from the thermal factor, as well as the total effect of these factors considering their equal contribution, were calculated [48,49].

To quantify the contribution of the thermal and wind–wave components to the coast dynamics, an additional parameter Σ was introduced, taking into account the weight of each of these two factors, so that the sum of their weights was always 100% [48,50].

$$\Sigma = E_{we} \times WE + E_t \times T \tag{1}$$

where WE is the normalized value of wind–wave energy, T is the normalized value of accumulated temperatures, E_{we}, E_t indicate the contribution of each factor (i.e., $E_{we} + E_t = 1$).

For five key sites of the Kara Sea, the correlation coefficient between the total parameter Σ and the coastal erosion rate was calculated depending on the values of E_{we} and E_t, with a step of 0.01 (1%). These weights were selected in such a way that the correlation coefficient was maximum, that is, the value of E_{we} or E_t corresponding to the maximum of this correlation function determined the ratio of the thermal and energy factors of the coast dynamics in the selected key site. Having determined the relationship between the coast retreat rate and variations in the determining hydrometeorological factors (accumulated positive air temperatures T and wind–wave energy WE), it was possible to quantify the response of the retreat rate to climate change, manifested through changes in air temperature and wind–wave energy. The correlation coefficient connects the increment of the total thermo-energy effect caused by the change in temperature or wave energy with the increment of the retreat rate. In turn, the increment of the total thermal energy effect normalized to the standard deviation is determined by the normalized increment of the changed factor, taken with its weight. Thus, the normalized increment of the coast retreat rate was represented as a weighted product of the correlation coefficient and the normalized increment of the determining factor. If we assume that the increment of the determining factor occurs by a value equal to its standard deviation, then the increment of the coast retreat is determined by the weighted coefficient of its correlation with the specified factor and the variance of the retreat rate. A quantitative assessment of the thermal and wave components that contribute to the permafrost coastal dynamics of the Kara Sea was performed. A retrospective analysis was carried out based on the obtained results, which allowed predicting the reaction of the coastal retreat rates to climate changes [51]. For simplicity and clarity, 2 types of climate scenarios were considered: the current trends in climate change [3,4,35] and maximum possible warming CMIP6 data models with the climate change scenario SSP5-8.5 [45,46].

3.3. The Technogenic Impacts at the Kharasavey Coast

A survey of technogenic disturbances of the natural environment was carried out during fieldwork (route and aerial) on the Kara Sea coast from Cape Kharasavey to Cape Burunny. The aerial surveys were made using a quadcopter Phantom 4pro (developed by Chinese technology company DJI, Shenzhen, Guangdong, China), which was subsequently deciphered during office processing. Violations were photographed and documented during the route survey. The technogenic disturbances of the surface were also recorded using a Garmin GPSmap 64st (developed by American multinational technology company Garmin Ltd., Schaffhausen, Switzerland). The interpretation of aerial photographs from quadcopter was supplemented by mapping using modern high-resolution satellite images from Google Earth (developed by American multinational technology company Google LLC, Mountain View, CA, USA).

3.4. Assessment of the Damaged Cost

To assess the direct economic damage, data from the Public Cadastral Map of the Federal Service for State Registration of Cadastre and Cartography of Russia (Rosreestr) [52] were used. The public cadastral map is an online service that reproduces in graphical and textual forms the information contained in the state real estate cadaster. It provides information on cadastral numbers, cadastral value of land plots and real estate, their area, land category, types of permitted use and other important parameters.

Methodological guidelines on the state cadastral valuation (Order of Rosreestr dated 04.08.2021 N P/0336 “On approval of the Guidelines on the state cadastral valuation” https://www.consultant.ru/document/cons_doc_LAW_403900/ (accessed on 1 May 2023)) regulate the pricing factors that affect the cadastral value of land. For the assessment, a regression model was used that displays the relationship between the dependent variable (cadastral value) and the values of the independent variables (pricing factors). Significant limitations on the use of the cadastral value in forecasting the economic damage from natural hazards were described in detail in previous authors’ works [22]. According to the Russian law (Federal Law No. 237-FZ of 3 July 2016 “On State Cadastral Valuation” http://www.consultant.ru/document/cons_doc_LAW_200504/390404c1ffde9e26bf2d7a526f557434a85e04ca/ (accessed on 1 May 2023)), the powers to determine the cadastral value of objects belong to the regions. In this regard, it is not advisable to make quantitative estimates using the method of the ratio of the cadastral and market values for different regions and municipalities, taking into account the existing inter-regional differences in the approach to assessing the cadastral value of buildings and structures. Another important limitation is that the cadastral values are calculated once every few years, which makes it difficult to link them to the current price levels for different territories.

It was found that, on average, for the Russian Arctic, the market values of buildings and structures exceeded their cadastral values by 1.9 times, which is generally consistent with the results of other similar studies for Russia (for example, [53,54]). Therefore, the damage values obtained in this work can be at least doubled. At the same time, in the case of land plots, the situation in the Arctic territories under consideration is even more complicated, since the land market is practically not developed there; so, it is impossible to make direct analogies. However, due to the lack of alternative sources, the authors used, in this study, the only available information, i.e., data on the cadastral value.

The first step involved analyzing maps for coastal dynamics with different typical retreat rates. According to these data, each segment of the study area was described (see Section 3.1). The length of each segment was determined by the ArcGIS software package (ArcMap 10.4.1). Since the purpose of the article was to assess the damage from coastal dynamics due to climate change, the area of the lost territory was estimated for two types of climate scenarios (see Section 3.2). For simplicity, the area of the lost territory was calculated by multiplying the segment length by the speed and by the number of years. During the maximum possible warming [46], the trend of an increase in the air-thawing index and, as a result, the coastal erosion increase, were considered linear.

In the next stage, using the ESRI ArcGIS tools, the layer with the boundaries of land plots from the Public Cadastral Map was digitized and superimposed on the main GIS. Data on the size and cadastral value, land category and type of permitted use of each of the considered plots were taken manually from the online map and entered into the GIS. The average cost of one square meter was calculated. It is important to note that surveying for a significant part of the plots on the territory under consideration was not carried out. Therefore, in this case, the average values for the district were taken, considering the differentiation of the costs for various types of economic objects and inter-settlement territories. These data were integrated with indicators characterizing the dynamics of the coastline, and a database was created (a fragment of the database is presented in Table 1).

Table 1. Database of indicators characterizing the coastline of the Pechora and Kara Seas.

No.	Midpoint Coordinates of the Plot	Average Coast Retreat Rate within the Boundaries of the Plot, m/year	Section Length, m	Cadastral Value of 1 sq. m within the Boundaries of the Plot	Land Category	Permitted Use	Presence of Man-Made Objects
1	68.7692; 57.7296	1.8	29,000	103.6	Agricultural land	Subsoil use	-
2	68.8362; 58.1405	3.2	8000	25,600	Lands of industry, energy, transport, communications, radio broadcasting, television, informatics, land for space activities, defense, security and other special-purpose lands	Subsoil use; placement of capital construction facilities; for storage of materials; under the Varandey airfield site, etc.	+
3	68.8530; 66.8986	0.9	1800	1.8	Lands of industry, energy, transport, communications, radio broadcasting, television, informatics, land for space activities, defense, security and other special-purpose lands	Pipeline transport	+
4	69.3438; 64.7869	0.35	35,067	0.002	Agricultural land	For reindeer breeding	-

Source: compiled by the authors.

Furthermore, an approach was developed for the regulatory assessment of the probable direct damage to transport infrastructure facilities (roads and pipelines) that falls into the zone of influence of hazardous coastal processes. This approach consists in assessing the replacement cost, that is, the cost of building a new similar facility, instead of one deformed and subsequently decommissioned due to the impact of hazardous coastal processes.

To determine the cost of replacement construction, the current federal unit prices for construction work (FUP) (Source: https://minstroyrf.gov.ru/trades/view.fer-2020.php (accessed on 1 May 2023)) established by the Ministry of Construction of Russia were used: FUP 81-02-25-2001 “Main and field pipelines” and FUP 81-02-27-2001 “Motor roads”. These resources provide detailed information on the cost in each stage of the construction work for objects with given characteristics. However, the normative indicators for the construction of large gas pipelines are significantly underestimated in relation to the actual costs; so, they need to be adjusted based on empirical data (data on the cost of implementing specific investment projects in that area).

The average cost of building a 1 km of main onshore gas pipeline with the same technical characteristics in Russia differs significantly depending on the natural and climatic conditions in which they are located. It should be noted that the financial indicators of Gasporom's projects are not always disclosed with sufficient detail. According to some expert estimates, the cost of the construction of 1 km of the Kharasavey-Bovanenkovo gas pipeline was about 4 million USD (Source: https://www.rbc.ru/newspaper/2019/05/30/5ce51aea9a79470cab282344 (accessed on 1 May 2023)) (at the weighted average rate for the 1st quarter of 2023). However, this figure can be considered somewhat underestimated, since for the Bovanenkovo—Ukhta gas pipeline (main pipe diameter—1420 mm, operating pressure—11.8 MPa), into which this branch should be integrated, the figure was 18 million USD (in 2008 prices, at the start of the construction). Nevertheless, this figure is given taking into account the cost of the associated infrastructure—nine compressor stations. In general, in Arctic conditions in other countries, such projects have comparable investment costs. For instance, the cost of building 1 km of the Alaska LNG Project (gas pipeline) was about 12.4 million dollars per 1 km (including compressor stations) [55].

To estimate the costs for the replacement construction of the 1655 m motorway in Kharasavey, which may be affected by natural hazards, the available data on the estimated cost of its construction, posted on Rostender ("RosTender" is an open information resource containing documentation on purchases and tenders carried out on the territory of the Russian Federation), were used. They were compared with the federal unit prices for construction, the average cost of consumables, and the estimated cost of transporting materials. An analysis of the documentation showed that the cost of building 1 km of this road would be about 2 million USD. Based on an analysis of similar projects related to the repair and reconstruction of roads in the Yamalo-Nenets Autonomous Okrug, it was found that the average cost of a major overhaul of 1 km of roads was about 0.66 million US dollars (in 2022 prices).

The above land and infrastructure cost estimates were then integrated into the coastline retreat forecast. Thus, by multiplying the area of land potentially lost until 2050 by the value of this land and the infrastructure located on it, the amount of probable damage was obtained.

4. Results and Discussion

4.1. Coastal Erosion on Key Sites

The coastal retreat in key areas varies widely (Figure 3). A historical study in the Varandey key area [36,56,57] showed an average coastal erosion of 2.2 m/year, but the median values are slightly lower. Due to the fact that part of the coast is located on a low surface, one strong storm led to a retreat rate of 19.6 m/year [58]. The Spindler coast retreats [29,32] slightly more slowly, with an average erosion rate of 1.9 m/year, which is comparable to the rate of retreat of the Ural coast of Baidaratskaya Bay. The maximum retreat rates on the Spindler coast are associated with massive ice [29]. The Yamal coast of the Baidaratskaya Bay of the Kara Sea is the most stable, with average retreat rates of 1.1 m/year. The maximum retreat rates are associated with low surfaces affected by wave action, as on the Ural coast. The coastal retreat rates near the Marre-Sale weather station [9,37,59,60] are slightly higher than those for other key sites and average 1.8–2.6 m/year. The Kharasavey cliff retreats at a rate of 1–1.3 m/year.

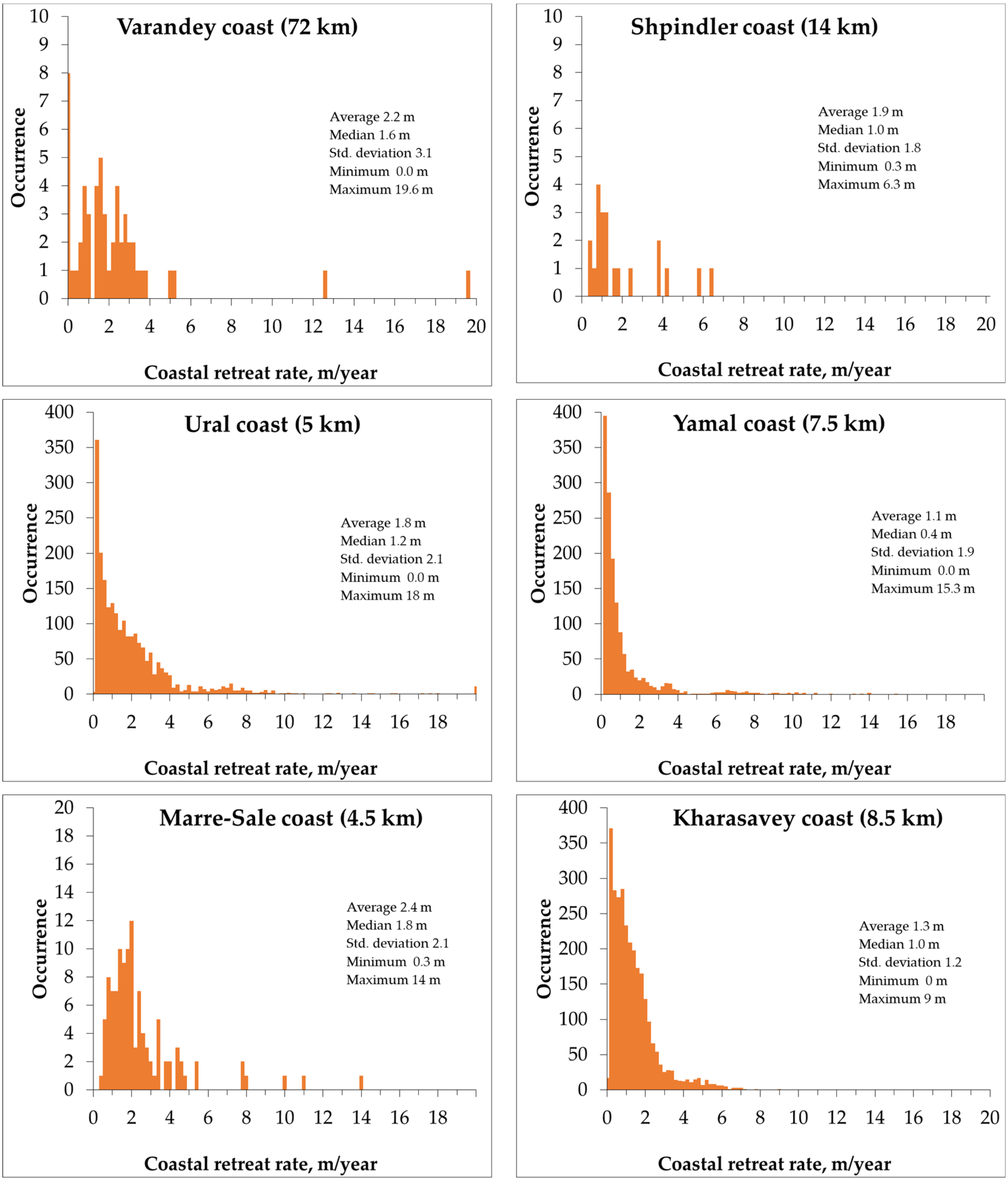


Figure 3. The distribution of the coastal retreat rates for chosen key sites: Varandey; Shpindler; Ural; Yamal; Marre-Sale; Kharasavey.

Correlations (Table 2) of the normalized values of the coastal erosion from wind–wave energy and the thermal factor, as well as the total effect of these factors considering their equal contribution, were calculated for different observation periods for each key site [48,51].

The correlation between the coast retreat rate and the sum of positive air temperatures prevailed over the correlation between the coast retreat rate and the wind–wave energy, except for Varandey and the Yamal coast.

Table 2. Coefficients of the correlation between retreat rate and climate factors.

Study Are	Coefficient of Correlation between Retreat Rate and Various Factors		
	Thermal	Wind-Wave	Total Effect
Varandey [1]	N/D	0.8	0.6
Shpindler [2]	0.941	−0.346	0.866
Ural coast [2]	0.870	0.644	0.890
Yamal coast [2]	0.419	0.448	0.440
Marre-Sale [2]	0.751	0.217	0.603
Kharasavey [2]	0.983	0.973	0.980

[1] Data [48], [2] Data [51].

Based on the obtained correlation coefficients and the factor weight (Table 3) of the thermal effect and wind-wave energy in the case of an increase sum of positive air temperatures of 187.5 °C·day/year, the retreat rate of the Spindler coast would change by 0.9–1.3 m/year. In the case of a thawing index increase of 176.9 °C·day/year, the coastal erosion rate on the Ural coast will change from 0.7 to 1.3 m/year. The erosion rate of the Marre-Sale coast will increase from 1.1 to 1.4 m/year when the sum of positive air temperatures rises by 151.5 °C·day/year. The coastal dynamic at the Kharasavey site will change by 1.3–1.5 m/year with an increase in the thermal factor of 141 °C·day/year. With an increase in wind–wave energy by 358.7 thousand tons, the erosion rates on the Yamal coast will vary from 0.6 to 2.3 m/year [51].

Table 3. Climate factors weight.

Study Area	Factor Weight, %	
	Thermal	Wind-Wave
Varandey	N/D	N/D
Shpindler [1]	64	36
Ural coast [1]	56	44
Yamal coast [1]	21	79
Marre-Sale [1]	82	18
Kharasavey [1]	77	23

[1] Data [51].

4.2. Prediction of Coastal Erosion under Climate Changes

The average trend for the increasing thawing index is of 9.55 °C·day/year based on data on climate change from 1979 to 2017 for the study area [4]. If this trend continues, by 2050 the sum of degree days will increase by 257.9 °C·day/year. Under the warmest possible climate scenario, the increased sum of positive air temperatures by 2050 will be 335.3 °C·day/year according to [46]. This prediction was made for both scenarios of climate change based on data [4,46] and the obtained correlations for key sites. The coastal retreat rates will increase 1.5–3 times as the climate changes from the current trends to more intense warming. The obtained results were extended to the entire study region (Figure 4). It was noted that the retreat of the coast in key areas near any infrastructure was greater than in undeveloped areas. This may be due both to the economic activity itself and to natural reasons due to the fact that natural territories can be more difficult to study because of their inaccessibility. After all, fieldwork was carried out in key sites, and more detailed data were obtained than by studying processes using remote data.

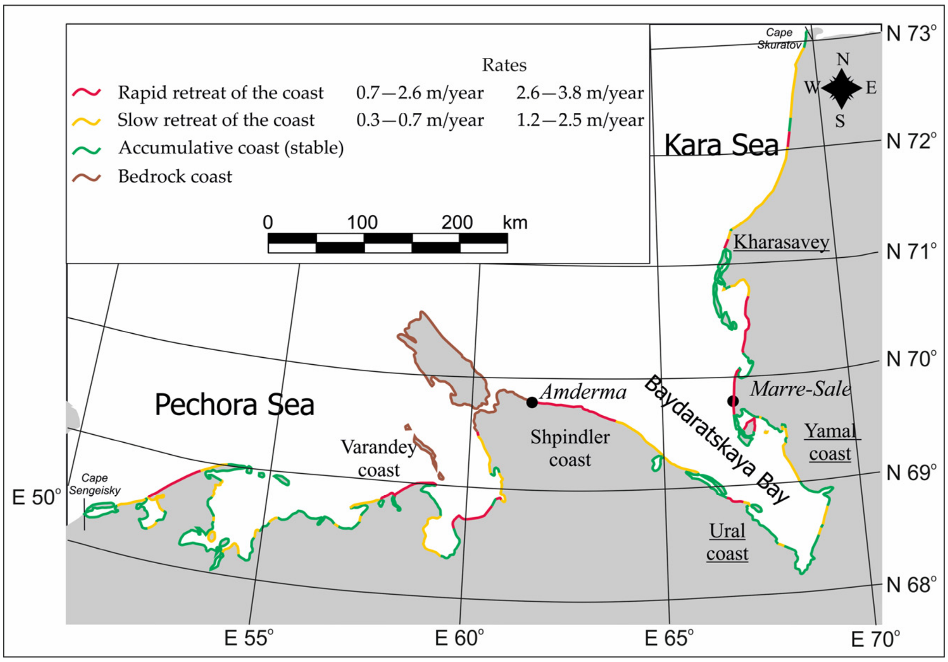


Figure 4. Predictive coastal erosion rates in the study area.

4.3. Technogenic Disturbances in the Kharasavey Coast

The key site is located between Cape Kharasavey and Cape Burunny. The territory of the village is located on a stable coast; to the north of the village, the coast is accumulative, and to the south, it is characterized by thermal abrasion. The average coastal retreat rate during 1978–2001 was 1.4 m/year, with a maximum of 3 m/year [61,62]. From 1964 to 2016, coastal erosion was 1.1 m/year, and the maximum value was recorded in 1977–1988 and reached 6.5 m/year [63].

Although the village is located on a stable part of the coast, human activity still has an impact. The communications leak together with climate change contributes to the development of ravines. The lack of building materials and the remote location of the village make coastal protection very expensive. Therefore, construction waste is widely used to stop erosion (Figure 5).

Figure 5. Construction waste used to stop gully development. Photos by D. Bogatova.

Significant violations of natural reliefs and landscapes, soil and vegetation cover were detected in the key site area. Laying a sand base over natural landscapes is the most common practice. In recent decades, the territory was actively developed, and a port was built south of this area. A road consisting of concrete blocks was laid from the village to the port. The construction of the road was disrupted by the meltwater flow, as a result of which thermokarst actively developed along the road in several sections (the total length of disturbed road was 1 km). A scheme of the technogenic disturbances at the Kharasavey field is shown in Figure 6.

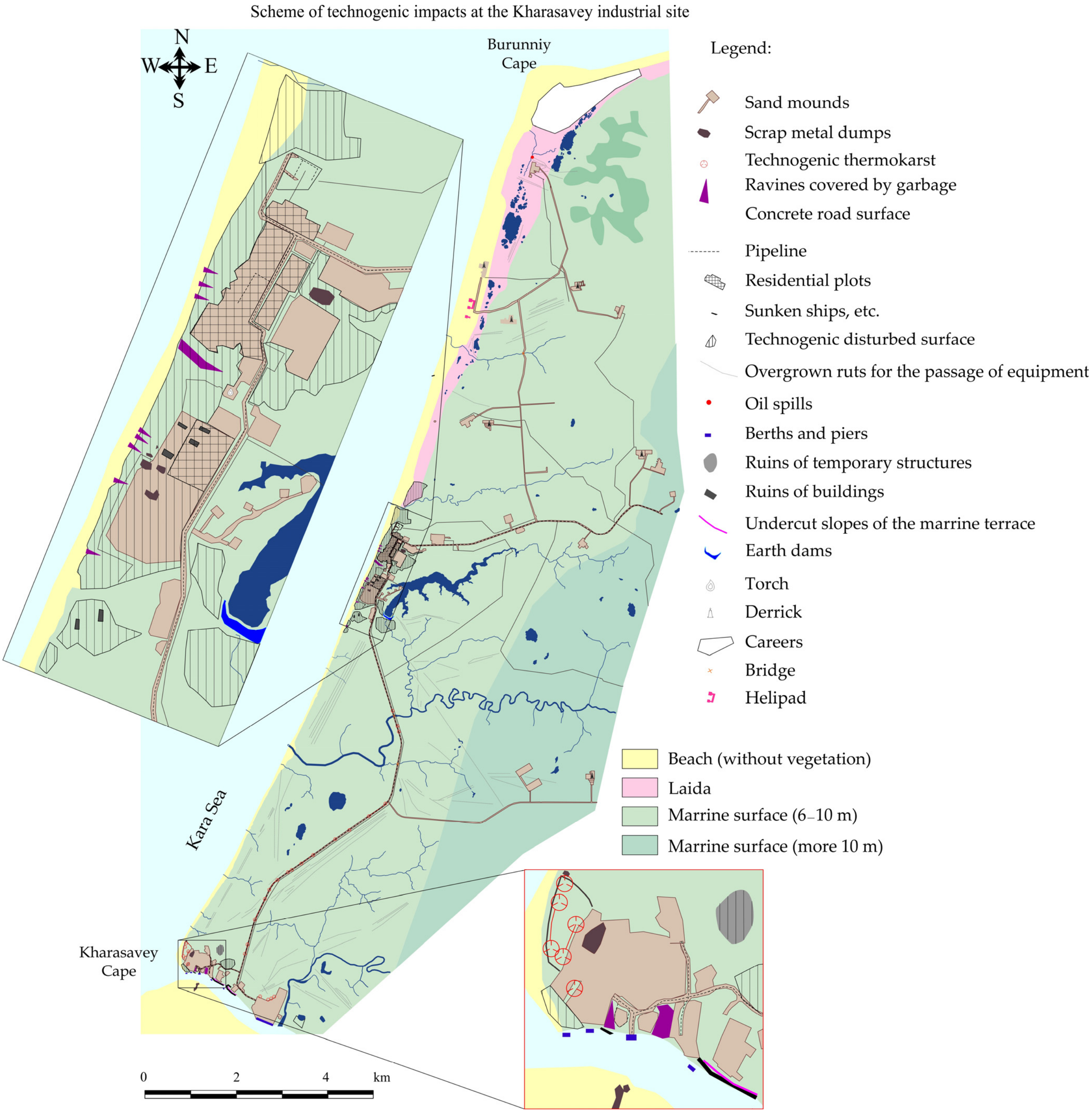


Figure 6. Technogenic disturbances at the Kharasavey field.

According to earlier studies [8] in the port area, the level of the sea terrace was 6–12 m, but our analyses showed absolute marks of 6–8 m. This may indicate a significant change in the natural landscape during construction. In addition, we detected the location of the 400 m pipeline close to the shore, where the coastal retreat rates reached 3–4 m/year, but now the coastal slope begins to be covered with vegetation, which indicates the attenuation of the erosion process.

4.4. Potential Economic Damage

The damage from the loss of natural territory (undeveloped) due to coastal retreat is much lower than that caused by infrastructure. The difference may vary by several times (Table 4). As the current trend of climate change continues in the world, the potential economic damage incurred by territories with infrastructure is expected to rise significantly due to coastal dynamics. In the study area, the damage in these territories is projected to increase from USD 7,744,406 to USD 15,609,810 under the SSP5-8.5 scenario, which represents a high greenhouse gas emission pathway. The Zapolyarny District in NAO is expected to incur the highest costs under both scenarios, followed by the Priuralsky District in YaNAO and the Yamalsky District in YaNAO. These findings highlight the urgent need for mitigation measures and adaptation strategies to reduce the impacts of climate change on infrastructure and mitigate its associated economic damage.

Table 4. Potential economic damage.

Climate Change	Territory	Natural Territory		Territory with Infrastructure	
		From	To	From	To
Current trend [4]	All study area	$598,535	$1,453,618	$2,650,655	$7,744,406
	Zapolyarny District NAO	$572,713	$1,387,989	$2,893,896	$7,517,564
	Priuralsky District YaNAO	$9530	$34,851	$96,596	$191,568
	Yamalsky District YaNAO	$13,191	$30,778	$16,504	$35,274
SSP5-8.5 [43]	All study area	$2,378,515	$4,826,750	$9,863,941	$15,609,810
	Zapolyarny District NAO	$2,280,162	$4,663,939	$9,646,498	$15,233,096
	Priuralsky District YaNAO	$35,512	$52,888	$148,697	$261,845
	Yamalsky District YaNAO	$52,763	$109,922	$57,622	$116,880

At a first glance, it seems that the losses of underdeveloped territory in terms of money are insignificant on the scale of the region, and even more on the scale of the country as a whole. However, in accordance with the Russian legislation, the land tax is a local tax, that is, it is collected at the level of municipalities and is often a key source of local budget revenues. For instance, the own budget revenues of the Zapolyarny district of the Nenets Autonomous Okrug in 2022 amounted to about USD 15 million, that is, a figure quite comparable to the costs of the predicted damage.

The cost of undeveloped territory in the Russian Arctic is quite cheap. Potential economic damage was assessed for Kharasavey key site. The part of the coast most vulnerable to coastal retreat is located between the port and the village. Due to the lack of any infrastructure there, the loss of land will cost from USD 950 to USD 2450 under the current climate change trends, and with maximum warming, from USD 2750 to USD 3110. The cost will be much higher, i.e., USD 1,600,000 if a close-to-the-cliff pipeline collapses. A failure of a 1 km long road will also be expensive and cost USD 1,909,233.

5. Conclusions

The consideration of the dynamics of the western part of the Arctic coasts of Russia showed a wide range of coastal retreat values. Significant rates of coastal retreat are typical for a short time period on a local scale. The climate, which includes air temperature, the duration of the ice-free periods and wind direction and speed on the long term, determines the coastal dynamics. The coast retreat rates were predicted for two scenarios of climate change, the first one including the current trends, and the second one considering the maximum possible warming.

Even in one single climate scenario, the erosion rate can change several times, affecting the area of the lost territory and, as a result, the range of potential economic risks.

In this article, the topical scientific and fundamental problem of damage assessment from climate change was considered in the context of the coastal dynamics in the Western sector of the Russian Arctic. It is important to note that this is a pioneer study for Russia and allowed us to identify only the main significant patterns.

Due to the lack of a land market, underdeveloped land plots subject to coastal abrasion within the territory under consideration have a rather low cost. The study clearly demonstrated how significantly the increase in damage is when economic objects fall into the risk zone of coastal abrasion. Therefore, taking into account further plans for the economic development of this territory, which, for instance, in the near future involve the construction of port infrastructure in order to develop the Northern Sea Route, it is undoubtedly necessary to take into account the factor of coastal retreat. Early adaptation measures and the placement of new facilities in the safest areas can significantly reduce the amount of potential damage.

It is important to highlight the significance of the problem and the need for further research and action to protect the Arctic region. Therefore, further research should be worth expanding, and it will be necessary to include an analysis of the losses for local communities and companies dependent on the fishing and mining industries. In addition, further research will need to assess the impact of coastal dynamics on the coastline and biodiversity of the region, as well as the potential socio-economic consequences for local communities.

Author Contributions: Methodology, S.B. and D.B.; investigation, S.B. and D.B.; writing—original draft preparation, D.B. and S.B.; writing—review and editing, S.O. and S.B.; visualization, D.B.; project administration, S.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Russian Science Foundation, Grant 22-17-00097.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: [https://pkk.rosreestr.ru/, (accessed on 28 May 2023)]. Besides the data presented in this study are available in referenced articles (see section "References").

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zakharov, V.F. *Arctic Ice and Modern Natural Processes*; Gidrometeoizdat: Leningrad, Russia, 1981; 136p. (In Russian)
2. Alekseev, G.V. Research on climate change in the Arctic in the XX century. *Tr. AANII* **2003**, *446*, 6–21. (In Russian)
3. Shabanova, N.; Ogorodov, S.; Shabanov, P.; Baranskaya, A. Hydrometeorological forcing of western russian arctic coastal dynamics: XX-century history and current state. *GES* **2018**, *1*, 113–129. [CrossRef]
4. Ogorodov, S.A.; Shabanova, N.N.; Kessel, A.S.; Baranskaya, A.V.; Razumov, S.O. Changes of the hydrometeorological potential of thermoabrasion on the Russian Arctic sea coasts. In *Vestnik Moskovskogo universiteta. Seriya 5, Geografiya*; Moscow State University: Moscow, Russia, 2022; pp. 26–42. (In Russian)
5. Brouchkov, A.V. Frozen saline soils of the Arctic coast: Their distribution and engineering properties. In Proceedings of the 8th International Conference on Permafrost, Zürich, Switzerland, 21–25 July 2003; pp. 95–100.
6. Ogorodov, S.A.; Baranskaya, A.V.; Belova, N.G.; Kamalov, A.M.; Kuznetsov, D.E.; Overduin, P.; Shabanova, N.N.; Vergun, A.P. Coastal Dynamics of the Pechora and Kara Seas Under Changing Climatic Conditions and Human Disturbances. *GES* **2016**, *3*, 53–73. [CrossRef] [PubMed]
7. Novikova, A.; Belova, N.; Baranskaya, A.; Aleksyutina, D.; Maslakov, A.; Zelenin, E.; Shabanova, N.; Ogorodov, S. Dynamics of Permafrost Coasts of Baydaratskaya Bay (Kara Sea) Based on Multi-Temporal Remote Sensing Data. *Remote Sens.* **2018**, *10*, 1481. [CrossRef]
8. Belova, N.G.; Shabanova, N.N.; Ogorodov, S.A.; Kamalov, A.M.; Kuznetsov, D.E.; Baranskaya, A.V.; Novikova, A.V. Erosion of permafrost coasts of Kara Sea near Kharasavey Cape, Western Yamal. *Kriosf. Zemli* **2017**, *6*, 85–97. [CrossRef]
9. Vasiliev, A.; Kanevskiy, M.; Cherkashov, G.; Vanshtein, B. Coastal dynamics at the Barents and Kara Sea key sites. *Geo-Mar. Lett.* **2005**, *25*, 110–120. [CrossRef]
10. Manson, G.K.; Solomon, S.M. Past and Future Forcing of the Beaufort Sea Coastal Change. *Atmos -Ocean.* **2007**, *45*, 107–122. [CrossRef]
11. Henqutte, A.; Desrosiers, M.; Hill, P.R.; Forbes, D.L. The influence of coastal morphology on shoreface sediment transport under storm-combined flows, Canadian Beaufort Sea. *J. Coast. Res.* **2001**, *17*, 507–516.
12. Baird & Associates Staff. Thermal-Mechanical Mode for Erosion on Arctic Coasts. In *Final Report prepared for Geological Survey of Canada*; Bedford Institute of Oceanography: Oakville, ON, Canada, 1995; 128p.
13. Kobayashi, N. Formation of thermoerosional niches into frozen bluffs due to storm surges on the Beaufort Sea Coast. *J. Geophys. Res.* **1985**, *90*, 11983–11988. [CrossRef]
14. Implementation of Cost Benefit Analysis of Coastal Risk Management Prevention Measures against Natural Hazards. Available online: https://civil-protection-humanitarian-aid.ec.europa.eu/system/files/2017-11/ecoshaz_guidelines_1.pdf (accessed on 10 May 2023).

15. Penning-Rowsell, E.C.; Priest, S.; Parker, D.; Morris, J.; Tunstall, S.; Viavattene, C.; Chatterton, J.; Owen, D. *Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal*; Routledge: London, UK; New York, NY, USA, 2013.
16. Flood and Coastal Erosion Risk Management and the Local Economy. Available online: https://assets.publishing.service.gov.uk/media/6033e1838fa8f54331b08155/_FD2662_full_toolkit.pdf (accessed on 10 May 2023).
17. Chang, J.I.; Yoon, S. The economic benefit of coastal erosion control in Korea. *J. Coast. Res.* **2016**, *75*, 1317–1321. [CrossRef]
18. Landry, C.E. Coastal erosion as a natural resource management problem: An economic perspective. *Coast. Manag.* **2011**, *3*, 259–281. [CrossRef]
19. Repkina, T.Y.; Lugovoy, N.N.; Romanenko, F.A.; Lukyanova, S.A. Sea coasts of the Russian Arctic: Types and chronology of human-induced changes. *Vestn. Mosk. Universiteta. Seriya 5 Geogr.* **2020**, *6*, 10–20. (In Russian)
20. Khavanskiy, A.D.; Khoroshev, O.A.; Merinova, Y.Y. Assessment of the material damage of abrasive and landslide processes effect in municipalities in the coastal zone of the Azov Sea. *Sci. South Russ.* **2021**, *2*, 74–82. (In Russian)
21. Arctic Monitoring and Assessment Programme (AMAP). Snow, Water, Ice and Permafrost in the Arctic (SWIPA); Oslo, Norway, 2017; p. 269. Available online: https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610 (accessed on 10 May 2023).
22. Badina, S.V.; Pankratov, A.A. The value of buildings and structures for permafrost damage prediction: The case of eastern Russian Arctic. *GES* **2021**, *4*, 83–92. [CrossRef]
23. Pilyasov, A.N.; Putilova, E.S. New projects for the development of Russian Arctic: Space matters. *Arct. North* **2020**, *38*, 20–42.
24. Gusev, E.A.; Rekant, P.V.; Anokhin, V.M.; Bolshiyanov, D.Y.; Zarkhidze, D.V.; Shkarubo, S.I.; Sharin, V.V.; Dymov, V.A. Comparison of late Quaternary conditions in the western and eastern sectors of the Russian Arctic. In *Abstracts of the International Workshop "The Problem of Correlation of Pleistocene Events in the Russian North", 4–6 December 2006, St. Petersburg, Russia*; VSEGEI Publisher: St. Petersburg, Russia, 2006; p. 37.
25. Luk'yanova, S.A.; Saf'yanov, G.A.; Solov'eva, G.D.; Shipilova, L.M. Types of Arctic coasts of Russia. *Oceanology* **2008**, *2*, 268–274. (In Russian) [CrossRef]
26. Kizyakov, A.I.; Ermolov, A.A. Morphodynamic segmentation of the Kara Sea coast. In *Arctic Coasts: The Path to Sustainability; Proceedings of the XXVII International Coastal Conference, Murmansk, Russia, 24–29 September 2018*; Murmansk Arctic State University: Murmansk, Russia, 2018; pp. 92–95, ISBN 978-5-4222-0367-3. (In Russian)
27. Yershov, E.D. (Ed.) *Geocryologic Map of the USSR. Scale 1:2, 500,000 Million*; State Cartographic Factory: Vinnytsia, Ukraine, 1991. (In Russian)
28. Ogorodov, S.A. Barents Sea Coasts. *GES* **2011**, *4*, 34–51. [CrossRef]
29. Kizyakov, A.I.; Leibman, M.O.; Perednya, D.D. Destructive relief-forming processes at the coasts of the Arctic plains with tabular ground ice. *Kriosf. Zemli* **2006**, *2*, 79–89. (In Russian)
30. Aleksyutina, D.; Ogorodov, S.; Shilova, O.S. Simulation of coastal dynamics at the Kara Sea. *Glob. Coast. Issues 2020 J. Coast. Res.* **2020**, *95*, 330–335. [CrossRef]
31. Guégan, E.; Sinitsyn, A.; Kokin, O.; Ogorodov, S. Coastal Geomorphology and Ground Thermal Regime of the Varandey Area. *J. Coast. Res.* **2016**, *321*, 1025–1031. [CrossRef]
32. Kizyakov, A.I. The dynamics of thermodenudation processes at the Yugorsky Peninsula coast. *Kriosf. Zemli* **2005**, *9*, 63–68. (In Russian)
33. Aleksyutina, D.; Belova, N.; Baranskaya, A.; Ogorodov, S. Morphological and permafrost factors of coastal dynamics at Kara Sea 14th MEDCOAST Congress on Coastal and Marine Sciences, Engineering, Management and Conservation. *Medcoast* **2019**, *2*, 639–649.
34. Aleksyutina, D.; Motenko, R.; Belova, N.; Shilova, O. Properties of frozen and thawed soils, baydaratskaya bay coast, Kara Sea: Variability and trends. In Proceedings of the International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management SGEM, Albena, Bulgaria, 30 June–9 July 2018; STEF92 Technology Ltd.: Sofia, Bulgaria, 2018; Volume 18, pp. 397–404. [CrossRef]
35. Ogorodov, S.A.; Aleksyutina, D.M.; Baranskaya, A.V.; Shabanova, N.N.; Shilova, O.S. Coastal erosion of the Russian Arctic: An overview. *Glob. Coast. Issues 2020 J. Coast. Res.* **2020**, *95*, 599–604. [CrossRef]
36. Sinitsyn, A.; Guegan, E.; Kokin, O.; Vergun, A.; Udalov, L.; Ogorodov, S. Investigations of coastal erosion processes in Varandey area, Barents Sea. In Proceedings of the SPE Conference, Arctic and Extreme Environments (Moscow, Russia, Society of Petroleum Engineers), Moscow, Russia, 15–17 October 2013. [CrossRef]
37. Kritsuk, L.N.; Dubrovin, V.A.; Yastreba, N.V. Some results of integrated study of the Kara coastal dynamics in the Marre-Sale meteorological station area, with the use of GIS technologies. *Kriosf. Zemli* **2014**, *4*, 59–69.
38. Aleksyutina, D.; Novikova, A.; Baranskaya, A.; Shilova, O.; Ogorodov, S. Using multi-temporal aerial and space imagery for coastal dynamics investigations at Kara and Pechora Seas, Russian Arctic. In Proceedings of the International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management SGEM, Albena, Bulgaria, 30 June–9 July 2018; STEF92 Technology Ltd.: Sofia, Bulgaria, 2018; Volume 18, pp. 265–272. [CrossRef]
39. Baranskaya, A.; Novikova, A.; Shabanova, N.; Belova, N.; Maznev, S.; Ogorodov, S.; Jones, B.M. The Role of Thermal Denudation in Erosion of Ice-Rich Permafrost Coasts in an Enclosed Bay (Gulf of Kruzenstern, Western Yamal, Russia). *Front. Earth Sci.* **2021**, *8*, 566227. [CrossRef]

40. Bulygina, O.N.; Razuvayev, V.N.; Trofimenko, L.T.; Shvets, N.V. Description of Daily Air Temperature and Precipitation Data Set from Russian Meteorological Stations and from Some Meteorological Stations Over the Former USSR Territory (TTTR). 2014. Available online: http://meteo.ru/english/climate/d_temp.php (accessed on 10 January 2019).
41. Ivanova, N.V.; Rivkin, F.M.; Vlasova, U.V. The permafrost structure and formation regularities on the Pechora Sea coast. *Kriosf. Zemli* **2008**, *2*, 19–24.
42. Lantuit, H.; Overduin, P.P.; Wetterich, S. Recent Progress Regarding Permafrost Coasts. *Permafr. Periglac. Process.* **2013**, *24*, 120–130. [CrossRef]
43. Atlas of Abrasion and Ice-Exaration Hazards in the Coastal-Shelf Zone of the Russian Arctic. Electronic Edition. Version 12.2020. Moscow, Research Laboratory of Geoecology of the North, Geographic Faculty of Moscow State University. 2020. Available online: http://www.geogr.msu.ru/structure/labs/geos/links/Atlas2020/Atlas12.2020-%D1%81%D0%B6%D0%B0%D1%82%D1%8B%D0%B9.pdf (accessed on 15 March 2023).
44. Irrgang, A.M.; Bendixen, M.; Farquharson, L.M.; Baranskaya, A.V.; Erikson, L.H.; Gibbs, A.E.; Ogorodov, S.A.; Overduin, P.P.; Lantuit, H.; Grigoriev, M.N.; et al. Drivers, dynamics and impacts of changing Arctic coasts. *Nat. Rev. Earth Environ.* **2022**, *3*, 39–54. [CrossRef]
45. Kislov, A.V.; Alyautdinov, A.R.; Baranskaya, A.V.; Belova, N.G.; Bogatova, D.M.; Vikulina, M.A.; Zheleznova, I.V.; Surkova, G.V.; Kraev, G.N. Forecast of climate change and the intensity of exogenous processes in the Yamalo-Nenets Autonomous Okrug. *Rep. Russ. Acad. Sci. Earth Sci.* **2023**, *2*, 233–240. (In Russian)
46. Kislov, A.; Alyautdinov, A.; Baranskaya, A.; Belova, N.; Bogatova, D.; Vikulina, M.; Zheleznova, I.; Surlova, G. A spatially detailed projection of environmental conditions in the Arctic initiated by climate change. *Atmosphere*, 2023; *in press*.
47. Shabanov, P.A.; Shabanova, N.N. Ice-free period detection method in the Arctic coastal zone. *Russ. J. Earth Sci.* **2020**, *20*, ES6016. [CrossRef]
48. Ogorodov, S.A. Effects of Changing Climate and Sea Ice Extent on Dynamics of Russian Arctic. *Probl. Arct. Antarct.* **2008**, *1*, 123–128. (In Russian)
49. Ogorodov, S.A. Morpholithodynamics of the coastal zone of the Varandey region of the Pechora Sea in the conditions of anthropogenic pressure. *Geoecology Eng. Geol. Hydrogeol. Geocryol.* **2004**, *3*, 1–6. (In Russian)
50. Kopa-Ovdienko, N.V.; Ogorodov, S.A. Peculiarities of the dynamics of thermoabrasive coasts of the Baydaratskaya Bay of the Kara Sea at the present stage. *Geomorfologiya* **2016**, *3*, 12–21.
51. Bogatova, D.M.; Shabanova, N.N.; Ogorodov, S.A. Contribution of the thermak and wave energy drivers to permafrost coastal dynamics in the Kara Sea. *Nat. Tech. Sci.* **2021**, *9*, 74–81. (In Russian)
52. Rosreestr. Available online: https://pkk.rosreestr.ru/ (accessed on 1 May 2023).
53. Berdnikova, V.N. Cadastral and Market Value: The Similarities and Differences. Bulletin of Chelyabinsk State University. *Econ. Sci.* **2019**, *9*, 210–216. (In Russian)
54. Kotlyarov, M.A.; Tatarkin, D.A.; Animitsa, P.E. The relationship between the market and cadastral value of real estate for tax purposes. *Econ. Taxes Law* **2012**, *6*, 25–30.
55. Frolov, A. Expensive gas pipelines. *Corp. Mag. GAZPROM* **2012**, *3*, 24–26. (In Russian). Available online: https://www.gazprom.ru/press/journal/ (accessed on 10 May 2023).
56. Ogorodov, S.A. Human impacts on coastal stability in the Pechora Sea. *Geo-Mar. Lett.* **2005**, *2*, 190–195. [CrossRef]
57. Novikov, V.N.; Fedorova, E.V. Destruction of coasts in the southeastern part of the Barents Sea. In *Bulletin of Moscow State University, Series 5 Geography*; Moscow State University: Moscow, Russia, 1989; pp. 64–68. (In Russian)
58. Sinitsyn, A.O.; Guegan, E.; Shabanova, N.; Kokin, O.; Ogorodov, S. Fifty four years of coastal erosion and hydrometeorological parameters in the Varandey region, Barents Sea. *Coast. Eng.* **2020**, *157*, 103610. [CrossRef]
59. Sovershaev, V.A.; Kamalov, A.M. Stability of seashores in permafrost. In *Geoecology of the North: An Introduction to Geocryoecology*; MGU publisher: Moscow, Russia, 1992; pp. 95–103.
60. Romanenko, F.A. Intensity of geomorphological processes on the islands and coasts of the Kara and Laptev seas (based on observations from polar stations). *Geomorphology* **2008**, *1*, 56–64. (In Russian)
61. Vasiliev, A.A.; Streletskaya, I.D.; Cherkashev, G.A.; Vanshtein, B.G. The Kara Sea coastal dynamics. *Kriosf. Zemli* **2006**, *2*, 56–67. (In Russian)
62. Yuryev, I.V. Problems of operation of gas facilities in the coastal zone of Western Yamal. *Kriosf. Zemli* **2009**, *13*, 46–54.
63. Belova, N.G.; Shabanova, N.N.; Ogorodov, S.A.; Baranskaya, A.V.; Novilova, A.V. Coastal Erosion at Kharasavey Gas Condensate Field, Western Yamal Peninsula. In Proceedings of the SPE Russian Petroleum Technology Conference 2018 (Moscow, Russia), Moscow, Russia, 15–17 October 2018. [CrossRef]