

A GEOMORPHOLOGICAL APPROACH TO ASSESSING THE ENVIRONMENTAL SENSITIVITY OF THE BARENTS SEA COASTS TO OIL SPILLS

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ABSTRACT. The prospects for the development of offshore fields and the growth in the volume of transportation of petroleum products along the Northern Sea Route inevitably increase the risks of accidental spills in the Barents Sea region. This determines the relevance of research on seashores as the most sensitive to oil pollution and difficult to clean up natural ecosystems. The article presents results of geomorphological classification and segmentation of the coastline of the Russian sector of the Barents Sea with a total length of over 13,900 km and assesses their environmental sensitivity to oil spills using the international Environmental Sensitivity Index (ESI). A comprehensive geomorphological analysis was carried out using data from the authors' expedition studies, published literature, cartographic and satellite imagery data, and available photographic materials. The assessment of the environmental sensitivity of the coasts to oil spills resulted in the development of special forecast and assessment maps that illustrate the degree of possible oil pollution (pollution safety, difficulty of cleaning) of individual coastal areas, identify areas of priority protection, and are an important part of oil spill prevention and response plans. The developed maps provide a basis for characterizing the regional geomorphological structure of the coast and can be used to predict environmental risks and the activation of hazardous processes associated with the expansion of oil-production and transportation infrastructure.

KEYWORDS: Arctic coasts, oil spills, environmental sensitivity index, geomorphological analysis

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INTRODUCTION

General information

It is estimated that between 0.5 and 11 million tons of oil enter the world's oceans annually. Contrary to popular belief, accidental spills caused by the production and transportation of liquid hydrocarbons are not the main source of environmental pollution. It is important to note that these sources are responsible for only 12% of the overall oil pollution that occurs on a global scale. Approximately 27% of oil entering the oceans is attributable to shipping, 24% is of natural origin (entering from cracks and fractures of the Earth's crust), 30% is derived from domestic and industrial waste, and 7% is attributed to atmospheric precipitation (Lisichkin and Kulakova 2022). In recent decades, there has been an overall reduction in oil entering the ocean, which has been linked, among other things, to a downward trend in accidents involving oil tankers (Nemirovskaya 2013; Risks

2013). Nevertheless, accidents involving tanker vessels continue to represent a significant environmental hazard. Recent accidents in marine waters include the sinking of the tanker *Volgoneft-139* and the spill of 1,000–1,200 tons of oil products in the Kerch Strait in 2007, a breach in the vessel *FULL City* in the North Sea offshore Norway and the spill of 120 tons of fuel and 100 tons of heavy oil in July 2009, the *Deepwater Horizon* oil rig disaster in the Gulf of Mexico in April 2010 and the spill of approximately 700,000 tons of oil; and the accident on the *ELLY* oil rig offshore of Southern California, which resulted in the spill of over 400 tons of oil in October 2021. In December 2024, two tankers, *Volgoneft-212* and *Volgoneft-239*, sank in the Kerch Strait, causing a world-first spill of over 3,000 tons of heavy fuel oil (the tankers were carrying 9,200 tons of fuel oil in total) and pollution of the coastlines of the Taman and Crimea peninsulas.

Oil spills pose a particular danger in Arctic seas. This danger is due to both the properties of the pollutant itself,

which has direct and indirect negative impacts on the environment, and unique natural conditions in the Arctic regions. The lack of infrastructure and the inaccessibility of coastal areas increase the risk of adverse events in case of an oil spill. Even in the Barents Sea with relatively low sea ice extent, the localization of ports and major industrial centers with the resources to organize oil spill response measures currently does not allow for a rapid response in case of an emergency. In addition, the choice of cleaning methods is limited—mechanical collection, incineration, the use of oil-oxidizing microorganisms, sorbents, and other methods (Guide... 2002; Arctic... 2013; Zhuravel 2015; IOGP Report 2015; Lisichkin and Kulakova 2022; Toropov et al. 2018) often cannot be used on the coasts of freezing seas and/or are capable of having a negative impact on the Arctic ecosystems, which are extremely sensitive to any man-made impact.

The prospects for offshore field development and the growing volume of liquid hydrocarbon production increase the volume of marine cargo transportation. Most shipping using the Northern Sea Route enters it through the Barents Sea. This increases the risk of accidental spills in the region. Developing offshore and coastal fields remains technically complex and potentially hazardous, fraught with both man-made and natural risks. The situation is getting worse due to the deterioration of onshore oil production and processing infrastructure and the risk of water pollution, including the Pechora River, the region's largest watercourse. Existing experience with oil and gas exploration and development in the Pechora Sea and Pechora River Delta, including the negative experience of developing the Kumzhinskoye Field (Bogoyavlensky et al. 2017), and the resulting (cumulative) environmental damage, highlights the particular importance of environmental protection measures.

Along with cargo shipping along the Northern Maritime Transport Corridor and offshore platforms, existing industrial areas remain potential sources of oil pollution in the Barents Sea: the Varandey oil export terminal (onshore storage tank farm, underwater oil pipelines, etc.), connected to the Pirazlomnaya offshore ice-resistant platform (located 60 km from the coast), the Murmansk transport hub (Shavykin and Ilyin 2010), the port of Naryan-Mar; as well as oil production and transportation infrastructure as a part of the Madachag oil field development.

Coastal zone and oil pollution risks

International experience in marine oil spill response shows that the most severe ecological consequences of accidents occur in the coastal zone (Guide... 2002; Arctic... 2013; IOGP Report 2015; IOGP Report 2016). The coast, as a natural environmental boundary, serves as a barrier to the spread of an oil spill and, under certain conditions, can accumulate oil and products of its transformation. Such pollution leads to the loss of recreational appeal, economic value, and biological productivity of the coast as a whole. Coastal cleanup is also extremely complex. For example, cleaning the coasts of the Baltic Sea, including the famous beaches of Palanga, which were polluted as a result of the wreck of the tanker *Globe Asimi* in 1981 and the spill of 17,000 tons of fuel oil, required the removal of more than 600,000 tons of sand and fuel oil mixture from the beaches. Approximately 200,000 tons of sand and fuel oil mixture have already been removed from Anapa's beaches, but emissions of buried fuel oil may resume. Mechanized coastline cleanup methods affect the rate of coastal erosion (Beland et al. 2017; Zengel et al. 2022).

Pollution disrupts the dynamic equilibrium within ecosystems by altering the entire complex of physicochemical and biological properties of marine sediments. Moreover, the period of natural self-purification on the coasts of freezing seas is significantly shortened due to low water and air temperatures, the presence of sea ice, and the prolonged absence of solar radiation. Oil accumulation in areas with low hydrodynamic activity, such as shallow coastal zones and marshes (laydas), poses a particular hazard. Remediation of oil buried in coarse-grained sediments or when contaminated oil is overlain by sediment in areas of intense coastal erosion is difficult.

All these peculiarities prioritize coastal protection when planning and implementing oil spill response measures, necessitating the identification of both the most environmentally valuable coastal areas and those most sensitive to oil pollution and difficult to clean up. For these purposes, coastal environmental sensitivity analyses are conducted, and specialized maps are developed based on a comprehensive expert assessment. These maps serve as a tool for rapid decision-making. After all, time is often the most crucial factor in ensuring the successful implementation of protective measures and/or pollution cleanup with minimal negative anthropogenic impact. Oil spill response planning, including the creation of maps of coastal environmental sensitivity, is essential for offshore resource development.

The aim of the study is to refine and expand the territorial scope of the previously conducted (Mokievsky et al. 2020) assessment of the environmental sensitivity of the Barents Sea coast to oil spills based on a comprehensive geomorphological analysis and the international Environmental Sensitivity Indexes (ESI) (Petersen et al. 2019; IOGP Report 2012). Key objectives of the study include the methodological substantiation of a geomorphological approach to the ecological segmentation of the coastline and the development of a universal morphodynamic mapping of the coasts of freezing seas, taking into account the diverse geological and hydrometeorological conditions of the Arctic seas. During the environmental assessment, international experience was considered, and a regional adaptation of the Environmental Sensitivity Index system was performed.

MATERIALS AND METHODS

The international system of Environmental Sensitivity Indexes

The ESI was first proposed in 1976 by American scientists (Gundlach and Hayes 1978) to support measures and prioritize protection during oil spill response. Based on data on oil and emulsion behavior, 10 base indexes with varying sensitivities to oil pollution were identified. The ranking is based on differences in coastal morphology, sediment grain size, and the intensity of hydrometeorological factors affecting the coast. These factors determine the depth of penetration, the conditions and duration of oil persistence on the coast, and the difficulty of cleanup.

The ESI index system has become an integral part of oil spill response planning and has gained widespread adoption. ESI maps have been compiled for the coasts of countries such as the United States, Canada, Australia, Brazil, Kuwait, Saudi Arabia, the Netherlands, Norway, the United Kingdom, New Zealand, and others (Rustandi et al. 2020; Feng et al. 2021; D'Affonseca et al. 2023). Today, according to the requirements of the International Maritime Organization (IMO), sensitivity maps should be compiled for all coastal marine areas where there is a risk

of oil pollution. Maps are proposed to be developed using an updated assessment methodology developed through collaboration between the IMO, the International Petroleum Industry Environmental Conservation Association (IPIECA), and the International Association of Oil and Gas Producers (IOGP) (IOGP Report 2012; Petersen et al. 2019).

The ESI index system and the methodology for assessing environmental sensitivity continue to be refined based on the experience of oil-producing companies, modern scientific advances, and technology. Today, the ESI still includes 10 main levels (indexes) from 1 (low sensitivity) to 10 (high sensitivity). Each level is color-coded according to an accepted color scale, indicating an increase in the ESI from cool to warm. This allows for clear identification of coastal environmental sensitivity during mapping and simplifies operational spill response efforts. Levels include several types of coastlines, designated by letter indexes and distinguished by shades of color. There are 43 coastline types (Petersen et al. 2019), which are classified based on three main factors:

- coastline type (grain size, slope) which determines the capacity of oil penetration and/or burial on the coast and movement;
- exposure to waves (and tidal energy) which determines the natural persistence time of oil on the coastline; and
- general biological productivity and sensitivity.

However, the authors of the original idea (Gundlach and Hayes 1978) do not recommend combining biological and other components in a single sensitivity index. When making decisions, it is important to understand the relative sensitivity of each ecosystem component to tailor responses for a specific time and place. Taking these factors into account, we deliberately do not consider biological productivity in our study. This is undoubtedly a critical component from a conservation perspective. However, it cannot currently be assessed due to the limited research and limited representativeness of available data for remote Arctic regions. Only general patterns of plant and animal community distribution in the coastal-shelf zone are considered.

Comprehensive geomorphological approach for coastal environmental assessment

As is known (Safyanov 1996), coastal lithodynamic processes determine the direction and characteristics of sediment movement and cause the presence of erosion, transit zones, and sediment accumulation in the coastal zone. The study of these processes has traditionally been the task of coastal geomorphology.

The transit and accumulation of oil products in coastal zones, particularly heavy fractions, are subject to the same laws of lithodynamics as wave marine sediments. Therefore, we use the methodology of Arctic coast classification and assess their environmental sensitivity to oil spills from the perspective of traditional concepts of coastal morphology and dynamics (Zenkovich 1962; Leontyev 1961; Leontyev et al. 1975; Safyanov 1996) on the one hand, and an analysis of coastal conditions and changes unfavorable for living organisms and the conditions under which ecosystems function during oil pollution, on the other.

Geomorphological coastline segmentation should be used as a basis for identifying priority protection areas, mitigating the environmental impacts of oil spills, and conducting pollution cleanup operations. This is due to the spatiotemporal heterogeneity of the topography and relief-forming processes, as well as the coastal zone ecosystems as a whole, which also determine the spatial

and typological differentiation of nature management. The degree of geomorphological differentiation of an area determines its environmental sustainability as a resilience or susceptibility to anthropogenic or natural impacts (Timofeev 2011). This task of identifying areas that are relatively homogeneous within their boundaries is addressed by the environmental-geomorphological approach, which forms a basis for classification and segmentation of the coastline in accordance with the ESI.

Coastal-zone topography, its morphological and morphometric characteristics, largely determine the potential for pollution spread, which depends on coastal slope inclination, beach widths, and coastal cliff heights. Coastal dynamics influence the rate and range of pollution spread. All these factors constitute a single system with complex interaction. As a "distributor of matter and energy flows," topography organizes geographic space into territorial systems and determines the distribution of matter movement rates (Environmental... 2013). This determines the differentiation of coastal geosystems and their spatial variability.

The analysis of coastal oil pollution distribution pathways and accumulation areas is nothing more than a comprehensive geomorphological analysis of the territory, based on a morphosystem approach (Environmental... 2013). Given the importance of the degree of oil pollution on seacoasts for human life and living organisms, such an analysis is environmental-geomorphological.

Systems analysis involves a thorough study of all elements of a natural system and their changes, as well as the nature of the processes occurring within it. External connections between spatially related morphosystems are critical. Identifying patterns in morphosystem dynamics over time is a crucial element of environmental-geomorphological forecasting (Simonov and Kruzhalin 1993).

Assessing the environmental sensitivity of sea coasts to oil spills results in the development of maps, which identifies priority protection areas. The development of oil spill prevention and response plans underpins operational decision-making in emergency situations and is mandatory not only for offshore development but also for any economic use of the waters and seacoasts, rivers, and lake shores related to oil transportation and storage.

In contrast to the traditional conceptualization of the coastal zone as an area of contemporary wave impact (including the coastal slope), the most important part of the coastal zone for environmental assessment is its upper portion, from the sea line at low tide to the line of maximum wave splash. It includes the beach, coastal cliffs, marshes, and estuaries. The variable width of this surf zone depends on the coastal slope surface, represented by marine sediments or bedrock, wave parameters, and the amplitude of tidal and surge fluctuations in sea level. This zone is the potential initial spread of oil pollution upon contact with land, characterized by unique coastal topography and the accumulation of unique layers of coastal sediments. This area is the subject of mapping when compiling coastal sensitivity maps to oil spills.

Coastal sensitivity was determined based on an expert ecological and geomorphological assessment of the topography, sediments' composition, permafrost presence, and hydrodynamic conditions of each coastal segment. The interactions between oil and various sediments and proposed pollution remediation methods were taken into account (Guide... 2002; Sochnev and Sochneva 2003). The conservation status of a particular coastline, its biodiversity, and its distance from key infrastructure facilities were not considered.

Maps of coastal environmental sensitivity are of predictive and assessment types, illustrating the varying degrees of potential oil pollution, the persistence of pollution, and the complexity of cleanup and, accordingly, the varying degrees of environmental risk. Although the primary audience for the maps and environmental assessment results are oil spill prevention and response specialists, the information they contain is understandable not only to specialists in the field but also to individuals in related fields. Furthermore, they provide an excellent basis for various coastal zone management programs and economic activity planning, including recreational activities.

For the classification and thematic mapping of the Barents Sea coastline, the primary sources of information were data on coast morphology, lithology, and dynamics obtained during expeditionary research by the authors and their colleagues. Specifically, fieldwork was conducted on the Murmansk coast (Rybachy and Sredny Peninsulas, the Teriberka region, etc.), the coasts of the Kolguyev, Varandey, and Pesyakov Islands, and the Pechora River estuary. The morphological and dynamic features of the coastlines in hard-to-reach areas were studied through visual interpretation of high- and very-high-resolution satellite imagery, as well as global coverage from ESRI and Yandex Maps. The results of interpreting various coastline types were verified by comparing with the authors' fieldwork data and available photographic and video materials. Image processing and interpretation, coastline segmentation, and map design were performed in ESRI ArcGIS software.

The development of an original classification of the Barents Sea coasts was carried out using cartographic, archival, and published data. The concepts of geomorphology and dynamics of the coastal zone (Safyanov 1996), existing classifications of seacoasts (Kaplin et al. 1991; Luk'yanova et al. 2008; Myslivets et al. 2016; Ogorodov 2003; The Pechora Sea 2003; Popov et al. 1988; Romanenko et al. 2015) were taken into account. The coastline segmentation was carried out at a scale of 1:50,000 – 1:100,000, subsequent generalization considered the possibilities of cartographic representation of individual segments of the indented coastline.

RESULTS

Morphodynamic types of coasts

The continental coastline and islands of the Barents Sea have a heterogeneous geological and tectonic structure (Vernikovskiy et al. 2013). It determines the differentiation of recent crustal movements and the presence of coastal systems that differ markedly in geological properties: a crystalline basement composed of Archean and Proterozoic metamorphic and igneous rocks, as well as Paleozoic intrusions, and an unevenly distributed sedimentary cover formed by Riphean and Quaternary marine and continental deposits. Depending on the inclination of coastal slope, the lithology of the deposits, and the rate and direction of tectonic movements and glacio-isostatic adjustment (GIA) (Baranskaya 2024), the transformation of the coastal contour during postglacial transgression proceeded with varying intensity. As a result, the topography and coasts of the Barents Sea are characterized by great diversity (Fig. 1, Table 1). This is largely due to the heterogeneous hydrological and meteorological conditions of different parts of the sea, which determine the varying intensity of such coastal zone development factors as waves, currents, storm surges, tides, and sea ice.

Within the general type of bedrock abrasion and abrasion-denudation coasts, three subtypes, which differ in wave-cut zone landforms, have been identified. These are coasts with deep coastal zones exposed to sea waves with cliffs and benches (1), coasts with boulder riprap at the foot of the bedrock cliffs (2), and coasts of lagoons, bays, and gulfs sheltered from wave action with abrasional-denudational cliffs and boulder riprap (3). These bedrock coasts are widespread on the Kola Peninsula, the islands of Novaya Zemlya, Franz Josef Land, Vaygach, and elsewhere. Sites of bedrock abrasion coasts are located on the Kanin Peninsula (Cape Mikulkin and Kanin Nos), in the northeast of the Cheshskaya Bay (Cape Barmin), Cape Svyatoy Nos, as well as on the islands of Matveyev, Dolgy, Golets, Bolshoy, and Maly Zelentsy, which represent a linearly elongated ledge of terrigenous-carbonate rocks on the western edge of the Ural-Novaya Zemlya folded zone.

The ice caps and glaciers of Novaya Zemlya and the Franz Josef Land islands, which reach the sea, form unique icy coasts (4). The persistent trend of climate warming in the Arctic is contributing to a reduction in glacier areas, and, consequently, the length of these icy coasts is gradually decreasing.

Thermal abrasion and thermal denudation processes are less widespread on the coasts of the Barents Sea compared to other Arctic seas. This is due to the limited extent of permafrost within the region and deep seasonal thawing of coastal cliffs. In this regard, we combined the coasts with a dominant role of abrasion, thermal abrasion, and thermal denudation processes into a group of retreating coasts (5, 6), built of unlithified sediments, including frozen ones. Such coasts have been identified on the mainland coast of the southeastern Barents Sea and Kolguev Island (Fig. 2), on the Kanin Peninsula, and in the Indiga, Pechora, Cheshskaya, and Khaipudyrskaya Bays; some sites are also located on the islands of the Arctic archipelagos. Within the bays and gulfs, abrasional coasts alternate with accumulative ones.

The southeastern part of the Barents Sea coastline is built of unlithified sediments, and usually there is an excess of debris on the coastal slope. Elongated accumulative coasts with longshore bars, spits, and tidal flats are formed here. Depending on the composition of the beach-forming sediments, coasts with sandy (7), sandy-pebble (8), and pebble-boulder (9) beaches are distinguished. The length of large accumulative landforms reaches 25–50 km (Medynsky Zavorot Peninsula, Pesyakov Island, the Gulyaevskie Koshki island bar, etc.). The accumulative coast, start from Gornostal'e Bay to the eastern end of the Russky Zavorot Peninsula exceeds 200 km (with short sites of abrasion). Short portions of accumulative coasts are formed at the heads of bays and gulfs of the Murmansk coast (Klimovka Bay, Dolgaya, etc.) and on the islands of the Arctic archipelagos (Novaya Zemlya, Franz Josef Land).

Accumulative coasts with shallow coastal zone, windwatts, flats and shoals (10), laydas (11), and deltaic (12) are located in bays and gulfs of the southern and southeastern part of the Barents Sea, sheltered from the action of open sea waves. Accumulation not affected by wave action is usual for enclosed and semi-enclosed bays such as Cheshskaya, Kolokolkova, Pakhancheskaya, Varandeyevskaya, Perevoznaya, and Khaipudyrskaya Bays as well as for lagoons separated from the sea by bars (Peschanaya, Gornostalya, and others), and in the wave shadow of islands and peninsulas. The largest accumulation area is Pechora Bay and adjacent areas, which are fed by the sediment runoff of the Pechora River.

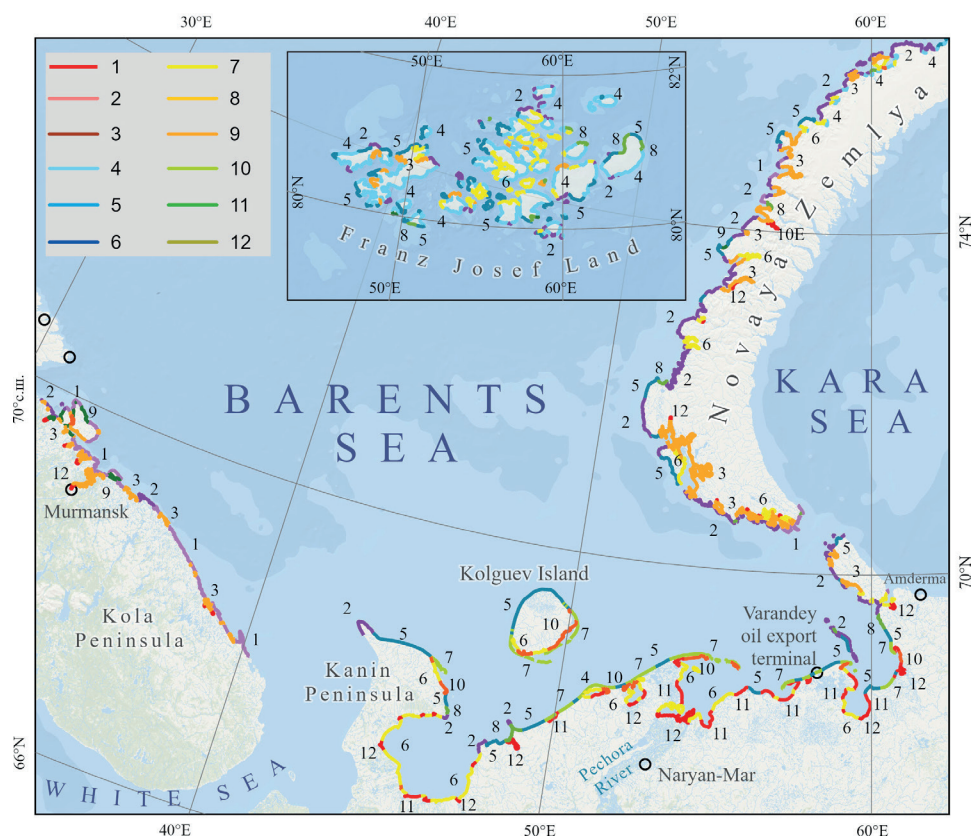


Fig. 1. Distribution of morphodynamic types of the Barents Sea coasts. Coast type indexes correspond to Table 1

Table 1. Types of the Barents Sea coasts

Morphodynamic types			Environmental types	
Coast type		Characteristic landforms within the surf zone	Coast type	ESI Index
Bedrock coasts:				
1.	Abrasional and abrasional-denudational	cliffs, benches	bedrock cliffs exposed to wave action	1A
2.		cliffs with boulder riprap at their foot	bedrock cliffs with boulder base exposed to wave action	1C
3.		cliffs with boulder riprap at their foot (in lagoons, bays and gulfs etc.)	sheltered bedrock cliffs with boulder base	8D
Outlet glaciers:				
4.	Thermal-denudation icy coasts, formed by ice walls of outlet glaciers	ice walls	icy cliffs exposed to wave action	1D
Unlithified coasts:				
5.	Abrasional, thermal-abrasional and thermal-denudational	cliffs with an adjacent sandy-pebble beach / clay bench	cliffs in unconsolidated sediments exposed to wave action	3B
6.		cliffs with an adjacent beach (in bays gulfs)	sheltered cliffs in unconsolidated sediments	8A
7.	Accumulative elongated coasts (including accumulative landforms such as longshore bars and spits)	sandy beaches	sandy beaches	4
8.		sand and gravel, pebble beaches	mixed sand and gravel beaches	5
9.		pebble and/or boulder beaches	gravel and pebble beaches	6B
10.	Accumulative coasts with a shallow coastal zone and windwatts, sheltered coasts (in lagoons, bays and gulfs etc.), deltaic	windwatts, flats and shoals	sheltered sandy-silty tidal and windwatts (mudflats), shoals	9A
11.		laydas (marshes)	laydas (low-lying wetlands inundated by tides), salt marshes	10A
12.		deltaic and estuarine accumulative landforms	flooded lowland tundra	10E

Environmental and geomorphological sensitivity of coasts to oil spills

A total of 12 types of coasts with varying levels of environmental sensitivity were identified (Table 1, Fig. 3). The most sensitive to oil pollution are accumulative sheltered and deltaic coasts with extensive flats, windwatts, and laydas (index 9A, 10A, and 10E). Due to the highly indented coastlines of some sites and the numerous small and large deltaic islands and peninsulas, the total length of the most sensitive coastlines with indexes 10A and 10E was 1,092 km, or 7.9% of the total length of the coastline under consideration. Areas with widespread flats and shoals (index 9A) occupy approximately 479 km, or 3.4% of the coastline (Fig. 4).

The least sensitive to oil pollution are abrasional and abrasional-denudational coasts exposed to wave action

with bedrock cliffs, benches, and boulder riprap (indexes 1A and 1C), occupying approximately 2,560 km, or 18.4% of the coastline. Thermal-denudation icy coasts, which extend significantly due to the rugged coastline of the Franz Josef Land islands, also have low environmental sensitivity (index 1D). According to analysis of Sentinel-2 imagery from the summer of 2019, the length of these coasts was 1,977 km, or approximately 14.2% of the total length of the Barents Sea coastline.

The longest are coastlines with the bedrock abrasional-denudational cliffs in bays and gulfs, protected from intense wave action and characterized by coarse-grained sediments at the foot of the cliffs (index 8D). These coasts extend 2,945 km, accounting for 21.1% of the total coastline. Slightly shorter coastlines are the sheltered thermal-abrasional and thermal-denudation coasts built by sandy-clayey sediments, including frozen ones (index



Fig. 2. The Barents Sea coasts: a) thermal-abrasional cliffs of Kolguev Island (ESI – 3B) (photo by P.M. Glazov); b) abrasional-denudational cliffs of the Rybachy Peninsula (ESI – 1A); c) pebble beaches of Dolgy Island (ESI – 5) (photo by D.S. Nikitin); d) boulder beaches of the Rybachy Peninsula (ESI – 6B); e) sandy flat of Pesyakov Island (ESI – 9A) (photo by O.V. Kokin); f) laydas (marshes) of the Pakhancheseskaya Guba (ESI – 10A) (photo by P.M. Glazov)

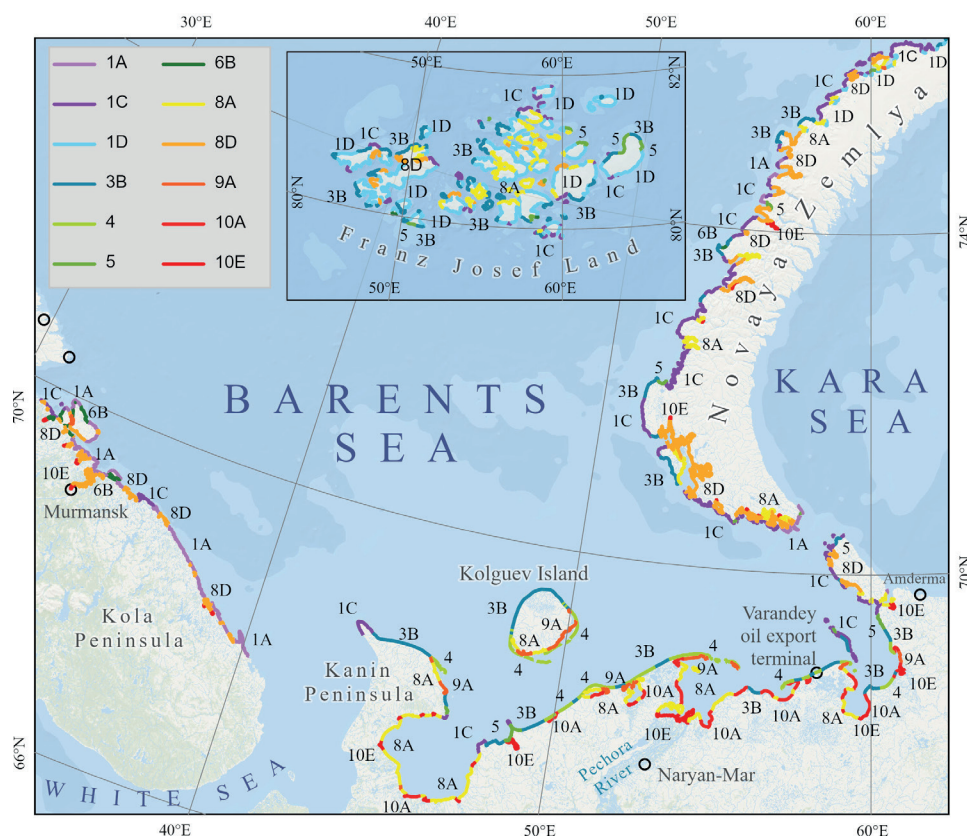


Fig. 3. Distribution of environmental types of the Barents Sea coasts.
Environmental Sensitivity Indexes correspond to Table 1

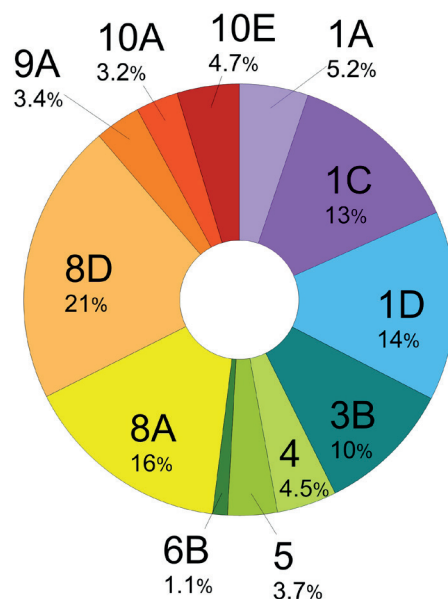


Fig. 4. The ratio of coast lengths with different environmental sensitivity to oil spills.
Environmental Sensitivity Indexes correspond to Table 1

8A). Their total length is 2,175 km, or 15.6% of the coastline. Exposed abrasional and thermal-abrasional coasts built of the same type of sediment (index 3B) extend for 1,410 km, accounting for 10.1% of the total coastline length. Accumulative, elongated coasts (indexes 4, 5, and 6B) occupy a total of 1,298 km, or 9.3% of the coastline length.

DISCUSSION

It has been established that the length of the Barents Sea coasts, which are the most sensitive to oil spills (indexes 9A, 10A, and 10E) is relatively short and does not exceed 15% of the entire coastline. Spatially, these areas are concentrated primarily in the southeastern part of the

Barents Sea, in the Pechora, Korovinskaya, Bolvanskaya, Pakhancheskaya, Varandeyeskaya, and Khaipudyrskaya bays. Taking into account the location of oil production and transport infrastructure facilities, the areas with the highest risk of potential pollution include Varandeyeskaya Bay and the coasts of the Varandey and Pesyakov Islands, as well as Pakhancheskaya and Khaipudyrskaya bays. The latter are shallow sites of predominant accumulation, which is largely determined by tidal currents and surges. The waves' action is insignificant. These are difficult-to-clean coastal portions, inaccessible by all modes of transport (sea, land, and off-road) except air. The shallow waters and low relative elevation of modern marine terraces above sea level do not preclude the possibility of widespread oil spills

during storm surges, when vast areas of low-lying laydas are inundated. However, the natural restoration of such areas in harsh climatic conditions can take decades.

It should be noted that other types of accumulative coasts in the Barents Sea (indexes 4, 5, and 6B) are also highly sensitive to oil pollution. This can be confirmed by a comparison with beaches near Anapa, which are attributed to ESI index 4 according to our assessment (Mokievsky et al. 2019) and are characterized by relatively low permeability to oil products, are exposed to sea waves, and are easier to clean. Nevertheless, over 10,000 people and over 500 pieces of equipment were deployed to clean up the Black Sea coastal zone in 2025.

The proposed environmental-geomorphological approach to coastal segmentation and assessing coastal sensitivity to oil spills emphasizes the importance of the geomorphological component in geoeological risk analysis. This approach takes into account the specific features of coastal systems in the Arctic and forms a scientific concept for the development of thematic maps. This increases the reliability of predictive assessments of coastal environmental sensitivity to oil pollution and the geoeological safety of coastal zones in general. The use of international standards for environmental sensitivity to oil pollution, such as the ESI index system, expands the possibilities for interdisciplinary application and ensures the integration of the assessment results within the framework of international collaboration.

The implementation of the environmental-geomorphological approach addresses another critical issue: selecting a rational method for spill response and coastal cleanup. Limitations relate to both the effectiveness of various cleanup methods in Arctic conditions and the need to consider secondary environmental damage to vulnerable ecosystems caused by incineration, dispersion, removal, and movement of contaminated sediments and other cleanup methods (Ermolov 2017; Lisichkin and Kulakova 2022; Guide... 2002; Shavykin and Karnatov 2020). Often, the combined effect of some cleanup technologies is comparable in its negative impact to the oil spill itself (Ermolov 2017) and can significantly limit or prevent the natural restoration of the ecosystem, especially in the Arctic. Therefore, environmental damage assessments from oil spills should be based on the Net Environmental Benefit Analysis (NEBA), a widely used methodology. It takes into account all the oil spill response measures and technologies that could cause secondary environmental harm beyond the spill itself. The topography and type of sediments play a key role in choosing coastal cleanup methods. These factors underlie the geomorphological differentiation of a territory and determine its susceptibility to external impacts (Guide... 2002).

In discussing the relevance and applicability of the proposed classification, it is worth reiterating the regional specifics of Arctic coastal ecosystems functioning, caused by the harsh climate. A key feature is the duration of the ice period, which can reach 7-8 months off the coast of the Arctic archipelagos in contrast with the ice-free western third part of the Barents Sea. The width of the fast ice also varies significantly along the coast, reaching several kilometers on shallow coasts, such as in Pechora Bay. Under conditions of permafrost and seasonal freezing

of sandbanks, beaches, and marshes, this effectively blocks most landforming processes in the coastal zone and significantly reduces or completely eliminates the possibility of oil product spread and infiltration. Exceptions include accidents involving underwater oil pipelines and underwater equipment on oil platforms, which can result in oil accumulating under the ice. Thus, the proposed environmental and geomorphological classification of coasts is relevant primarily during the ice-free period of the year. This should be taken into account when developing spill response plans, which should cover any season of the year.

CONCLUSIONS

The diversity of the Barents Sea coasts is determined by regional differences in geological structure, paleogeography, and current environmental conditions, which exhibit significant spatial variability. Despite the relatively short length of the most oil-spill-sensitive accumulative sheltered and deltaic coastlines, with extensive flats, windwatts, and laydas (indexes 9A, 10A, and 10E), amounting to 1,571 km, their proximity to the rapidly developing industrial areas of the southeastern Barents Sea increases the risk of potential oil pollution. This necessitates the development of coordinated investment plans aimed at enhancing response capacity in the region. Measures should be aimed at reducing the risk of accidents and improving pollution response capabilities. In the event of an oil spill, the primary goal is to contain the pollution and minimize its environmental impact.

In the challenging conditions of the Arctic, with limited rapid response capabilities, identifying the coastal sites most sensitive to oil pollution and difficult to clean up is a crucial step in planning protective measures. These are precisely the objectives of the developed forecast and assessment maps of the environmental sensitivity of the Barents Sea coast. These maps reflect the results of environmental and geomorphological analysis and are designed to reduce the risk of contamination of coastal zones that accumulate oil during spills and, if coastal damage is inevitable, to make an informed choice of response options and cleanup methods.

Furthermore, geomorphological zonation and coast classification reflect the overall environmental stability of the area and can be considered the basis for integrated coastal zone management and protection. The functionality of environmental sensitivity maps is not limited to oil spill prevention and response plans and can be used in planning economic and recreational activities, conducting scientific research, and environmental monitoring. For such comprehensive use, the results of geomorphological zonation should be supplemented with a classification of terrestrial, freshwater (estuarine), and marine habitats as potential recipients of oil pollution. Consideration of key biodiversity components, including the biosphere and ecological significance of natural habitats, the current state of habitats (including their anthropogenic modification), and the current or prospective conservation status of habitats, will undoubtedly expand the functionality of environmental sensitivity maps. ■

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