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Abrasion Risk Assessment on the Coasts of Seas and Water Reservoirs

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ABSTRACT. Destructive processes on seas and water reservoirs of Russia lead to significant losses of valuable coastal territories and damage to numerous economic objects located there. The article discusses the spatial and temporal patterns of the development of certain types of coasts and water bodies as a whole. An algorithm (methodology) for the quantitative assessment of abrasion risk is proposed, which is the main tool for determining the need for and priority of preventive measures. The general mathematical models for abrasion risk calculation are substantiated. The possibilities of assessing the abrasion risk with a minimum amount of data for choosing the optimal location of new reservoirs are considered. Specific examples of abrasion risk assessment are given for seas and large water reservoirs in Russia, with priority investments from the federal budget being indicated. Timely implementation of measures aimed at reducing losses from coast destruction will benefit for the rational and safe use of coastal areas.

Keywords: coast destruction processes, spatial and temporal patterns, abrasion risk, mathematical models of risk assessment, the use of risk assessments.

1. Introduction

Coasts of seas and artificial water reservoirs are usually the most developed and at the same time dynamically active areas of the Earth, within which a synergistically linked set of abrasion, landslide, karst-suffosion, surge and many other hazardous natural and techno-natural processes develop. The total shoreline of 2260 artificial water reservoirs and 13 seas of Russia is about 125 000 km long. Approximately 39% of shoreline (48 400 km) is being intensely destroyed leading to the irreversible loss of up to 6700 ha of valuable coastal land annually. Bank destruction, often leading to catastrophic events with human casualties, affects 53 cities and hundreds of minor settlements in Russia (Ragozin 2003). Undesirable effects of coastal destruction are mainly pronounced on large reservoirs of more than 10 km^3 in water volume. Over the past decades, such events have occurred

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within some coastal sections of the Caspian, Azov, Black and Baltic seas, the Rybinsk, Kuibyshev, Saratov, Volgograd and other water reservoirs (thus affecting the cities of Makhachkala, Kaspiysk, Derbent, Lagan, Taganrog, Greater Sochi, Svetlogorsk, Rybinsk, Volsk, etc.).

According to expert estimates making allowance for the land loss as well as the damage to economic facilities, the total economic loss from all kinds of coast destructive processes at seas and reservoirs is currently assessed at 2–2.5 billion US dollars per year (Ragozin 2003). Taking into account the dimensions of area involved and the losses caused, the coastal destruction processes are classified as the most widespread and the most hazardous natural processes in Russia along with floods, landslides and earthquakes.

There is no doubt that the problem of tremendous losses from shore destruction can be ignored neither by decision-makers and officials providing for the safe living in coastal areas nor by the scientific community involved in shore study throughout the world. Currently, the term “shore destruction” is understood by the most of researchers as the complex of interrelated denudation and accumulation processes (abrasion, landslide, karst-suffosion, deposition and sediment transfer, etc.) caused by the impact of water from the reservoir on the coast and leading to deformation and destruction of coastal area. The probable irreversible losses of land from these coast-destruction processes are usually referred as abrasion risk.

The purpose of this work is to develop an algorithm (i.e., methodology) for assessing the risk of total losses from shore-destructing processes. This risk corresponds to the physical (irreversible) land loss in its economic value, which is more clear to decision-makers. The proposed algorithm takes into account the regularities of the coast-destruction development, the choice of a risk formation model, a quantitative assessment of the abrasion risk and determination of the priority of cost-protection measures.

Many experts are involved in the study of coast destruction at seas and water reservoirs both in Russia and abroad (Artyukhin et al. 2016, King et al. 2011, London 2017, Myslivets et al. 2018). Risk indices are applied for assessing the status of coastal areas for the purpose of rational land use in many countries of the world, e.g., the USA, Australia, Holland, Belgium, Turkey, etc. These works are diverse, embrace a vast scope of problems and are of great interest for experts. However, for the most part these publications deal with assessing the negative consequences of flooding sea coasts as a result of water level rise (King et al. 2011, London et al. 2009, New South Wales & Department of Environment, Climate Change and Water NSW 2010, South Carolina Blue Ribbon Committee Shoreline Management 2013). In many countries of the world, the governmental programs have been launched aimed at the protection of sea coasts from flooding (Dyckman et al. 2014, Nesterov 2016, New South Wales & Department of Environment, Climate Change and Water NSW 2010, Ogie et al. 2020). The foreign authors consider the following principal local socio-ecological problems that arise from the water-level rise in the reservoirs: water supply, conservation of marine biodiversity, creation of beaches using the seabed sediments, salinization of coastal territories, etc. (Bonsignore et al. 2018, Jin et al. 2019, Piet et al. 2019, Ľim°ek et al. 2019). In our opinion, the use of remote sensing for monitoring coastal territories appears to be very efficient and promising, as described in a number of publications (Elkhrachy 2018, Jin et al. 2019). However, almost no studies address the assessment of abrasion risk as the index of irreversible loss of coastal land. Note also that coastal land-loss is particularly pronounced in Russia, where 6 of 10 largest reservoirs are situated. Therefore, the estimates proposed by us appear to be timely and acute.

The proposed methodology is undoubtedly of great importance as it permits to estimate the losses from coast destruction (abrasion risk) on a federal and regional level for the whole country. On this scale, the abrasion risk has been assessed nowhere yet. Until recently, there was only one example of a complete analysis of the abrasion risk performed for the Russian coast of the Caspian Sea, which resulted in the adoption and implementation of design decisions on coast engineering protection (Ragozin et al. 1996).

The advantage of the proposed algorithm consists in its versatility. It also permits assessing risk quickly using the minimum data on the considered process.

2. Materials and Methods

Our research involved shores of artificial water reservoirs (>10 km^3 in volume) and the seas of Russia, showing certain regularities of shore destruction. Time stages are the common feature of coast-destruction development. The stages are distinguished in the formation of both certain types of coasts and water bodies as a whole as a single natural (seas) or natural-technogenic systems (water reservoirs). At present, almost all Russian reservoirs are found at the second (accumulative-abrasive) stage of formation, which lasts for tens and hundreds of years. This stage has replaced the first one, which lasted for 5–8 years, during the period of filling reservoir with water, being accompanied by intense initial shore destruction. During the second stage, the shores are processed at approximately the same rate, the shoreline is retreating at the constant velocity per year, and hence, the irreversible land loss is not attenuating in time (Ragozin 2003).

2.1. General Risk Analysis

As defined above, abrasion risk is understood as a probabilistic measure of hazard of all coastal destructive processes (not only abrasion, but also water-induced landslides, karst-suffosion, surge, sediment transfer etc.) operating in seas and reservoirs, established for a certain coastal section or for a water reservoir in general in the form of possible land losses in a certain time.

Abrasion risk analysis appears to be, above all, an up-to-date tool for making scientifically grounded decisions in order to mitigate undesirable consequences of coast destruction based on the use of quantitative indices of possible losses understandable not only for experts but also for decision-makers, and public in general.

The main stages of the general procedure for such an analysis include forecasting shore destruction, assessing abrasion risk and making decisions on risk reduction according to the priority value order. When risk approximates a zero value, the possibilities of economic use of coastal areas is also assessed.

It is completely obvious that the nature and methods of solving problems in risk analysis depend significantly on the decision-making level, though the ultimate goal consists in reducing losses from the geohazard manifestation at all levels. Depending on the tasks that correspond to each analytical level, different methods of expressing quantitative risk indices are used. Federal and regional levels use maps or tables allowing experts to develop a decision-making strategy (Burova 2015).

Currently, these studies including those related to coastal areas are being carried out in many countries of the world. However, in the author's opinion, the results presented in this paper on the assessment of physical and economic abrasion risk for all the seas and major reservoirs in Russia, appear to be versatile and applicable to other world regions (Bruno et al. 2019, Ogie et al. 2020, Ľim°ek et al. 2019, Sobol' 2016).

2.2. Abrasion Risk Assessment

Abrasion risk at reservoirs and seas can be calculated in the form of possible physical (material) or economic losses of coastal territories, either taking or not into account the number and cost of economic facilities located within them (Osipov et al. 2017, Ragozin 2003). Calculation of abrasion risk is carried out according to the following general formulas:

$$R_m(A) = V_a \cdot P(V_a) \cdot P(L) \cdot L_t \tag{1}$$

$$R_e(A) = R_m(A) \cdot D_n \tag{2}$$

where:

$R_m(A)$ and $R_e(A)$ – physical and economic abrasion risk

V_a – coast retreat velocity, m/year

$P(V_a)$ – probability of realizing this velocity

$P(L) = L_n \cdot L_t^{-1}$ – geometric probability of linear damage to the territory by destruction

L_n – the length of affected coast, km

L_t – the total length of the estimated sea or reservoir coastline, km

D_n – density of national wealth within the coasts unprotected from destruction (rubles/ha, rubles/km^2).

Such a risk characterizes the possible total loss of the evaluated objects as a whole, which makes it difficult to compare them by the considered index. With equal rates of bank destruction, density of national wealth and other characteristics of sources and recipients of hazard, the higher risk is always attributed to a larger facility. Therefore, the specific risk values reduced to a length or square unit of the estimated coast appear to be more adequate for the analysis, mapping and justification of loss-reducing decisions):

$$R_{sm}(A) = R_m(A) \cdot S^{-1} \tag{3}$$

$$R_{se}(A) = R_e(A) \cdot S^{-1} \tag{4}$$

where:

$R_{sm}(A)$ and $R_{se}(A)$ are specific physical and economic abrasion risk, respectively (ha/km · year, ha/ha · year, rubles/ha · year, etc.).

To assess the abrasion risk for a certain large water reservoir or sea for a period of 10 and more years, the average values of coastal land loss velocity (the velocity of coastline retreat) are usually used. This technique simplifies equation (1) significantly. In this case, the probability of implementation of the average shore destruction velocity may be taken equal to 1, since it corresponds to the most probable scenario of coast retreat over a long period, covering years with different water content, wave energies and other factors influencing the coast destruction.

2.3. Assessment Methods

To assess the abrasion risk in accordance with equations (1) and (2) and taking into consideration the coast-destruction regularities, the data on the total coastline length, the length of affected shores, the coastline retreat velocity, and stages are necessary.

To obtain these data, the author has analyzed the actual data on hundreds of observation sections at the Volga River reservoir cascade. The published data have been collected including monographs, reports, maps, reservoir directories, and numerous proceedings of thematic conferences covering the topics of coastline retreat, mechanism, probability and process development intensity at other large reservoirs and seas, as well as the data on the cost of land and coastal facilities. The risks of physical and economic losses have been calculated for coasts composed of various rock complexes proceeding from the coastline retreat velocity, the degree of coast destruction, and monetary parameters.

If the data on the coast-destruction intensity (linear or volumetric velocities, which are not the reference information) are absent, it is recommended to use any established relationship between the destruction intensity and any other parameter. In particular, it is possible to use the relationship between the length of the ice-free period and the average coastal retreat velocity for the reservoir as a whole (Table 1, Figure 1). This approach appears to be very convenient and justified upon conducting the preliminary overview risk assessment at the federal level, as well as upon choosing sites for allocating new reservoirs.

The long-term average values of the ice-free period can be obtained for various regions of Russia as reference and generally accessible data.

According to the established linear relationship (the value of reliability approximation is 0.8934) for any artificial water reservoir, the average long-term coastline retreat velocities and, next, the predicted values of physical and economic losses can be calculated according to equations (1)-(4).

To assess the abrasion risk for the reservoir and to compile a schematic map of abrasion risk at the regional level, the author used the data on the geological structure, geomorphological parameters, and actual observations over the distribution and intensity of coast destruction, etc. The final assessment of the abrasion risk and the schematic map compilation for the shores of the Tsimlyansk reservoir was carried out by the author of this paper using the values of the specific irreversible land loss due to abrasion only, abrasion in combination with landslides, and abrasion in combination with rockfalls.

Table 1. *Average coastline retreat velocities and ice-free periods at the Russian water reservoirs.*

Reservoirs	Ice-free period t, days	Average velocity of shore retreats l, m/year
Serebryanskoe	118	0.10
Sytykanskoe	125	0.12
Vilyuiskoe	151	0.42
Rayakoski	161	0.56
Imandrovskoe	164	0.58
Vodlozerskoe	169	0.68
Krasnoyarskoe	174	0.73
Bratskoe	180	0.80
Sheksninskoe	184	0.60
Novosibirskoe	190	0.92
Sayanskoe	195	1.00
Rybinskoe	201	0.96
Gorkovskoe	204	1.31
Irkutskoe	210	1.56
Valdaiskoe	216	1.29
Kuibyshevskoe	218	1.92
Pestovskoe	224	1.38
Uglichskoe	229	1.94
Vadinskoe	233	1.49
Saratovskoe	239	2.24
Volgogradskoe	242	1.79

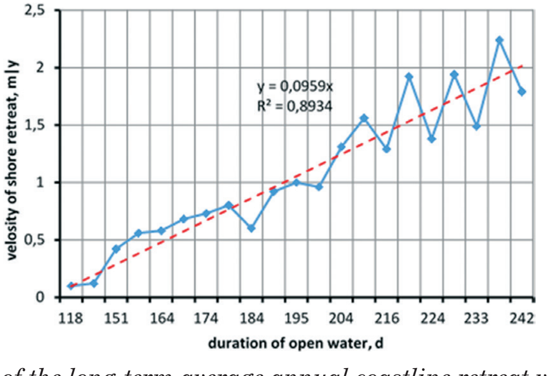

Fig. 1. *Dependence of the long-term average annual coastline retreat velocity (m/year) on the ice-free period (days).*

3. Results

A methodology is proposed and the physical and economic risks of land loss are calculated for some seas and water reservoirs of Russia (Table 2, Figure 2). The coast destruction at water reservoirs is a very dynamic process, but the share of affected coasts remains almost the same within the reservoir for a rather long time (30–40 years). As mentioned above, almost all large Russian reservoirs are passing the second stage of their development now. Consequently, the obtained abrasion risk values for the reservoir as a whole will remain relevant for a rather long period, except for the cases when the conditions change abruptly and radically for a very long time span, as it happened for the Caspian Sea during the last 17 years.

By the example of Tsimlyansk reservoir, the results obtained show vividly the spatial distribution of abrasion risks by the Russia territory and make it possible to identify the most hazard-prone regions (seas and reservoirs as a whole) and shoreline sections within certain water reservoirs.

Table 2. *Abrasive physical and economic risk of land loss for some seas and water reservoirs in Russia.*

Seas and reservoirs	Coastline, km	Extended the abrasion coast, km	Risk			
			Physical, ha/year	Specific physical $n \cdot 10^{-2}$ ha/ km·year	Economic, mln $/year	Specific economic, mln $/ km·year
Black	378	227	31.8	8.4	3.69	0.97
Azov	572	310	62	10.8	5.59	0.97
Baltic	660	140	9.1	5.3	1.32	0.2
Caspian	695	695	34.5	4.9	1.16	0.17
Caspian*	695*	695*	5560*	800*	33.78*	48.61*
Barents	10227	3849	111.6	1.09	7.06	0.07
Bering	11289	4724	51.9	0.46	3.6	0.03
White	3226	706	30.3	0.94	1.92	0.06
East Siberian	4379	916	26.5	0.6	1.68	0.04
Kara	6000	1500	42	0.7	2.66	0.04
Laptev	3750	1000	56	1.49	3.54	0.09
Okhotsk	12262	5632	33.8	0.27	2.35	0.02
Chukchi	2693	693	17.3	0.64	1.09	0.04
Rybinskoe	2460	871	83.6	3.4	4.87	0.19
Gorkovskoe	2170	1403	183.8	8.4	11.38	0.53
Kama	1166	591	70.9	6	3.69	0.32
Votkinskoe	972	378	42.3	4.4	2.21	0.23
Kuibyshevskoe	2375	1329	329.6	13.8	22.81	0.96
Saratovskoe	962	676	151.4	15.7	8.63	0.89
Volgogradskoe	1416	1014	179.4	12.6	10.23	0.72
Novosibirskoe	520	275	24.7	4.7	1.07	0.21
Krasnoyarskoe	1600	1110	77.7	4.8	2.7	0.17
Bratskoe	6000	2473	197.8	3.3	6.87	0.12

*Note: * – The risk of loss of land and economic objects in the phase of sea level rise.*

The artificial water reservoirs in the European part of Russia show the largest values of the specific economic risks of losses from shore destruction (Kuibyshevskoe, Saratovskoe and Volgogradskoe reservoirs). These values are 3.5 to 4 times lower in the Eastern and Western Siberia (Krasnoyarskoe, Novosibirskoe and Bratskoe reservoirs).

The highest values of abrasion risk (48.61 million dollars/km · year) were obtained for the coast of the Caspian Sea, during the period of its intense water level rise (1978–1995). Currently, the abrasion risk on the Caspian coast of Russia constitutes 0.17 million dollars/km · year. The phase of water level rise by 245 cm lasted for 17 years (1978–1995); in subsequent years its relative stabilization began, and the stage of intense coast destruction continued until 2005. At present, the level of the Caspian Sea averages –27.89 m a.s.l., with the maximum and minimum values being –27.68 and –28.25 m a.s.l., respectively, and the amplitude of oscillations not exceeding 30–35 cm (EMERCOM of Russia 2015, 2016, Nesterov 2016). Therefore, in the period of sea level stabilization (2005–present), the abrasion risk shows different values (Table 2).

For the warm southern seas (the Black and Azov seas), the abrasion risk is close to that established for the Volga cascade reservoirs. On the contrary, for the Far East seas (Beringovo, Okhotsk), the specific economic risk is low due to the relatively low density of national wealth there and the insignificant velocities of coastal destruction. The latter does not exceed 0.02 million dollars/km · year (average values).

On the coasts of the Arctic seas, the abrasion risk varies from 0.04 (the Chukchi Sea) to 0.09 million dollars/km · year (the Laptev Sea), because the coasts composed of easily erodible fine soil deposits with a high ice content are destroyed there at a higher velocity than those at the Far East seas.

Ranking the abrasion risk (specific and physical risk) for the Tsimlyansk reservoir shores made it possible to distinguish five categories of abrasion risk, which are shown by shading on the schematic map (Figure 2).

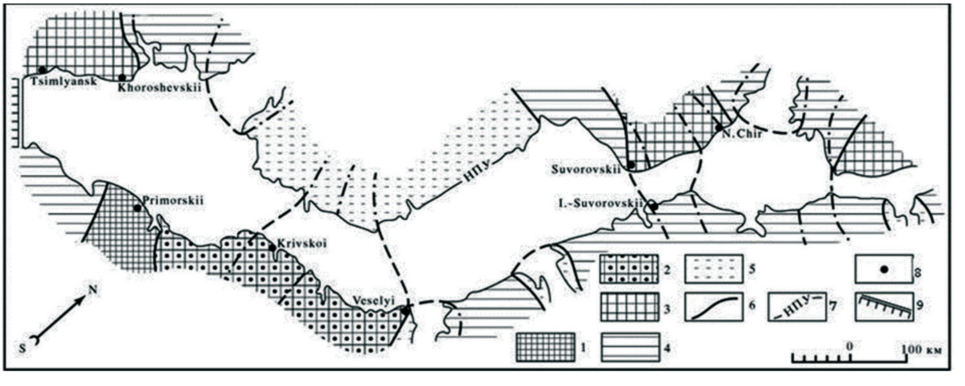

Fig. 2. *A schematic map of the specific risk of loss of coastal land at the Tsimlyansk reservoir.*

Risk categories (specific land losses, 10–2 ha/km · year): 1 – large (20–30); 2 – significant (10–20); 3 – medium (5–10); 4 – small (1.3–5); 5 – small (<1.3). Borders: 6 – coastal areas with different risk categories; 7 – normal retaining level; 8 – settlements; 9 – dam site.

4. Discussion

In this paper, the abrasion risk has been assessed according to the proposed methodology at the federal (for the seas and the largest reservoirs in Russia) and regional (for the Tsimlyansk reservoir) levels. This methodology allows researchers to carry out the relevant assessment for existing water bodies (reservoirs and seas), as well as to make predictive express estimates of possible irreversible land loss (using the dependencies between the parameters controlling the average long-term coast destruction velocities) and to select promising regions for the allocation of new water bodies (reservoirs).

The data obtained on quantitative assessment of abrasion risk allow us to assess the current state (dynamics of losses) of the coastal territories in the whole country and to select the most hazardous regions, within which the protective abrasion-control measures should be undertaken.

It appears impossible to compare the results obtained with the results of other authors, since other researchers' investigations were performed at a different scale. For the most part, all other investigations, both by Russian and foreign specialists, were carried out at a larger scale, being confined to the study and assessment of a certain part of the water body. In addition, as noted above, the studies by foreign authors do not deal with the estimates of irreversible losses of coastal land (physical and economic risks), being mainly focused at assessing changes in the state (pollution, death of a certain biota, etc.) of the coastal territory (Bonsignore et al. 2018, Piet et al. 2019), as well as future coastal management issues (Nicholls et al. 2015).

At present, however, the proposed methodology is actively applied in various regions of Russia. In particular, the shore-protection measures are being undertaken at the Rybinsk water reservoir by federal and local authorities, where 1.9 km-long engineering structures managed to stop the shore destruction. The order of the work is based on indices of risk abrasion aiming at bringing it to 0.

Sadykova and Ivanenko have calculated the abrasion risk values using the proposed methodology for seven abrasion-prone sections of the western coast of Crimea (Sadykova and Ivanenko 2016). The results obtained, in their opinion, allowed preliminary ranking of coastal territories and objects of various sizes according to the degree of environmental and engineering hazard, taking into account the effectiveness of engineering protection facilities for preventing exogenous geohazards and unfavorable anthropogenic load on the adjacent territories (Sadykova and Ivanenko 2016).

It is noteworthy that the basic principles of the proposed methodology for assessing abrasion risks and its applicability to the rational use of coastal areas are widely used not only in Russia but also in neighbor countries. In the Republic of Belarus, the abrasion risk is assessed using the main general theoretical approaches proposed by us earlier (Ragozin 2003). This assessment is taken into account in forecast calculation of sustainable development of regions (Levkevich 2015, 2019). This provision confirms the relevance and significance of the proposed methodology for assessing abrasion risk.

It should be noted that the results obtained in their final form are specific and intended not only for decision-makers, but also for specialists all over the world, as they summarize a lot of data on coast destruction. In our opinion, this approach is very appropriate and promising for creating conditions for the safe use of coastal areas; it agrees with the global policy of study and use of coastal areas, with its advantage consisting in its versatility and ease of use of the proposed assessment algorithm.

5. Conclusion

The main positions of the proposed algorithm are related to:

- substantiation of the stage of development of the reservoir or individual types of coasts and the choice of a risk formation model;
- quantitative assessment of the physical and (or) economic risk of losses according to the selected mathematical models (using actual or calculated values of the coast retreat velocity depending on the availability of information);
- the sequence of preventive measures to protect the coast, according to the obtained risk values;
- taking into account the data obtained when working out programs for the use of coastal territories.

Abrasion risks (in terms of their specific economic values) at large reservoirs are comparable with risks within the warm seas and exceed significantly such risks on the Arctic and Far East coasts. Therefore, the priority investments from the federal budget for the activities related to the reduction of losses from shore destruction should be made, first of all, on the shores of the "warm" seas and reservoirs of the Volga cascade. Naturally, the procedure for using these funds should be specified for each specific reservoir using a more detailed abrasion risk assessment, as it was done for the Tsimlyansk reservoir.

Scientific research on the quantitative assessment of abrasion risk should be developed further in the following main areas: a) revealing quantitative patterns and improvement of methods for predicting coastal destruction; b) development of methods for assessing environmental and social losses from the destruction of reservoir shores, which will contribute to developing programs of managing coastal territories, taking into account numerous criteria of their safe development.

The obtained results on abrasion risk assessment can be recommended now to federal and regional authorities for the development of programs on the safe functioning of coastal territories.

Consideration of foreign experience in the use of coastal territories on the basis of governmental programs, and the use of the proposed algorithm for assessing physical and economic abrasion risks will reduce significantly the negative consequences associated with the destruction of shores of reservoirs and seas in Russia.

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Procjena rizika od abrazije na obalama mora i spremnicima za vodu

SAŽETAK. Destruktivni procesi na obalama mora i spremnicima za vodu u Rusiji doveli su do značajnih gubitaka dragocjenih obalnih područja i do oštećenja brojnih gospodarskih objekata na tim područjima. U članku se razmatraju prostorni i vremenski obrasci razvoja određenih vrsta obala i vodenih površina u cjelini. Predlaže se algoritam (metodologija) za kvantitativnu procjenu rizika od abrazije kao glavnog alata za utvrđivanje potrebe kao i prioriteta preventivnih mjera. Kao dokaz poslužili su opći matematički modeli za izračun rizika od abrazije. Razmatraju se mogućnosti procjene rizika od abrazije s minimalnom količinom podataka za odabir lokacije novih spremnika. Navedeni su posebni primjeri procjene rizika od abrazije za mora i velike spremnike za vodu u Rusiji s prikazanim prioritetnim investicijskim ulaganjima iz saveznog proračuna. Pravodobna provedba mjera usmjerenih na smanjivanje gubitaka uzrokovanih uništenjem obala pridonijet će racionalnom i sigurnom korištenju obalnih područja.

Ključne riječi: procesi uništavanja obale, prostorni i vremenski obrasci, rizik od abrazije, matematički modeli procjene rizika, korištenje procjene rizika.

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