Improving the quality of navigation and hydrographic support in the Arctic rivers estuarine waterways

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Abstract. On the rivers of the Arctic region common navigation conditions are characterized by quickly changing water levels, a wide riverbed with narrow and embayed fairways, numerous point and spatial navigation hazards. Spatial navigational hazards represent dangerous isobaths of irregular geometric shape which do not follow the bank configuration. For reliable visual positioning of the vessel during passage floating marks are widely used. For the winter period floating marks are removed as not designed for use in ice conditions. The most difficult periods for navigation thus come when floating marks are being removed from their adopted positions or being put back. Difficult weather and navigational conditions in conjunction with absence of floating marks increase effect of random component on accuracy of positioning and maneuvering of vessels. Normally safety of the vessels in narrows is assessed by the methods of systems theory. It uses mathematical models of the movement of vessels, which takes into account the totality of all hydrodynamic and mechanical forces acting on the vessel. Intension to support navigational safety during period when floating marks are partially removed makes it important to take into account the stochastic nature of many factors affecting the efficiency of solving navigation tasks. By means of the situational approach based on the methods of mathematical statistics it possible to estimate the levels of navigation safety in congested sea areas, on inland waterways, when designing sea channels, approach routes to ports, etc.

1. Introduction
The Russian Federation has inland waterways of long-distance navigation, which plays an important role both for the national economy and for individual regions. The period of time during which a particular area of inland waterway is open for navigation depends on its physiographic position and set by local basin administrations in relation to the features of separate navigation, but as a rule, taking into account established practice and experience.

There are a lot of rivers on the territory of the Arctic region of the Russian Federation, which are used for navigation purposes. Among which are Onega, Northern Dvina, Mezen, Pechora, Ob, Yenisei, Nadym, Pur, Taz, and others. For the rivers of the Arctic region, one of the characteristic features is a significant variation in periods of navigation, which mainly depends on weather conditions, such as average air temperature, ice formation, rainfall, etc.

A comparison of the actual calendar dates of navigation with the actual dates of commencement of the conditions, in which navigation is not possible, shows a significant temporary discrepancy. This discrepancy is due to the required period of time to work on the removal of floating navigation equipment from the regular places due to unsuitability for operation in ice conditions.

According to the requirements of regulatory documents, the operation of shipping as a complete system is possible only if navigation equipment is available at regular places and work properly.
Navigation equipment, both floating and stationary, is set at the appropriate regular positions, according to approved schemes, which have both theoretical and practical justification. Therefore, as soon as the floating navigation equipment is removed, the navigational conditions are considered not safe, since the position of navigation equipment marks does not correspond to the scheme of navigation hazards marking, developed by many years of operating experience.

Navigational hazards on rivers as applied to navigation safety methods can be divided into point and spatial. Point hazards are obstacles in the middle of the channel, for marking of which one nautical mark is enough. To pass at a safe distance, it is sufficient to estimate only the distance to the mark in the vicinity of this danger.

Spatial hazards are dangerous isobaths, which, as a rule, have an irregular geometric shape, and in most cases do not follow the bank configuration, i.e. are rugged. For their visual marking for the visual control purpose, a set of floating marks of navigation equipment, which forms the system, is used.

Basically navigators working in a particular area are well aware of floating navigation marks schemes and can fix vessel position reliably themselves with it. If floating navigation marks are partially or completely removed, then the load on the navigators will increase dramatically. This will happen even if the vessels are equipped with all modern navigation facilities. Let us give a specific example: when navigating at night through a narrow channel, the navigator can see only lights of the navigation equipment marks, but depending on the light brightness, the navigator not always can reliably determine which of the marks is closer. At the same time, a high accuracy of the vessel positioning is achieved precisely visually, not by observing single marks, but their groups. Taking into account the time to make decision on the maneuver, maneuvering qualities of the vessel in the existing navigation conditions, especially the visibility from the helm station, the accuracy of assessment and so forth, there is no time to analyze the electronic chart data. For proper understanding of navigation particulars caused by unique environmental conditions of the Arctic region description of the most important factors follows below.

2. The Arctic region rivers environmental conditions and its effect on navigation

The most difficult periods for navigation through the rivers of the Arctic region within the territorial boundaries of the Russian Federation are due to several main reasons:
- global climate change;
- ice conditions.

Currently, climate change is observed on the territory of the Russian Federation, namely, a rise in global temperature, which occurs faster and larger than in other regions of the Earth. Significant growth trends in global temperature are observed in the Arctic region [1, 2].

Global temperature growth may have an effect on the reduction of ice-covered period on rivers and water bodies and decreasing of the maximum ice thickness, which will contribute to a noticeable extension of the navigation period.

An increase in the annual and dry-weather streamflow and a change in the duration of navigation caused by climate change expected for almost all major rivers of Russia. It can potentially be favorable to prolonging the period of river navigation. At the same time, an increase in the frequency and intensity of dangerous meteorological and hydrological occasions (gales, squalls, rain showers, flash floods, etc.) that are likely to occur during climate warming may affect the safety of navigation.

The most significant adverse factors for navigation through the rivers of the Arctic region are storm waves, visibility restrictions, fluctuations in sea level in the coastal zone and water basins connected. Storm waves reduce the vessel’s speed, and the degree of this decrease depends on the parameters of the waves (height, period) and the ship’s actual displacement. Waves can influence the speed of the vessel navigating not only through inland waterways river reaches with maritime navigation (the large river mouths, lakes, reservoirs).

During strong winds over the areas of such water bodies as rivers, canals, the direction of the winds coincides with the direction of the river bed i.e. the direction of the winds, relative to the direction of the vessel’s movement, will be either following or head-on. Arisen seas on the long-distance river reaches can occur, so that vessels moving in the opposite direction will have speed losses. Very often intending to get more speed during river passage some vessels take only very small quantity of ballast.
into stern tanks. Proceeding in head-on seas with such ballasting can result in heavy slamming and extremely necessity to take more ballast.

During proceeding in windy weather through river reaches with the wide riverbed and narrow fairway, which is often on large river mouths or reservoirs, vessel can meet waves from other directions. In this case waves will effect vessel’s steering and maneuvering abilities. Yaw caused by waves will effect accuracy of visual positioning and course keeping. For the navigator it will be much more difficult to determine the wheel over and hard over point and control over the vessel’s movement parameters during passing turns.

Visibility restrictions may be caused by either one meteorological effect, such as drizzle, rain shower, snowfall, fog, or their combination, which is often observed in the early spring and late autumn periods of navigation. In these cases, especially on river navigation conditions, vessels are forced to stop or proceed at significantly reduced speed, which leads to loss of time.

An unfavorable combination of navigational conditions can be, for example, arisen waves at the large river mouth in combination with snowfall or heavy rain.

During proceeding through fairway of large river mouth, the navigator, who controls the vessel can use both leading lights and floating buoys for positioning of the vessel. Such meteorological factors as snowfall or rainfall significantly reduces the visual observability by leading lights, and anxiety affects the display of floating buoys on the radar screen. In such circumstances, the passage is a significant risk and must be carried out with special precautions and in accordance with good ship handling practices.

Sea level fluctuations in the coastal zone, caused by surges, are under the influence of strong continuous winds. Such fluctuations cause a change in the water level not only in the coastal zone, but also in the estuaries of rivers. For navigation through such areas, the most dangerous events are when the water level may decrease by several tens of centimeters to 1.0–1.5 m within a few hours, which, in turn, can make it impossible for ships to pass through the fairways.

In many cases, to change the characteristics of wind waves and surge events, it is enough to change the prevailing direction of strong winds (even without changing its speed), since this can change the length of the wind wave run-up (the larger the run, the higher the wave) and the value perpendicular to the shoreline component of the wind (the larger it is, the more intense the surge). However, in contrast to an increase in wind speed, a change in its prevailing direction during climate change can be both an unfavorable and a favorable factor for navigation, depending on the angle between the direction of the wind and the coastline, as well as the configuration of the estuarine riverbed with respect to the prevailing direction the spread of heavy waves.

The most dangerous factors for navigation of vessels through inland waterways that are prone to freezing during onset of below zero temperatures. Usually these unfavorable navigation conditions are coming close to periods of ice-covering and opening of the river from the ice.

Ice on the rivers of the region of interest appears during rather prolonged period. The average length of the autumn slush and ice drift for most medium rivers is about 10 days. The average duration of the freezing period is from 10 days for deep water reaches on medium rivers to 30–40 days for rapids. Freezing on the medium and large rivers begins with slush and ice drift, formation of ice jam later.

Ice factors such as slush and ice jam usually cause change of water levels and current conditions. The duration slush or ice jam formation depends on the flow rate and the physical characteristics of ice and slush, the speed of their freezing, as well as the hydraulic characteristics of the flow in the river section [3, 4]. Water level during slush or ice jam formation can vary in different ways. Speed of the river current highly depends on the present water level and being a vector quantity varies in direction and modulo. This causes the most difficult navigation conditions for ship handling, because such important turning circle parameters as a diameter and an advance highly depend on vessel’s speed.

The brief description of environmental conditions on the rivers of the Arctic region, which effect safety of vessels navigation, proves their negative impact. At the same time the need to develop measures to extend navigation, i.e. extension of the period during navigation, is permitted, but navigation equipment has already been beginning to be removed from the regular positions and possibly, with preservation of a sufficient level of navigation safety.

The need to ensure a sufficient level of safety of navigation makes it necessary to use scientifically based methods for solving the problem of optimizing the scheme of floating navigation marks
positioning. The technique described in this article can be used to solve the problem of the minimum necessary amount of navigation equipment to ensure the safe extension of the navigation period, including on the rivers of the Arctic region.

The solution of the problem of optimizing navigation equipment schemes that can be used during the period of extending navigation is based on the results of mathematical modeling of the controlled movement of the vessel on the navigation simulator and methods of statistical modelling.

3. Description of mathematical modeling method

Navigation is a system consisting of three main components: the navigator, the vessel and the environment. Perhaps the most difficult component to assess is the navigator.

To assess the practical capabilities of navigators in ship handling in difficult navigation conditions successfully methods of mathematical modeling are applied. The basis of the method of mathematical modeling is the use of information technology to reproduce the virtual navigation system.

This virtual system includes the visualization of the navigation area with all stationary and temporary objects of the navigation equipment of the navigation area, a virtual system of navigation and hydrographic conditions (fields of depths, fairways, beacons and buoys, leading lights, etc.), as well as the possibility of imitating hydrometeorological conditions, waves, visibility, currents, etc.

Mathematical models of navigation include ships themselves, which are described by forth-order differential equations, basic and auxiliary control systems with appropriate interfaces.

The method of mathematical modeling is based on the formation of special databases on ship models, cartographic databases for the electronic navigation chart and information display system (ECDIS) and databases on the visual surface situation in the expected navigation area with the aim of sharing them in virtual information systems on «bridge» for making decisions on ship handling in virtual reality navigation conditions.

Such information systems are very widely used for assessment practical ship handling competencies using ECDIS associated with various external information sensors, such as GNSS, ARPA, AIS, etc. [5, 6].

Recently, this kind of simulation models are increasingly used to assess the navigation safety and the assessment of navigation risks [7, 8].

The advantages of information systems include:
1. The ability to use the mathematical model of the vessel, taking into account the main features: the nonlinearity of the elements of the ship’s dynamics, the nonlinearity of the influence of wind, waves, currents, etc. The adequacy of mathematical models can be checked by comparing its maneuvering characteristics (acceleration and deceleration characteristics) with the original.
2. An almost complete presentation of cartographic information corresponding to current measurements, the position of dangerous isobaths, the configuration of the navigation equipment system of the navigation area, etc.
3. Formalization of the concept of characteristic winds, currents along suitable recommended tracks.
4. Skilled navigators, pilots, trainer instructors and other experts can be employed as captains (watch assistants) of virtual ships for solving various types of applied tasks.
5. Mathematical modeling, as a rule, precedes the full-scale tests of prototypes of marine equipment, since it makes it possible to reveal the basic properties of the analyzed systems in more economically justified ways.
6. Mathematical modeling does not at all exclude the carrying out of field experiments; however, it allows one to identify in advance the strengths of the analyzed organizational and technical system of vessel control [9].

The disadvantages include:
1. The final accuracy and completeness of reproduction navigation-hydrographic and hydrometeorological conditions of the navigation area [10].
2. Limited opportunity for a holistic description of the ship model, disturbing factors and their influence on the ship’s dynamics [11].
3. Difficulties in the formation of the psychological and physiological environment of the bridge of a real vessel, i.e. such properties of the environment, which are characterized by responsibility for
decisions made on the maneuver, speed of reaction, susceptibility of information. All that distinguishes the real picture of the actions of the operator on the bridge from the virtual bridge [12].

Based on the analysis of the identified advantages and disadvantages of this method, the following conclusion can be made. In general, the navigation simulation model quite fully includes all the main components of the real navigation system and can be used quite effectively to solve the optimization problem of the floating navigation environment marking in order to extend navigation period on the rivers of the Arctic region.

4. Probabilistic modeling method
The position of the vessel on the ship's course can be described by the following parameters: the distance from the center of mass of the vessel from the axis of the fairway, the linear dimensions of the hull and fairway and drift angle of the vessel.

As is well known, the position of the center of mass relative to the middle of the channel can be attributed to the parameter characterizing the quality of control of the vessel, and the drift parameter will characterize the effects of wind and current in the navigation area. Taking into account the current state of the navigation equipment system in the navigation regions of the Arctic region of Russia, the position of the vessel (center of mass of the vessel) can be measured quite accurately (with an error of 1–3 m with a probability of 0.997). In addition, modern shipboard navigation technology allows measuring and evaluating a whole range of navigation parameters, among which there is also a drift angle.

During maneuvering of a real vessel, the change in its position on the fairway cannot be accurately calculated by theoretical methods, since it is exposed to a large number of individual errors, the effect of which in aggregate leads to errors of some order.

Let us consider, for example, the factors leading to the displacement of the center of mass of the vessel relative to the axis of the fairway due to the peculiarity of navigation equipment of the navigation area.

![Figure 1. Section of the river Severnaya Dvina where only one limit of the fairway is marked with floating marks.](image)

1. The presence of curved sections in which only one side is marked by buoys. However, in some areas the isobath may extend beyond the line of buoys. Thus, when oriented relative to the line of buoys, there is the possibility of excessive approach of the vessel to a dangerous isobath. Such approximation
may be caused by various reasons: excessive yaw of the vessel due to the influence of external factors, lack of sufficient experience of navigation in the area, or insufficient work experience on a particular vessel. In the process of maneuvering in the head-on situation, when one of the vessels is positioning visually by the limit of the channel marked by bouys and another does not have the ability of visual control of the dangerous isobath.

As an example, figure 1 shows a section of river Severnaya Dvina with only one limit of the fairway is marked with floating marks. This figure shows a navigational electronic chart of the narrow fairway within the wide riverbed marked by floating marks and leading lines according to the navigation equipment system adopted for inland waterways of the Russian Federation. Red rectangular symbols mark starboard-hand limit of the fairway and green triangular symbols show port-hand limit of the fairway. Moving in figure 1 from left to right according to the represented symbols at first only starboard-hand limit of the fairway is seen as marked with cylindrical buoys. After the same marking of the port-hand, the limit of the fairway can be seen.

From figure 1 it can be also seen that in some areas the distances between the port-hand light buoys are significant and, when used for visual positioning, the vessel can approach the dangerous isobath.

2. The limits of the canals are partially equipped with the beacons "Landmark" or “Track Light”, which are installed on stationary bases near the edge of the channel or on the banks. When using only such signs for orientation, the risk of approaching the vessel to a dangerous isobath increases.

![Figure 1](image1.png)

**Figure 1.** Section of the fairway on the river Severnaya Dvina with only one limit of the fairway marked with floating marks.

3. The use of the middle fairway buoyage system when the navigator can visually control only the limit which is on port side of its vessel and passes in the middle of the river fairway.

4. The possibility of low sensitivity of the alignment with a significant length of the non-navigational length of the alignment, which takes place on the White Sea-Baltic channel. Low sensitivity of the alignment leads to an increase in the minimum distance of the vessel along the perpendicular to the axis of the alignment, at which the solution of marks becomes noticeable. This circumstance can play a very significant role in ensuring the safety of navigation in the spring and autumn, when the floating marks are partially removed.
5. On some river reaches, the position of the channel can significantly change its direction during navigation; therefore the use of floating marks as main reference points is justified. In addition, on such reaches, the possibility of shifting the hazardous isobaths beyond the line of buoys is increasing.

6. When making turn from the section of the considerable width to the narrow one, high accuracy of maneuvering is required especially in heavy weather. In case of partially removed floating marks, errors equal to the dimensions of the vessel can happen. The appropriate section of the fairway on the river Yenisei is shown in figure 2. Figure 2 shows the navigational electronic chart of the wide section, Yenisei riverbed is divided into several channels by islands. Channels are deep enough but depths close to their limits are very shallow that makes it necessary to perform positioning and maneuvering of the vessel very accurately. The most reliable and suitable one for the navigation channel is marked with floating marks and leading lines according to the navigation equipment system adopted for inland waterways of the Russian Federation.

A visual assessment of the distance from the ship’s side to the corresponding limit of the fairway is carried out on the basis of a comparison of the free space from each side with the part of the hull visible from the bridge. Thus, the distance observed from each side can be quantified in relation to the apparent width of the hull, i.e. in fractions of the apparent width of the hull.

Estimating the change in the maneuvering characteristics of the vessel in various navigation conditions, it can be concluded that their values also significantly depend on a large number of random components.

Despite the large number of adverse factors affecting the navigation safety of navigation, the master will use all his knowledge and experience to keep the vessel on the axis of the channel or at a safe distance from the navigational hazard.

Thus, the position of the center of mass of the vessel will have a pronounced tendency to group around the axis of the channel, with equiprobable deviations towards the right and left sides, the frequency of such deviations will decrease with increasing its value.

This makes it possible to apply the law of a normal Gaussian distribution to perform statistical evaluation of the parameters of this distribution.

From probability theory [13] it is known that the density of the normal distribution is written as:

$$\Phi(x,a,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-a)^2}{2\sigma^2}}$$  \hspace{1cm} (1)

where $\alpha$ and $\sigma^2$ are law parameters interpreted respectively as the mean and variance of a given random variable (due to the special role of the normal distribution, we will use special symbols to denote its density function and distribution function). Visually, the normal density plot is the famous bell-shaped curve.

The corresponding distribution function of a normal random variable $\xi(a,\sigma^2)$ is denoted by $\Phi(x; a, \sigma^2)$ and is given by the relation:

$$\Phi(x,a,\sigma^2) = P(\xi(a,\sigma^2) \leq x) = \frac{1}{\sqrt{2\pi\sigma}} \int_{-\infty}^{x} e^{-\frac{(t-a)^2}{2\sigma^2}} dt.$$  \hspace{1cm} (2)

The use of mathematical statistics methods for assessing the navigation safety of a ship’s navigation relies on a number of typical assumptions peculiar to statistical systems analysis:

- the analyzed processes are ergodic;
- the analyzed processes are independent;
- analyzed processes are normal.

The entire set of assumptions is verified by experimental data obtained in the course of imitation or full-scale experiments. As follows from the research results, these initial classical hypotheses are fully justified.
The parameters of the normal distribution, calculated on the basis of the data set obtained from the results of mathematical modeling, are used for the subsequent calculation of the numerical values of the navigation safety probability, the analysis of the causes of such values and methods for its increase.

5. Application of mathematical modeling method and statistical analysis for assessing navigational safety

Using the data obtained by the method of mathematical modeling and their subsequent statistical analysis, we can numerically assess the safety of a vessel navigation relative to the influence of various factors, such as the size limits of a vessel that may be allowed to sail along a certain section of the waterway, maximum wind or current values, and efficiency of navigation aids. equipment, etc.

Below is an example of assessing the efficiency of navigator's orientation in the presence of floating marks of navigation equipment and in their absence.

Figure 3. A fragment of the chart of the considered area with floating and stationary navigation equipment.

To assess the effectiveness of the use of floating marks of navigation equipment in relation to specific problems solved by the navigator, while controlling the vessel on the inland waterways of the Arctic region, a number of model runs of the estimated vessel were conducted. For carrying out mathematical modeling the section of Svir river which is difficult for navigation was chosen from the areas available in the base of the navigation simulator Transas NTPro-4000.

The simulation was carried out in real time, on hand steering control mode of the vessel. For positioning during passing the section paper charts and atlases were used. The standard deviation of the vessel from the axis of the channel is taken as a criterion for assessing safety.

This area is shallow, embayed with limited dimensions of the channel and proximity of navigation hazards to the limits of the fairway. Fragments of the electronic navigation chart of the considered area in the presence of floating navigation equipment marks and their absence are presented in figures 3 and 4.
These figures show navigational electronic chart of narrow fairway marked by floating marks beacons and leading lines according to navigation equipment system adopted for inland waterways of the Russian Federation. Red rectangular symbols represent buoys of cylindrical shape and red color marking starboard-hand limit of the fairway and white and black rectangular symbols represent buoys of conical shape and white or black color showing port-hand limit of the fairway. Pairs of red circles symbols surrounded by red rings placed in line represent leading lights on starboard-hand bank of the river, green ones - leading lights on port-hand bank of the river. Separate greed and red circles symbols surrounded by rings of the same color are beacons "Landmark".

When navigating on the considered section, a vessel should be kept strictly along the leading lines, since the edges of the fairway are submerged and stony, and the depths behind the edges in the shallows are small; the turn from one leading line to another almost everywhere should be done smoothly. Following the section, it is necessary to keep the course of the vessel in such a way as to ensure its good controllability, especially during turns. When positioning by front and rear leading lines, one must bear in mind that the leading marks under certain conditions can be difficult to distinguish.

When turning from one straight leg to another with significant change of the course, the turning process requires careful control of the vessel’s position relative to the marks of the navigation equipment, and first of all the floating equipment.

Performing ship handling without floating buoys due to less positioning accuracy cross-track error will increase and will result in ship-bank, ship-bottom interaction effects due to the proximity of banks and bottom. As a result, the maneuvering behaviour of the vessel will increasingly be influenced by these interaction effects. This difference in vessel’s maneuvering behaviour itself will also cause increasing of cross-track error.

Proceeding downstream, when the vessel approaches the wheel over the point, the rotation of the vessel due to the influence of shallow water will not be sufficient and even a small delay in turning will not allow one to take the right course in time. In addition, under the influence of a current the vessel will receive an unacceptable deviation from the axis of the fairway and will go stranded. It is also important to determine the moment of the end of the turn, since the ship acquires a greater angular velocity and, due to the inertia, it may be impossible to make hard over in time.
When proceeding through this section against the current, its effect on the vessel increases especially when approaching the wheel over the point. In such conditions, control of ship turn turning is of great importance that’s why proper attention should be paid to the rudder angle and rate of turn. Even small delay in decision on beginning of turn despite rudder angle values and the duration of its period will cause the rate of turn reduction because of current effect. This leads to impossibility for a ship to change course in time and, under the influence of the current, going out of the fairway limits. As a result of the vessel runs on the navigation simulator, an array of numerical values of the deviations of the center of mass of the vessel relative to the axis of the channel is obtained.

Measurements of such deviations were carried out through a distance equal to the length over all of the estimated vessel. Next, the statistical processing of the data obtained in the program Statistica [14] is carried out. The corresponding data is presented in figures 5 and 6.

**Figure 5.** The frequency of vessel mass center normal deviation from the axis when conducting model runs through the unbuoyed fairway.

Comparison of vessel mass center normal deviations when passing buoyed and unbuoyed mentioned section shows a greater variation in the values when following the unbuoyed fairway. During passing the same buoyed section, the standard deviation has a slightly smaller value, which accordingly shows that the values in the set are grouped more closely.

It was decided to use ship normal deviation from the axis of the channel as a criterion for assessing the safety of navigation. The analysis showed the effectiveness of floating navigational marks for control over the vessel during the passage of long turns, as well as sharp turns, where the leading lines do not cross within the limits of the channel.
Figure 6. The frequency of the vessel mass center normal deviation from the axis when conducting model runs through the buoyed fairway.

Conducting mathematical modeling of the controlled movement of vessels on navigation simulators allows getting an exhaustive array of data on the parameters of vessel movement in various hydro-meteorological and navigational navigation conditions when maneuvering by navigators who have different navigation experience in the area.

The advantage of modeling on the simulator is the absolute knowledge of the researcher about the conditions of navigation, which are set, and the possibility of their change in a certain sequence. Subsequent statistical processing allows us to obtain the numerical values of the criteria for navigational safety for a comparative analysis.

Statistical processing allows obtaining the most probable values of navigation safety criteria and their statistical characteristics. Using the criteria of safety of navigation, it is possible to carry out comparative assessments of the levels of safety of navigation of ships in various navigation conditions.

6. Conclusions
For rivers of the Arctic region of the Russian Federation, a characteristic feature is the instability of the dates of the beginning and end of navigation in connection with the removal of navigation equipment from the regular places. To extend the navigation, we can recommend the development of navigation equipment diagrams on the basis of conducting mathematical modeling on navigation simulators with subsequent statistical processing. The use of numerical values of the sailing safety criteria will allow the navigators to assess the effectiveness of the use of various truncated navigation equipment arrangements allowing them to leave only the navigation marks that play a significant role in visual positioning.
Improving the quality of navigation and hydrographic navigation support in difficult navigation conditions to extend the navigation period in the estuaries of the rivers of the Arctic region is possible through the use of a simulation method and a statistical analysis of navigation risks. Thus, the main directions of improving the quality of navigation and hydrographic support of the estuaries of the Arctic region are:

- the use of special techniques for assessing navigation equipment schemes to enhance both visual orientation and orientation using radar;
- the use of floating navigational signs of a special design, ensuring that they are located in regular places in the winter period.

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