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ПРАКТИЧНІ ПИТАННЯ ЗАБЕЗПЕЧЕННЯ ЗАХОДІВ БЕЗПЕКИ МОРЕПЛАВСТВА З УРАХУВАННЯМ ЕКОЛОГІЧНИХ НАСЛІДКІВ АВАРІЙ

М.П. Булгаков
к. т. наук, доцент,
доцент кафедри судноводіння і морської безпеки
О.Я. Пастернак
ст. викладач кафедри навігації та безпеки мореплавства
О.М. Мельник
д. т. наук,
професор, кафедра навігації та безпеки мореплавства
К.С. Корякін
ст. викладач кафедри навігації та безпеки мореплавства
С.В. Заяць
ст. викладач кафедри навігації та безпеки мореплавства

Одеський національний морський університет, Одеса, Україна

Анотація. *У статті досліджуються основні зони ризику в морській навігації, пов'язані з людським фактором, відмовами обладнання та складними погодними умовами. Особливу увагу приділено аналізу екологічних наслідків морських аварій, зокрема розливів нафти та деградації морських екосистем. Розглянуто положення міжнародних конвенцій з безпеки судноплавства (SOLAS, COLREG-72, ISM Code) та сучасні підходи до управління ризиками, серед яких – підготовка екіпажу, автоматизація процесів, моніторинг технічного стану та охорона довкілля.*

Окрему наукову цінність становить запропонована система математичних моделей оцінки екологічного ризику, що враховують імовірність аварії, обсяг забруднення, чутливість морського середовища та економічні втрати. Представлені моделі забезпечують прийняття обґрунтованих рішень щодо планування профілактичних заходів і оптимізації дій у надзвичайних ситуаціях.

У статті також здійснено порівняльний аналіз ефективності інвестицій у підготовку екіпажу, системи моніторингу й автоматизацію, що демонструє здатність таких заходів значно знижувати рівень ризиків і забезпечувати стійку безпеку судноплавства. Комплексний підхід, що поєднує технічні, людські та екологічні чинники, створює наукову основу для розробки ефективної стратегії управління морськими ризиками.

Ключові слова: *морський траснспорт, безпека судноплавства, розливи нафти, оцінка екологічного ризику, людський фактор, автоматизація, моніторинг, запобігання аваріям, математичне моделювання, управління ризиками, охорона довкілля.*

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PRACTICAL ISSUES OF ENSURING MARITIME SAFETY MEASURES CONSIDERING ENVIRONMENTAL CONSEQUENCES OF ACCIDENTS

Mykola Bulgakov
PhD, Associate Professor,
Associate Professor of the Department of Navigation and Maritime Safety
Oleksiy Melnyk
Doctor of Technical Sciences,
Professor Department of Navigation and Maritime Safety
Oleg Pasternak
Senior Lecturer, Department of Navigation and Maritime Safety
Konstantin Koryakin
Senior Lecturer, Department of Navigation and Maritime Safety
Sergiy Zayats
Senior Lecturer, Department of Navigation and Maritime Safety

Odesa National Maritime University, Odesa, Ukraine

Abstract. *The article explores the main risk areas in maritime navigation related to human factors, equipment failures and severe weather conditions. Particular attention is paid to the analysis of the environmental consequences of maritime accidents, in particular oil spills and degradation of marine ecosystems.*

The provisions of international conventions on safety of navigation (SOLAS, COLREG-72, ISM Code) and modern approaches to risk management, including crew training, process automation, technical condition monitoring and environmental protection, are considered.

Of particular scientific value is the proposed system of mathematical models for assessing environmental risk, which take into account the probability of an accident, the amount of pollution, the sensitivity of the marine environment, and economic losses.

The presented models provide for making informed decisions on planning preventive measures and optimizing actions in emergency situations.

The article also provides a comparative analysis of the effectiveness of investments in crew training, monitoring and automation systems, which demonstrates the ability of such measures to significantly reduce the level of risks and ensure sustainable shipping safety.

An integrated approach that combines technical, human and environmental factors creates a scientific basis for developing an effective maritime risk management strategy.

Keywords: *maritime transport, shipping safety, oil spills, environmental risk assessment, human factor, automation, monitoring, accident prevention, mathematical modeling, risk management, environmental protection.*

Introduction. Ship collisions with loss of crew are the second most frequent maritime incidents with serious consequences. Emergencies occurring at sea are not particularly exceptional. Each crew member, while performing his or her duties on board, must always be ready to ensure the safe navigation of the vessel and professionally participate in emergency actions to rescue it and eliminate the consequences of incidents.

Problem statement. The analysis of statistics shows that there is a positive trend in the intensity of shipping, which leads to an increase in the number of ships and the need to minimize the number of maritime accidents. Maritime safety is the main requirement for all vessels, their crews and shipping companies that navigate the entire world's oceans.

The purpose of the article is to analyze international regulations governing shipping safety and aimed at preventing maritime accidents. The study also aims to identify the key factors that most often lead to maritime incidents and assess the effectiveness of existing risk minimization measures.

To achieve the research objective, **the following tasks** are defined: analyze statistical data on maritime accidents (2014–2023) to identify key trends and contributing factors; examine international maritime safety regulations (COLREG-72, SOLAS, ISM Code) and assess their effectiveness in accident prevention; evaluate the impact of human errors and technical failures on maritime incidents, considering crew training and automation; assess environmental risks of maritime accidents and propose strategies for minimizing their impact.

An analysis of recent research in maritime safety indicates growing attention to factors influencing accident rates in maritime transport, as well as the development of technologies aimed at minimizing risks. In particular, attention is paid to the following aspects:

- evaluation of international conventions and regulations, particularly the International Convention for the Prevention of Collisions (COLREG-72), the SOLAS Convention and the ISM Code.
- identification of the most common accident factors based on statistical data and analytical reports.
- review modern risk management approaches, including technological innovations, crew training and environmental strategies.
- development of recommendations for improving the level of safety of navigation, including improvement of regulations, process automation and environmental measures.

The article also focuses not only on the traditional causes of maritime accidents, but also on their economic and environmental impact, which allows us to consider the problem in a comprehensive manner.

From the analysis conducted during safety investigations, it was found that from 2014 to 2023, 58,4 % of accident events were related to human actions, and 49,8 % of contributing factors were related to human behavior. When considering both events related to human actions and factors related to human behavior, the human factor is attributed to 80,1 % of the maritime accidents and incidents studied. These trends are characteristic of all types of vessels [1].

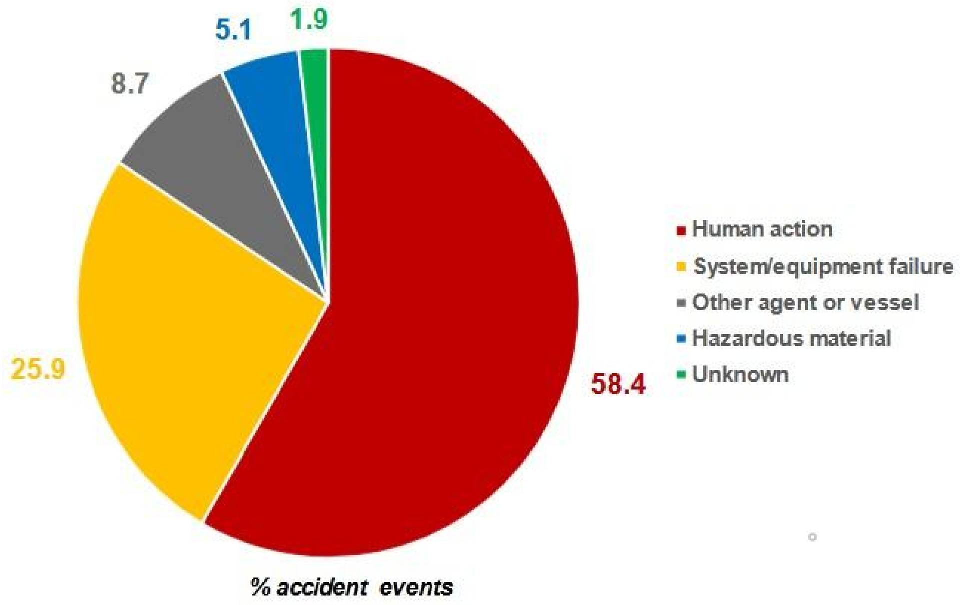

Fig. 1. Percentage of accidents for the period 2014-2023, organized by type of accident [1]

According to EMSA (European Maritime Safety Agency), from 2014 to 2023, 21,4 % of accidents were related to loss of control and 21,3 % to collisions, demonstrating that human error and technical malfunctions remain the main causes of maritime incidents.

Table 1

Main causes of marine accidents (2014-2023)

Cause	**Share of all events, %**
Loss of control	21,4 %
Collision	21,3 %
Navigation errors	15,8 %
Technical malfunctions	13,5 %
Weather conditions	9,6 %

From 2014 to 2023, in the category of «Other Agents or Ship Accidents», the primary contributing factor category was «Environment», accounting for 64,2 % of contributing factors. This was followed by «Human Behavior» with 17,8 %, «Regulations, Procedures, and Training» with 15,6 %, and «Tools and Equipment» with 2,4 %.

Presentation of the main material.

Main Sources of Risks. The risks of maritime accidents can be divided into three main categories: human factors, technical malfunctions and weather conditions. Each of these factors plays a vital role in shaping the overall level of danger and is interrelated with other risks. Human error remains one of the leading causes of maritime accidents. Crew fatigue, wrong decisions, insufficient training or non-compliance with procedures can lead to critical situations. In the initial stages of a vessel's operation, the level of human error can be high, but over time, through systematic training and improved safety procedures, this risk is reduced. At the same time, as fatigue accumulates during long voyages and psychological stress increases, the probability of crew errors increases. Over time, any equipment is subject to wear and tear, which increases the risk of mechanical failures. Insufficient maintenance, aging of key components, corrosion, and mechanical damage can lead to the failure of navigation systems, control systems, or engines. Without proper monitoring and timely repairs, technical problems can cause accidents or even a complete loss of control of the vessel. Weather factors are less predictable but play an important role in the overall level of risk. Stormy winds, high waves, limited visibility due to fog or heavy precipitation can pose a threat to navigation. Unlike the human factor or technical malfunctions, this risk remains relatively stable over time, but its impact can be minimized through modern forecasting and route adjustment systems. All three factors are closely interrelated and can influence each other: Insufficient training or fatigue can lead to improper vessel management, late response to technical failures, or incorrect assessment of weather conditions. Malfunctions of navigation systems, radars, or the main engine can strain the crew, increasing the probability of errors. For example, an autopilot failure in difficult weather conditions requires an immediate response, and a tired crew may be unable to cope with the situation. Adverse weather conditions, such as a storm or strong winds, can make it difficult to steer the ship, increasing the probability of crew errors. In addition, weather factors accelerate the wear and tear of technical systems, which can lead to equipment failure.

Thus, the human factor, technical malfunctions, and weather conditions are interrelated elements of risk. Their simultaneous impact can significantly increase the probability of accidents, so an effective safety management system should take into account all three components.

Table 2

Interconnection of Risks in Navigation

Risk Factor	Impact on Other Factors	Example of Consequences
Human Errors	Incorrect crew actions can lead to technical failures. Misjudging weather increases accident risk	Delayed response to a storm → loss of vessel control. Incorrect system handling → engine failure
Technical Failures	Malfunctioning navigation systems increase crew workload. System breakdowns can complicate maneuvering in bad weather	Autopilot failure in fog → need for manual control. Radar malfunction → inability to assess the correct course
Weather Conditions	Storms and fog make crew operations harder, increasing error probability. High waves and humidity accelerate equipment wear and tear	Strong wind → incorrect maneuvering → collision. High humidity → electronics corrosion → navigation failure

Environmental consequences of accidents. Maritime accidents can cause significant environmental disasters, including oil spills, water pollution, and the death of marine ecosystems. The greatest consequences are observed in cases of tanker accidents or damage to oil production platforms, when large volumes of oil products are released into the open ocean. Oil spills are known to have long-term effects on marine life. Oil forms a film on the water's surface that impedes gas exchange and destroys ecosystems, causing the death of fish, birds, and marine mammals. The economic losses from such accidents include response costs, compensation payments, fines, and loss of biological resources. As an example, the Deepwater Horizon accident (2010) resulted in the deaths of 11 people and the spill of 4,9 million barrels of oil into the Gulf of Mexico. This led to the death of hundreds of thousands of marine animals and caused economic losses of $65 billion.

Table 3

Consequences of Oil Spills

Accident	Year	Spill Volume (barrels)	Losses ($)
Deepwater Horizon	2010	4,9 million	65 billion
Exxon Valdez	1989	260 thousand	7 billion
Prestige	2002	77 thousand	4,3 billion

Accidents of this magnitude demonstrate the need to strengthen environmental control in shipping and develop effective strategies for rapid response to oil spills.

In today's intensified maritime transportation environment, quantitative assessment of environmental risks associated with possible ship accidents is becoming increasingly important. To this end, mathematical models are used to consider the probability of events, the amount of pollutants, the sensitivity of marine ecosystems, and the economic consequences. These models form a science-based basis for making management decisions on accident prevention, damage minimization, and response planning.

To complement qualitative analysis, the following quantitative models can be used to assess the environmental consequences of maritime accidents. An integral model for ecological risk assessment accounts for the variable probability of an accident $P_a(t)$, the volume of substance emission $Q_s(t)$, and the spatial and temporal index of environmental sensitivity $S_i(x,y,t)$

$$ER = \int_{t_0}^{t_1} P_a(t) \cdot Q_S(t) \cdot S_i(x,y,t)dt \tag{1}$$

The aggregate probability of an accident, taking into account *n* risk factors, each of which has a probability R_i and a weighting factor W_i

$$P_a = 1 - \prod_{i=1}^{n} (1 - R_i \cdot W_i), \tag{2}$$

above model aggregates the contribution of each of *n* risk factors (human, technical, navigation, etc.), taking into account R_i – is the basic probability of the factor *i*; W_i – is a weighting factor that reflects its significance.

Potential environmental damage by loss category or total ecological damage as the sum of cleanup costs C_{cj}, resource restoration C_{rj}, and economic losses L_j multiplied by the significance index γ_j for each category *j*

$$ED = \sum_{j=1}^{m} \left(C_{cj} + C_{rj} + \gamma_j \cdot L_j \right) \qquad (3)$$

Viscosity and temperature-adjusted spill impact index where viscosity (μ) and temperature (T) affect the behavior of oil products after an accident

$$I_s = A_s \cdot \rho_o \cdot \left(1 + \frac{\mu}{\mu_{ref}} \right) \cdot e^{-\beta T} \qquad (4)$$

Assessment of ecosystem vulnerability (weight-normalized model)

$$V_e = \frac{1}{Z} \sum_{i=1}^{n} \left(\alpha_i \cdot E_i^2 \cdot S_i \right), \qquad (5)$$

where α_i – weighting factor;

E_i is the degree of influence;

S_i – sensitivity;

Z – normalization factor.

Cost-effectiveness of environmental prevention, taking into account the effectiveness of prevention as risk reduction *ER* before and after measures *m*, taking into account costs C_m and implementation time T_m with an importance coefficient λ.

The basic integral environmental risk model takes into account time- and space-varying parameters: accident probability, pollution volume, and environmental sensitivity. The aggregate accident probability model allows us to assess the total risk, considering several individual factors (technical, navigational, human), each having probability and significance. To assess direct and indirect environmental damage, a model finds the costs of cleanup, ecological restoration, and economic losses in related sectors (fishing, tourism, etc.).

The pollution impact index is calculated considering the physical and chemical characteristics of the substance (e.g., oil), the area of the spill, temperature, and viscosity. The ecosystem vulnerability assessment allows us to understand which components of the marine environment are most sensitive to pollution and to set protection priorities. Finally, a model of the effectiveness of preventive measures allows for comparing different intervention options in terms of the effect achieved and costs. Such models can be used both at the route design stage and for real-time monitoring and post-accident analysis, contributing to the resilience of maritime transport to environmental threats.

Results and discussion. Maritime practice demonstrates that even minor errors in understanding the situation by any crew member – whether it concerns the separation of the vessel or the struggle to restore its seaworthiness – can significantly impact all subsequent decisions. This emphasizes the importance of professionalism, the absence of which is often the cause of incidents at sea.

Training on simulators enables decisions and actions to be taken and acted upon, including safe disconnection of vessels and in the event of a vessel's breach. It also enables seafarers to acquire the necessary competencies and the relevant certificate confirming them.

Further prevention of accidents at sea is ensured by regular training on board the ship:

– safe separation of ships;
– elimination of water leakage from the ship's hull;
– a breach, which should be eliminated immediately, using all the means available on the ship designed for this purpose;
– fire extinguishing;
– rescue of a person who fell overboard and his search;
– other trainings.

Only by practicing on board the vessel can training emergency situations be eliminated. The coordinated, professional work of the crew members and the ship's master is achieved, which ensures the seaworthiness and buoyancy of the vessel in an emergency situation and the possibility of continuing further navigation and maneuvering.

In the event of any danger to the vessel and crew, good maritime practice and safety guidelines require that a ship's alarm be sounded, which can be done by any crew member. According to the alarm schedule, all crew members are urgently assembled in the places designated by this schedule, after which the commanders of the emergency parties report to the captain's bridge on the presence of all or absence of someone, respectively, and a decision is made on further actions, prioritizing the saving of human life.

A competent commission assesses the consequences of the accident by examining all circumstances, documents, technical means, electronic equipment, and actions taken by the captain and crew. The factors that led to the incident are identified. Based on the investigation results, the Commission draws conclusions aimed at improving shipping safety, which are published in the World Fleet Accident Analyses.

For example, the requirements for mutual movement and ship responsibilities are clearly set out in the main international documents on maritime safety: the International Convention on International Regulations for the Prevention of Collision (STCW-72) and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers.

The foundation of all actions the navigator takes while maneuvering the vessel, especially when assessing a potential collision hazard, is the observation of the mutual movements of ships to identify and avert collisions.

This requirement, mandated by the Conventions, necessitates that these observations be performed continuously and adequately, namely:

– to maintain a safe speed, i.e. the speed that should be the basis for safe movement and maneuvering of ships;

– assess the danger and mutual displacement of vessel traffic.

When a safe maneuver has been chosen and assessed in a timely manner, vessels move apart at a sufficient distance to avoid collision.

This is possible with proper organization and the captain's requirements for the work of the ship's crew during the watch on the bridge. Proper compliance by the ship's crew with the above requirements of the International Convention Rules makes it possible to avoid a collision.

It should be noted that the international conventions in question do not prefer naval vessels, except when exercises or convoys are announced in advance in navigation.

The prevention of ship collisions is related to the organization of the work of the navigational staff on the bridge. Existing Conventions and Codes, the implementation of which should ensure 100% exclusion of maritime accidents, are useless if there are no regular exercises as significant factors affecting the crew's professionalism in emergencies.

Methods of risk management. Effective risk management in the maritime industry requires a comprehensive approach that includes measures to train personnel, prevent technical failures, and protect the environment.

The human factor remains the leading cause of maritime accidents, so systematic crew training is critical. The main methods of risk reduction:

- regular crew emergency response training;
- use of simulators to practice crises;
- compliance with international standards (STCW, ISM Code).

Prevention of technical failures, namely timely maintenance of vessels, helps to reduce the probability of breakdowns and increase safety:

- use of automated equipment condition monitoring systems;
- scheduled inspections and modernization of ship systems;
- implementation of artificial intelligence to predict malfunctions.

As noted above, maritime accidents can cause significant environmental damage, so it is important to have effective response mechanisms in place:

- use of environmentally friendly fuels and technologies;
- introduction of ballast water treatment systems.

Establishment of emergency environmental services capable of quickly eliminating the consequences of accidents.

Analysis of the costs of preventing accidents and their consequences. Effective risk management requires a balanced approach between the costs of preventive measures and the potential financial losses resulting from accidents. Investments in personnel training, monitoring systems and process automation can significantly reduce the probability of incidents and minimize the cost of their elimination.

Thus, crew training is the most affordable method of reducing risks. Training costs approximately $50,000 per year, but it can reduce the number of accidents by 30 %. Regular drills, training courses, and emergency simulations increase the crew's skill level and allow them to respond more quickly in the event of a hazard.

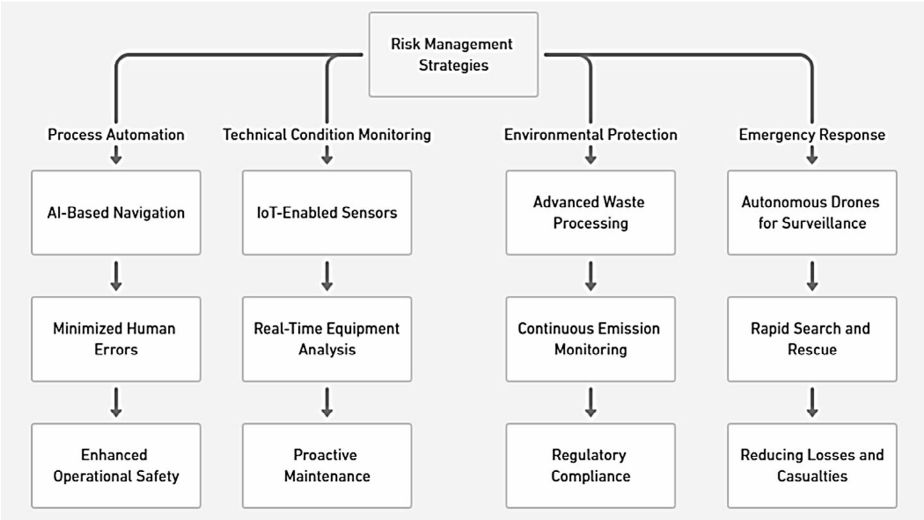

Fig. 2. Effective risk management measures

Monitoring systems provide continuous control over the vessel's condition, detecting potential malfunctions before they become critical. The cost of installing such systems is, on average, $200,000, but it reduces the number of technical failures by 40 %. As a result, companies avoid the cost of expensive repairs or the consequences of accidents due to technical malfunctions.

Automated systems significantly reduce the risks associated with the human factor. Full or partial automation of navigation, ship management, and emergency protocols can cost about $500,000, but it minimizes the impact of the human factor by 50 %. Automated algorithms reduce the risk of errors caused by crew fatigue, inattention, or lack of experience.

Thus, although accident prevention costs may seem high, they significantly reduce risks and help avoid catastrophic consequences. Investments in personnel training, monitoring, and automation are cost-effective and contribute to safe shipping in the long run.

Table 4

Comparison of Costs for Prevention and Accident Consequences

Measure	Average Cost ($)	Reduction in Risk
Crew Training	50,000 per year	Reduction in accidents by 30 %
Monitoring Systems	200,000	Reduction in failures by 40 %
Automated Systems	500,000	Reduction in human factor by 50 %

The analysis showed that human factors, technical malfunctions, and adverse weather conditions are the leading causes of maritime accidents. While it is impossible to eliminate risks, they can be significantly minimized through modern management practices. In particular, crew training, process automation, technical condition monitoring, and effective weather forecasting can reduce the probability of accidents.

Effective risk management in the maritime industry involves not only identifying threats but also implementing targeted measures to minimize them. Studies of maritime incidents and safety reports confirm that both technical and human factors play a crucial role. To ensure strategic planning and operational safety, it is advisable to systematize the main risks and link them to practical preventive actions. Table 5 summarizes the key risk categories, potential consequences, and appropriate mitigation measures advised by sound seamanship and standard maritime practices.

As the table shows, human error and technical malfunctions remain the leading causes of accidents in maritime transport. However, their impact can be significantly reduced by implementing systematic crew training, automated monitoring, and predictive maintenance. Effective environmental control is increasingly dependent on digital technologies and real-time data analysis. The integration of such measures into daily shipboard practice contributes to the formation of a proactive safety culture, reducing accidents and minimizing environmental damage in the modern maritime transport environment.

Table 5

Key Maritime Risk Factors and Recommended Mitigation Measures

Risk Factor	Potential Consequences	Recommended Mitigation
Human Error	Collision, grounding, cargo loss	Bridge resource management, checklists
Technical Failure	Machinery breakdown, blackouts	Predictive maintenance systems, redundancy
Severe Weather Conditions	Accidents due to reduced visibility or wave impact	Weather routing, dynamic positioning
Navigation in Congested Areas	Increased probability of collision and near misses	AIS use, enhanced situational awareness
Inadequate Maintenance	Accelerated equipment degradation, safety hazards	Regular inspections, condition-based maintenance
Lack of Crew Training	Incorrect emergency response, operational mistakes	Ongoing safety drills and simulator training
Poor Environmental Monitoring	Delayed spill detection, unmeasured ecological damage	Automated sensors, real-time data analysis

Conclusions. The study found that maritime accidents pose a complex threat encompassing technical, organizational, human, and environmental aspects. An analysis of typical accidents and the international regulatory framework has identified the key risk factors: imperfect maintenance, crew errors, the impact of adverse weather conditions, and insufficient automation on ships. It is proved that most accidents result from systemic shortcomings in personnel training, violations of safety procedures, and weak control over the technical condition of equipment.

Particular attention is paid to the assessment of environmental risks as one of the most serious consequences of maritime incidents. The proposed mathematical models for the quantitative evaluation of ecological risk allow taking into account the probability of an accident, the amount of pollution, the sensitivity of marine ecosystems, the spatial and temporal characteristics of a spill, and economic losses. Using such models increases the accuracy of forecasting and the efficiency of management decisions, particularly when planning prevention or response measures.

The analysis of the effectiveness of investments in monitoring systems, automated control, crew training, and environmental training showed that an integrated approach significantly reduces the risk of accidents, improves navigation safety, and reduces potential environmental damage. Such an integrated approach should become the basis of modern safety policy in maritime transportation.

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