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A Fuzzy Ballast Water Risk Assessment Model in Maritime Transport

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Abstract: Recent years have witnessed a growing awareness of the critical role that maritime transport plays in global sustainability, given its significant environmental, economic, and social impacts. Central to this concern is the management of ballast water, which, if not properly treated, can lead to the introduction of invasive species, biodiversity loss, and substantial economic and health repercussions. Traditional risk assessment models often fail to capture the complex uncertainties inherent in environmental risks associated with ballast water. This study introduces an innovative fuzzy logic-based risk assessment model designed to enhance decision-making processes in maritime operations by accurately assessing and mitigating the environmental risks of ballast water discharge. The model, structured using three fuzzy systems, integrates human reasoning with mathematical precision, providing an effective tool for sustainable maritime practices. The integrated fuzzy system employs 18 variables as inputs and yields three outputs (ballasting, ballast exchange, and de-ballasting risk). To evaluate the performance of the developed system, various data sets are used and tested through the MATLAB Fuzzy Toolbox. By aligning maritime operations with sustainability principles, this research contributes to the preservation of marine ecosystems, supports the economic stability of marine-dependent industries, and safeguards public health, underscoring the interconnectivity of maritime transport management with overarching sustainability objectives.

Keywords: ballast water; risk assessment; fuzzy logic system; maritime transport

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1. Introduction

Over the past few years, the natural environment has undergone significant alterations because of human activities. While the shipping industry stands as a crucial pillar of the global economy, it poses serious threats to the environment. Specifically, ballast water treatment processes, essential for ship safety, have led to severe ecological distortions and threats to both the environment and human health [1,2]. Water pumped during ballast discharge is directed to ballast tanks and subsequently released during cargo loading, resulting in the daily transportation of 850 species and countless microorganisms. When these species include invasive ones, they often jeopardize local ecosystems, leading to biodiversity loss. Addressing the terrestrial and marine impacts of this issue costs Europe EUR 12 billion annually. Alongside these organisms, many microorganisms and bacterial communities, exhibiting various levels of diversity, composition, and functions [3], mainly residing in the ballast sediment, are transported, causing outbreaks of diseases such as cholera and E. coli with deadly consequences, as exemplified by the 1991 cholera epidemic in Peru that claimed 10,000 lives [1]. Overall, habitat alteration by invasive aquatic organisms transported through shipping ranks among the four major anthropogenic threats to the seas [4].

As the threat of bio-invasions took on global dimensions, with their consequences that had been evident since the early 20th century, various organizations were urged to take action during the 1992 United Nations Conference on Environment and Development.

The International Maritime Organization (IMO) conducted relevant research for a decade, leading to the publication of guidelines [5] and, in 2004, the adoption of the "International Convention for the Control and Management of Ship's Ballast Water and Sediments", commonly known as the Ballast Water Management (BWM) convention [6]. Regulation D-1 suggests ballast water exchange at sea, under specific conditions, to prevent the transfer of organisms and microorganisms [7,8].

Ships subject to this legislation can be exempted according to Article A-4, supplemented by Article G-7, proposing three models for environmental risk analysis. These models assess environmental matching risk, biogeographical risk based on species, and individual risk assessment by species [9].

Ship ballast systems have been a focal point of academic research, addressing various critical aspects of ballast water management. The main research topics in this field include the development of effective technologies to treat ballast water and prevent the spread of aquatic non-native species [10,11], the efficiency of ballast systems [12], and compliance with regulations [13,14]. The advancements, complexities, and considerations in the field of ballast water treatment, focusing on the need for effective treatment systems to mitigate ecological, economic, environmental, and human health risks associated with the transfer of ballast water [15], inspire diverse technological solutions as either port-based [16,17] or onboard treatment systems [7,18].

The number of studies conducting environmental risk assessments in maritime transport is disproportionately limited compared with the magnitude of the bio-invasion problem. Below are some of the most noteworthy research studies.

A comprehensive overview of the environmental impact assessment of key pollutants generated during maritime transport operations discusses various risk assessment methods for maritime transport [19]. The way risks are now assessed only considers one dimension—time or space—making it difficult to address the complex, dynamic need for non-stationary risk management. Moreover, the absence of a consistent and clearly outlined organizational structure for data within Maritime Transport Risk Assessment could be enhanced by incorporating ontology, as seen in other sectors [20].

The study presented in [9] introduces a ballast water management risk assessment model aligned with Ballast Water Management Convention (BWMC) principles. This model, presented as a flowchart decision support system, was tested with port baseline surveys and shipping data. The ballast water management risk assessment and potential management strategies presented offer broad applicability, serving to enhance intricate decision-making processes in adhering to the directives outlined in the Ballast Water Management Convention. Another study gathered insights from 50 expert seafarers, including deck and engine personnel, in order to enhance decision-making regarding ballast water treatment systems based on practical experiences and evaluations [21].

The study in [22] introduces a risk assessment framework for harmful aquatic organisms and pathogens (HAOP) in ballast water under the Ballast Water Management Convention (BWMC). Developed through the Delphi method and the Analytic Hierarchy Process (AHP), the model identifies ten risk factors related to ballast water source and vessel characteristics. It serves as a decision-making tool for port states to pinpoint high-risk vessels and enhances BWMC enforcement. Collaboration with marine ecologists is crucial for obtaining data, and the model's application depends on effective collaboration and modification under Port State Control (PSC) jurisdiction.

The authors of [23] present a novel ballast water risk assessment model (FUZIMEA) using fuzzy logic and the infection mode and effect analysis (IMEA) technique. The model aims to handle vagueness, uncertainty, and data inadequacy in estimating hazards associated with infection modes and components. While the model has the potential for ecological risk assessment, it has limitations, including technical complexity and the need for validation through further tests and real-world applications.

The work in [24] addresses the critical role of human factors in maritime safety and proposes a risk assessment tool integrating human error prediction. The methodology employs the Success Likelihood Index Method (SLIM) extended with fuzzy logic to calculate human error probability (HEP) and assess risk severity. The approach is applied to the Ballast Water Treatment (BWT) system onboard ships, identifying maintenance activities as the riskiest phase.

The study presented in [25] emphasizes the significance of ballast water in ensuring ship stability for global cargo operations, with a focus on environmental and human health concerns. It reviews various ballast water management methods, including exchange, heating, filtration, ultrasonic treatment, ultraviolet irradiation, chemicals, and gas supersaturation, aiming to identify the most effective one. The research compares the physicochemical parameters of ballast tanks with the Persian Gulf environment, evaluating the ecological risks associated with heavy metals. Multiple ballast water exchanges during a voyage are recommended in order to align salinity and dissolved oxygen levels with destination requirements, and the results suggest that combining water exchange with either physical or chemical treatment is more effective in reducing heavy metal concentrations compared with individual methods.

Despite the growing recognition of the ecological and economic impacts of ballast water discharge, there is a lack of sophisticated risk assessment models that adequately account for the complexity and uncertainties inherent in this process. The existing models often overlook key factors and fail to provide actionable insights for effective decision-making in mitigating environmental pollution risks. This research aims to bridge this gap by developing a fuzzy risk assessment model to enhance the assessment of ballast water-related environmental risks using fuzzy systems through the MATLAB programming platform. Although fuzzy models have found applications in diverse fields [26–29], their potential within maritime environmental risk assessment remains unexplored.

By consolidating qualitative data from studies examining ballast tank contents and subjecting them to extreme conditions, we aim to create a system that accurately reflects the real risk level. Because of the substantial amount of acquired information, employing a single fuzzy system with multiple inputs is impractical. Therefore, we propose partitioning the system into three distinct sub-fuzzy systems corresponding to the three ballast water treatment processes—ballasting, ballast water exchange, and de-ballasting—for more effective utilization of information. The integrated fuzzy model utilizes expert knowledge expressed in linguistic terms to incorporate potential risk factors into the decision-making process for assessing the real risk situation.

This research on the Fuzzy Ballast Water Risk Assessment Model in Maritime Transport inherently contributes to sustainability by addressing the environmental, economic, and social dimensions of sustainable development. Environmentally, it seeks to mitigate the ecological impacts of invasive species and pathogens introduced through ballast water, thus preserving marine biodiversity and ecosystem health. Economically, by promoting effective ballast water management, it supports the sustainability of marine-dependent industries, safeguarding their long-term viability. Socially, the model contributes to protecting coastal communities and public health from the adverse effects associated with contaminated ballast water discharges. Together, these aspects underscore the critical role of sustainable maritime transport management in achieving holistic sustainability goals, making this research not only relevant but essential to the field of sustainability.

Despite the growing recognition of the ecological and economic impacts of ballast water discharge, a critical research gap exists in the development of comprehensive and adaptive risk assessment models. Traditional models often fail to account for the complex, dynamic, and uncertain nature of ecological interactions and the myriad of factors influencing the survivability and spread of invasive species. This gap highlights the need for innovative approaches that can encompass the multifaceted and stochastic characteristics of maritime environmental risks.

Guided by the identified research gap, this study aims to address the following questions:

Research question No.1: How can fuzzy logic be applied to develop a more adaptive and comprehensive ballast water risk assessment model that accounts for the inherent uncertainties in maritime environmental management?

Research question No.2: What are the key risk parameters that significantly influence the environmental impact of ballast water discharges, and how do they interact within the fuzzy logic framework?

Research question No.3: What is the performance of the fuzzy logic model in predicting and managing environmental risks associated with ballast water discharge?

Research question No.4: What are the practical implications of this study's findings for improving decision-making processes and environmental sustainability in maritime operations?

Based on the research questions, we formulate the following hypotheses: Firstly, employing fuzzy logic will yield a more precise and comprehensive risk assessment model for ballast water operations compared with conventional methodologies. Secondly, specific parameters, including turbidity, distance from sewage outfalls, and human error probability, will exert significant influence on the overall ballast water risk level. Thirdly, the developed fuzzy logic model will exhibit superior predictive capabilities and effectiveness in managing environmental risks associated with ballast water discharge compared with traditional models. Lastly, the implementation of this study's findings is expected to enhance decision-making processes and contribute to advancing environmental sustainability in maritime transport operations.

By addressing these research questions and hypotheses, this study aims to fill the identified research gap and contribute to the advancement of sustainable maritime environmental management practices.

The paper is organized as follows: Section 2 presents the fundamental concepts for ballast water issues associated with environmental impact. Section 3 provides a concise overview of the main parameters linked with the ballast water risk assessment system. Section 4 presents fuzzy logic concepts and analyzes the developed fuzzy ballast water risk assessment system, which consists of three fuzzy subsystems. The simulation results are presented in Section 5. Finally, conclusions and directions for further research are presented in Section 6.

2. Ballast Water Issues

2.1. Ballast Water Uses

Ships are designed to travel safely carrying a specified weight. On receipt or delivery of the cargo carried, the ship compensates for the change in weight by emptying or filling the tanks intended to receive the ballast water. This technique is used for the safety of the ship, ensuring stability, and flexibility but also reducing the stress that the hull may be subjected to during the voyage. It also keeps the ship at the depth required for the propeller and rudder to operate fully, keeps the bow from rising, and helps to compensate for the weight lost during fuel consumption on long voyages. The amount pumped depends largely on the weather conditions and the course to be followed. In addition, it is used in cases where the ship needs to cross a channel [1,7]. The ballast water cycle, as depicted in Figure 1, illustrates the sequence of interchanging cargo and ballast water.

2.2. Environmental Impact

The water pumped from the harbor contains various types of marine organisms and some sediment from the seabed. The types of organisms pumped in include mainly plants, fish, bacteria, and viruses. In order to enter the tank, organisms need to have a small body size to pass through the pumps and inlet ports, but there have also been imports of fish up to 15 cm in length. The amount of sediment to be taken depends on the conditions in the harbor, which determine the size of the sediment suspension that exists. The sediment may contain cysts, eggs, larvae, and various inert organisms. When the water and sediment settle to the bottom, they create an environment that can sustain many of the organisms being transported. This water, together with the organisms, remains in the tanks until the next cargo delivery when it is released at the next port. Should they manage to survive their introduction into the new ecosystem, they are likely to create conditions that are destructive to both the wetland and humans [1,7]. Ballast water management actively affects the physiochemical factors of water discharged into the port environment. An analysis of sediment accumulation patterns and identified problematic areas within the ballast tank model of a longitudinally framed double-bottom tanker provides insights into the sediment distribution within the tank, aiding in the development of strategies to mitigate sediment-related challenges [30].

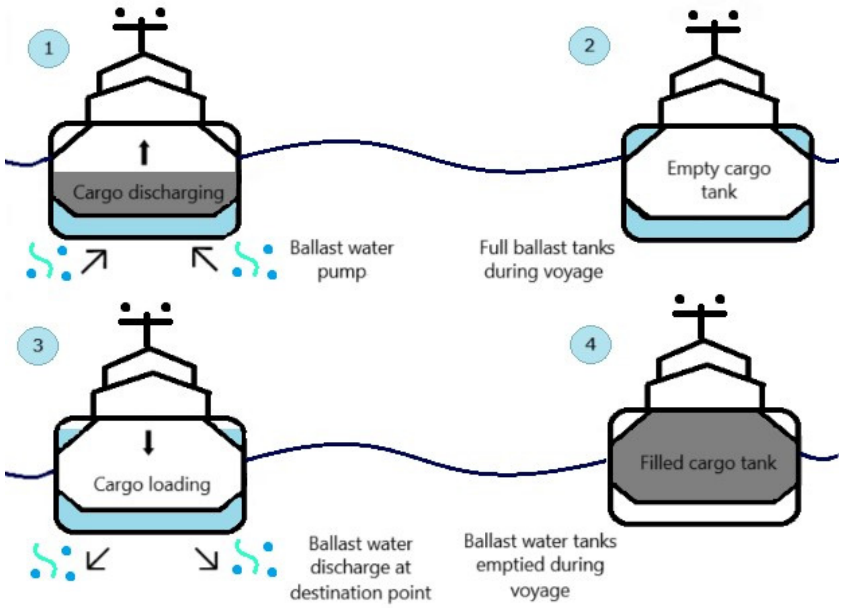

Figure 1. Ballast water cycle.

2.2.1. Marine Species

According to various measurements, it has been observed that about 3000 to 7000 organisms are transported through the creep process daily. Of these, it is estimated that at least 850 organisms will survive in the new ecosystem. If these organisms include non-native species, local habitats are threatened and there are serious implications for the global and local economy [1,31].

Invasive species, or bio-invaders, threaten biodiversity with alteration as they compete with native species for food, alter habitats, and can lead to the extinction of endemic species in the absence of a natural predator in the particular marine ecosystem. In addition, they may lead to the destruction of fish farms and also to the alteration of artificial environments, which include water supply facilities, irrigation works, and others.

There are many documented cases of disturbances in the ecological balance of marine ecosystems by bio-invasive species. In the Mediterranean Sea alone, more than 50% of the recorded transport of organisms is found. Annual management and mitigation costs in Europe amount to more than EUR 12 billion per year, which includes the management of the terrestrial impacts of these alterations [1]. One of the most catastrophic invasions due to the economic and ecological implications is the case of the Chinese mitten crab. The Chinese mitten crab is endemic to freshwater locations and prefers coastal rivers and their estuaries. In the early 20th century, the first invasive populations were observed in Europe, originating from East Asia. The cost of managing the consequences of the Chinese crab invasion in Germany alone has amounted to EUR 80 million since 1912 [32]. Another invasion case that had multiple consequences was the invasion of the Zebra mussel Dreissena. The Zebra mussel Dreissena invaded Europe and North America from the Black Sea, where it thrives. This mussel attaches itself to surfaces that have threads and has caused the destruction of installations such as water supplies or power plant installations. The annual cost of managing this invasion is USD 500 million [1].

2.2.2. Bacteria and Viruses

In addition to marine organisms, ballast water also carries viruses that may infect humans, such as *Vibrio cholerae* and *Escerichia coli*. The transport of bacteria and viruses by shipping has triggered several outbreaks of epidemics. One such incident took place in 1991 when a strain of cholera that occurred only in Bangladesh was transported to Peru and the Gulf of Mexico. Transmission appears to have been initiated by the consumption of fish whose stomach contents included the strain and oysters that had filtered the bacterium. By 1994, at least 10,000 people had died in Peru from this pathogenic strain. A 1995 study examining 71 ballast water samples in areas of Canada and North America detected a 45% incidence of E-coli bacteria and an 80% incidence of enterococci samples [1].

2.3. Regulations

In 2004, the IMO adopted the "International Convention for the Control and Management of Ships' Ballast Water and Sediment" or Ballast Water Management (BWM). This convention stipulates that every ship over 400 GT (Gross Tonnage) should have a Ballast Management Plan, and it is divided into two parts in order to facilitate the transition of older ships [1,4].

The first part of the convention is Regulation D-1. Regulation D-1 states that once water is taken from the port, it must be replaced with ocean water if allowed under the following regulation: The vessel must be located at least 200 nautical miles (nm) from the nearest shore and at a depth of at least 200 m. If this is not possible, the vessel must be at least 50 nm from the nearest shore. The minimum permissible depth must remain at 200 m. Where this cannot be achieved, depending on the geographical area, regulations with permitted ballast exchange locations may have been established by the State that owns the waters concerned. Ballast exchange may not take place if the safety of the ship is not confirmed and if the ship is adrift or delayed.

The second part of the Convention is Regulation D-2, which concerns ships fitted with a ballast water treatment system. Once the ballast has been processed, a sample should be taken so that it can be safely discharged. Discharge will take place provided that the content of harmful organisms does not exceed the permitted limits. The Convention came into full force in 2017 when it was ratified by 35% of the world's merchant shipping capacity, or at least 30 states, as set out by the organization [1,4].

3. Ballast Water Risk Parameters

In the following, the main parameters associated with the ballast water risk assessment system are presented and described in detail. These parameters have been carefully chosen to encompass key factors known to influence the environmental impact of ballast water discharge, ensuring a thorough evaluation of potential risks and hazards.

Tank Capacity: The capacity of the tank receiving the ballast water affects the number of microorganisms and fauna that will be transported from one port to another. The influence of the tank's capacity on the system is a medium risk; so, if the tank has a capacity of less than 1500 m^3, the risk is reduced, whereas it increases for high capacity (over 5000 m^3).

Ballast receptor filter clarity: The first stage of ballast water treatment is carried out by filtering the water as it enters the tank in order to retain large amounts of sediment and organisms. Cleaning is carried out internally with greater frequency but also externally by divers with less frequency because of the complexity of the process [33].

Since the filter through which the ballast is pumped is not freshly cleaned, the conditions for the growth and transport of microorganisms become favorable. Failure to maintain cleanliness automatically escalates the risk. In cases where it is clean, the risk is calculated based on the other parameters.

Harbor water turbidity: During ballasting, the personnel perform a visual check for the harbor's water turbidity. High turbidity is a reliable indicator of sediment levitation and sediment, which is usually rich in microorganisms, viruses, and bacteria. It is also a possible indicator of organic substance presence, like algae, which is linked to the red tide that causes respiratory system infections [34]. Though turbidity may be a reliable indicator for high concentrations of harmful organisms, it does not define the final outcome. It is used as an input that affects the risk, but not in an absolute manner.

Ship construction date: In the legislation concerning the entry force of the Ballast Water Management System, a distinction is made in the margins of compliance with the regulation, according to the following three cases: ships built before 2009, between 2009 and 2012, and after 2012. Their margins are related to the date of construction and to what extent preceded the entry into force of the regulations. These specific dates are used to take into account possible pipe failures or possible leaks. This particular variable affects the risk in combination, raising the risk when the ship is out of date. However, this does not imply an increase in risk if other variables are ideal [7].

Tank clarity before ballasting: Ballast tanks contain large quantities of sediment and organisms on their bottom, which act as "hatcheries" for particles either alive or in dormant phase [35]. An unclean tank may also contain residues from an undetected oil spill. Similar to water turbidity, this system input is primarily based on observational assessment. The internal tanks are cleaned by the ship's staff at regular intervals. The input values are shaped by factors such as the workload leading to the extension of the cleaning interval or the ballast management practices followed by the ship. A thoroughly cleaned tank reduces the risk of bacterial proliferation and the interaction of harmful organisms. Conversely, a tank with large amounts of sediment jeopardizes effective compliance with Regulation D-2 [36].

Distance from sewage outfalls: If sewage discharges are found near the ballasting site, there is a risk of pumping and carrying viruses and bacteria that may infect humans. As these organisms are dispersed in the water, it is necessary that the distance of the ship during the ballasting is increased. Based on research carried out in New Zealand and reported in [37], the content is still increased at a distance of 3.5 km; however, the first signs of a significant decrease are noted at 8 km. This is one of the most heavily weighted variables; therefore, if the distance is considered small, the risk is automatically considered high, and if the distance is considered moderate but combined with moderate risk variables, the risk is still high.

Distance from dredging operations: Dredging operations affect the aquatic ecosystem by the increased flow of sediment at higher levels from the bottom, which can travel in sufficient density up to about 1300 m. Particularly because of bottom excavation, organisms emerge that would not normally travel through the ballast. It holds equal significance to the distance from sewage outlets, as it overmultiplies the organisms contained in the ballast [38].

Weather conditions: Ballasting is performed mainly for stability reasons. Adverse weather conditions, on the one hand, constitute a risk to the integrity of the ship, as strong waves make it difficult to proceed to ballasting and, on the other hand, constitute the increased presence of sediment due to sea turbulence. Their main influence on the degree of risk concerns the cases that are unfavorable when the risk increases. In the medium and low category, the risk is adjusted in combination with the other variables.

Human error probability: The human error factor is defined by the staff. It is determined by fatigue, as well as by the experience of the staff in the respective post. For example, tasks, such as closing dump valves or performing sounding and ullage tests, are likely to be skipped in situations of increased fatigue or insufficient training. In cases where these factors are low, the risk is influenced by the remaining variables. However, if the factors are high, then the risk automatically becomes high. If they are moderate, they tip the scale towards increasing risk.

Depth during exchange: According to Regulation D-1, the minimum allowable exchange limit is 200 m. However, a depth of 2000 m appears to provide the most effective reduction in transported organisms [31]. At smaller depths, the risk increases dramatically, especially considering that exchanging ballast water below 200 m is forbidden by IMO. In moderate depths, the other inlets are taken into account, although the risk shifts to a higher value. If the depth is considered safe enough for the water not to contain many organisms, the risk is determined by the values of the rest variables.

Maritime traffic: When departing from a port, it is likely that there will be an increase in traffic. It is advisable not to carry out ballast exchange during this period, as the process may take several hours. If the congestion is not sufficient to prevent ballast exchange, the water in that location may contain more organisms than expected because of the other ships exchanging ballast.

Distance from coast: As per Regulation D-1, vessels are allowed to perform ballast exchange at least 200 nm away from the coast. However, if conditions are unfavorable, ballast exchange is only permitted if the vessel is at least 50 nm away from the coast [31]. The risk of ballast exchange increases significantly when the distance from the coast is short and is moderately affected by other variables when the distance is moderate. When the distance is long, the risk depends on other factors. A small distance increases the risk, while a moderate distance affects the risk with respect to the other variables, and a long distance has no negative impact on risk.

Harmful organism concentration: Under the D-2 ballast water treatment regulation, water sampling after chemical treatment is mandatory. Since it is possible for harmful organisms to have high concentrations even after the chemical treatment, this measure is taken in order to determine whether the water poses a threat to the aquatic ecosystem. This standard imposes the limits presented in Table 1.

Table 1. The limits according to the D-2 ballast water treatment regulation.

Organisms	Limits
Toxigenic *Vibrio cholerae* (O1 and O139)	<1 cfu*/100 mL ή <1 cfu*/gr (wet weight) of zooplankton sample
Escherichia coli	<250 cfu*/100 mL
Intestinal enterococci	<100 cfu*/100 mL

* cfu: Colony-forming unit.

This variable has a direct influence on the degree of risk, as samples are taken after chemical treatment and before disposal. Often, if the limits are exceeded, there is no time for further treatment. In these cases, the regulation indicates that the ballast should be delivered to a licensed reception facility on land [7].

Oxidant concentration: In order to ensure that the microorganisms extracted do not exceed the permissible limits, chemical purification is often used. The chemical residues generated by this process, most often chlorine by-products, pose a risk to the marine ecosystem if discharged into the sea. The by-products are measured by means of a sensor. If they exceed the maximum permissible limit set by the International Maritime Organization (IMO), which is <0.1 mg/L, appropriate measures should be taken. Depending on the type of chemical treatment, other harmful by-products such as hydrogen peroxide (<1000 μg/L) or peracetic acid (<500 μg/L) may also be produced [3,31,39]. As the amount of any harmful chemical above the threshold automatically increases the risk of discharge, the risk follows a path similar to the value of the variable in question.

Salinity difference: According to research, the salinity difference between the deposition water and the ballast water limits the chances of microorganisms surviving after discharge, as these differences seem to shock the organisms [40,41]. This input affects the risk combined with the rest of the inputs.

Temperature difference: Similarly to the salinity difference, the impact of the temperature difference is also studied. Although it did not play as decisive a role as salinity, it did have a notable effect, as organisms transitioning to waters with a large temperature difference are subject to "shock" and their chances of survival are reduced [40]. Similarly, as an input, it does not affect the degree of risk proportionally, but by accounting for the other variables.

Sailing days with ballast: Studies suggest that increased sailing days with ballast may help to reduce the organisms it contains [1,42]. Given that it does not inherently serve as a protective measure, it does not significantly dictate the degree of risk. However, when multiple sailing days are considered in conjunction with other parameters, the risk is diminished.

Exchanged water amount: According to Regulation D-2, a minimum of 95% of the tank must undergo ballast exchange. While it is generally considered safer to exchange three times the volume of the tank, this may not always be possible due to factors such as time, construction, and conditions. In some cases, ballast exchange may be impossible altogether. This process is important for risk assessment as the microorganism content in the open sea is significantly lower than in ports [43]. If no exchange occurs, the risk is automatically considered high. However, in cases where a significant exchange has taken place, other factors come into play to determine the level of risk.

4. The Fuzzy Ballast Water Risk Assessment System

The paper aims to develop a fuzzy risk analysis model to assess the environmental risk associated with ship ballast water management operations. Using a fuzzy model for ballast water risk assessment allows for a realistic representation of uncertainty and nonlinear relationships in environmental data, thus improving accuracy. It enables the incorporation of qualitative knowledge, enhancing reliability, and facilitating comprehensive decision-making in maritime environmental management. Fuzzy logic, known for its ability to handle vague and imprecise information, offers a promising approach to address this challenge. In the following subsections, the fundamental fuzzy concepts are presented, and the fuzzy ballast water risk assessment system is designed.

4.1. Fundamental Concepts on Fuzzy Logic

When employing mathematical logic to solve problems, binary logic is the solution when the answer is "true" or "false", "yes" or "no", and "0" and "1". Fuzzy logic entered the branch of mathematical logic to provide a solution to questions where the answer could not be so absolute. It reflects the complexity that underlies human life and allows for answers that lie somewhere in the middle. One of the properties of fuzzy logic is that it manages to capture the human reasoning process in mathematical terms, placing it in the realm of computational intelligence and, by extension, artificial intelligence [44].

Classical sets aim at the typological representation of a logical concept. For a set X and an element y, the characteristic function of set X would be:

That is, y either belongs or does not belong to X.

$$I_x(y) = \begin{cases} 1, & y \in X \\ 0, & y \notin X \end{cases} \quad (1)$$

When Zadeh [45] introduced the notion of a fuzzy set, he tried to represent sets with fuzzy rather than strict boundaries in the same way, as classical sets could not convey everyday verbal concepts such as "it is not very cold", which is a phrase that mathematics would require to have clear boundaries (either it is cold or it is not). So, the membership function of a fuzzy set can take any value between zero and one and is determined as $\mu_x(y) \in [0, 1]$, where:

$\mu_x(y) = 1$ indicates that y fully belongs to X;
$\mu_x(y) = 0$ indicates that y does not belong to X;
$0 < \mu_x(y) < 1$ indicates that y partially belongs to X.

The membership function $\mu_x(y)$ equals the degree of membership of element y in set X, i.e., a value between 0 and 1 expressing whether y belongs to set X. The membership function is defined based on the probability of a value occurring, measurements, estimates, or procedures involving neural networks.

The fuzzy rule is the means used to connect fuzzy sets and capture the knowledge the author has about the system he is composing. It is divided into the following two parts: the hypothesis and the decision. In the rule:

"If x is A, then y is B"

where the member "If x is A" represents the hypothesis, while "then y is B" represents the decision.

By combining the input data and the rules, once the output is calculated, the system will proceed to defuzzification following the next three steps including fuzzification, rule setting, and defuzzification.

4.2. The Designed Fuzzy System for the Ballasting Process

The ballasting process poses numerous risks to the marine ecosystem. To address these risks, the International Maritime Organization has established two main regulations as follows: ballast water exchange and ballast water treatment. While these regulations can reduce the risks, they do not entirely eliminate them. The system developed in this paper aims to assess the environmental risk by considering the contributing conditions. The aim of this work is also to compile all the information into one system so that the result will reflect the actual degree of risk as closely as possible.

Because of the substantial amount of information gathered, a fuzzy system with numerous inputs could be dysfunctional. Thus, it was considered that decomposing the system into three different fuzzy systems would utilize the information obtained in a functional manner.

The following three subsystems are related to the three ballasting processes:

1. Fuzzy ballasting system;
2. Fuzzy ballast exchange system;
3. Fuzzy de-ballasting system.

By decomposing the system, the environmental risk can now be assessed for each of the ballast processes separately. The inputs for the proposed system were derived from system parameters obtained from published studies investigating the contents of ballast tanks, as well as studies evaluating these contents under extreme conditions to assess organism and microorganism resistance.

For better understanding, an example is given. Consider a vessel traveling from a port known for high levels of sediment in its waters (affecting the ballasting process) to an area requiring a deep-sea ballast exchange (influencing the ballast exchange process), and finally, to a destination with strict environmental standards for discharged water (impacting the de-ballasting process). The partitioned subsystems allow for each of these stages to be evaluated individually, accounting for the specific conditions and risks present at each step. For instance, the ballasting subsystem would assess the risk based on high sediment levels, the ballast exchange subsystem would evaluate the feasibility and effectiveness of deep-sea exchange, and the de-ballasting subsystem would ensure compliance with the destination's environmental standards.

By partitioning the model, we ensure that each stage's unique conditions are accurately represented and managed, enhancing the model's overall effectiveness and operational utility in real-world scenarios. This approach not only provides a more comprehensive risk assessment but also offers targeted insights that can inform more precise and effective ballast water management strategies.

For the construction of the fuzzy ballast water risk assessment system, 19 input variables (described in Section 3) are imported. Then, the fuzzy ballast water risk assessment system determines three output variables as follows: ballasting risk, ballast exchange risk, and de-ballasting risk. All three outputs expressing the risks are represented by three linguistic terms as follows: low, medium, and high. Low risk suggests that discharging the ballast water into the destination port is considered safe for the marine ecosystem.

Medium risk suggests that a discharge should be performed with caution. High risk indicates that ballast water should be given for discharge in a reception facility on land [8].

This work was implemented through MATLAB programming through the Fuzzy Logic Toolbox. For the construction of the overall fuzzy system, three Mamdani fuzzy inference systems were used with a total of 18 inputs and three outputs. For the implemented systems, the min-operator was applied for implication, the max-operator was applied for aggregation and the centroid method was applied for defuzzification. The decision-making process is governed by a rule base consisting of a set of IF–THEN rules derived from expert knowledge. Each rule combines one or more linguistic variables representing input parameters related to ballast water management with linguistic terms denoting specific risk levels. For example, a rule might state "*IF the tank's clarity is high AND the distance from sewage outfalls is small, THEN the ballasting risk is high*". These rules encapsulate the qualitative relationships between input variables and output risk levels, allowing the model to make informed decisions based on the available information.

Figure 2 depicts the ballast water risk assessment architecture with an overall presentation of the fuzzy system, where three fuzzy subsystems are interconnected. Each subsystem consists of a different number of inputs and one output. In the next subsections, an analytical description of these three subsystems is presented.

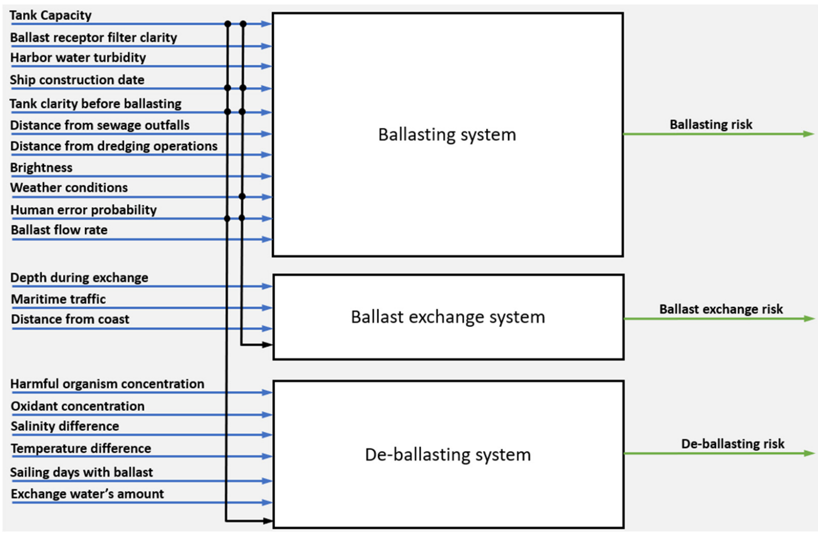

Figure 2. The ballast water risk assessment architecture.

4.2.1. The Fuzzy Ballasting System

Ballasting is the process whereby water is pumped out of the harbor alongside the release of the weight of the cargo, mainly for stability reasons. The ecological impact of the ballast water processes is determined by various conditions. The inputs used reflect the conditions that may affect the quality status of the water directly or indirectly before and after it is pumped from the harbor.

The first fuzzy subsystem block is the fuzzy ballasting system that outputs the ballasting risk, as shown in Figure 3. It takes the following eight variables as inputs: (1) tank capacity, (2) ballast receptor filter clarity, (3) harbor water turbidity, (4) ship construction date, (5) tank clarity before ballasting, (6) distance from sewage outfalls, (7) distance from dredging operations, and (8) human error probability.

Tank capacity is fuzzified using three linguistic values (Small, Medium, Large) represented by triangular membership functions, as depicted in Figure 4a. Similarly, the ballast receptor filter clarity is fuzzified using three linguistic values (Unclean, Medium Clean, Clean) expressed by triangular membership functions (Figure 5). The fuzzification of the rest of the input variables is presented in Figure 4a–h. It is noted that the range for certain input variables falls within [0, 1], indicating a percentage (0–100%) of a maximum value.

The output (ballasting risk) of the fuzzy subsystem was fuzzified, as shown in Figure 4i. A total of 62 fuzzy rules are constructed for this system (please refer to Appendix A for more details).

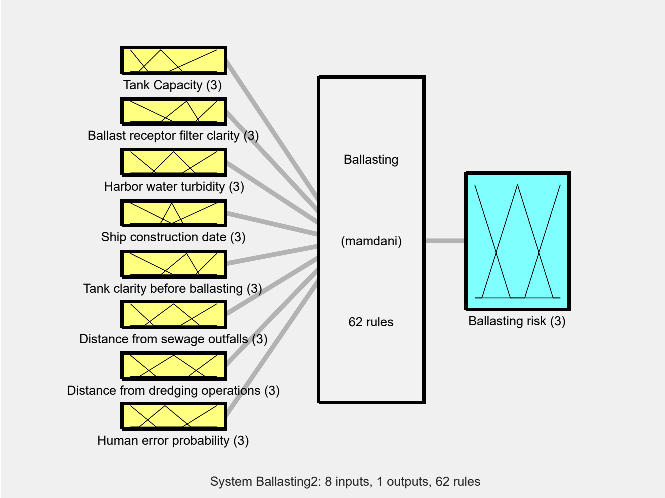

Figure 3. The fuzzy ballasting system.

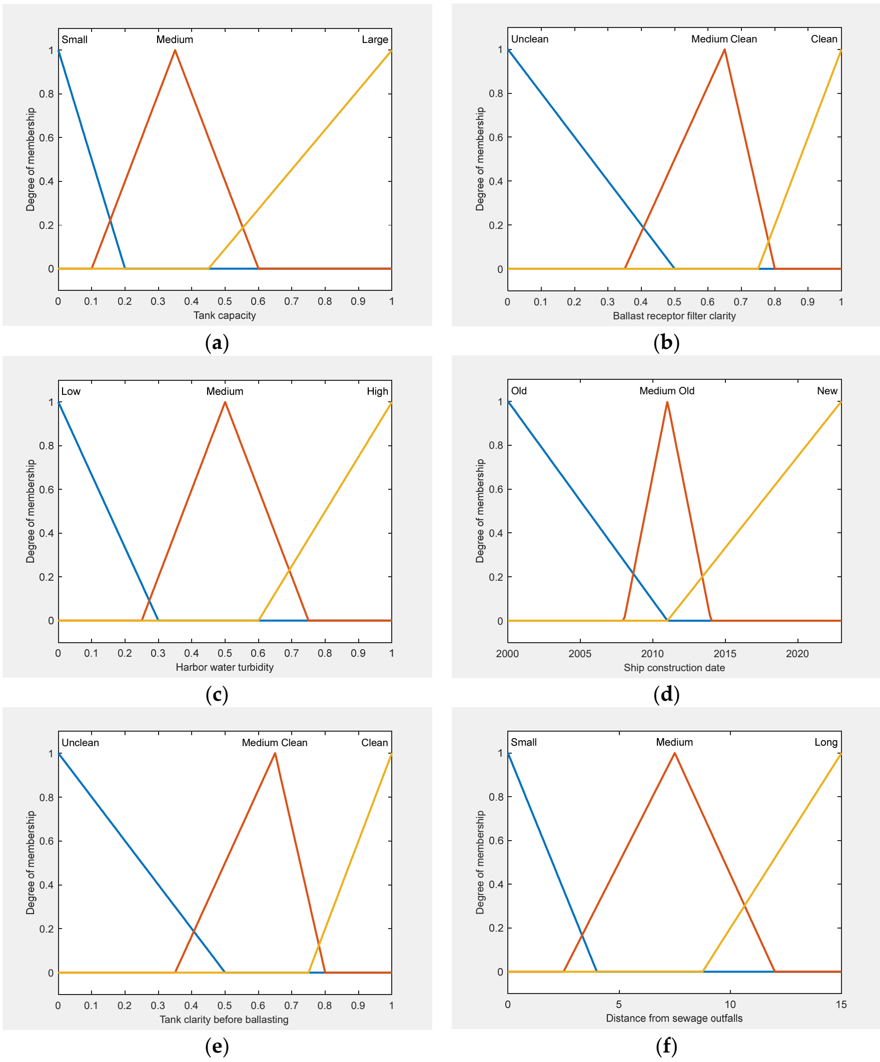

Figure 4. *Cont.*

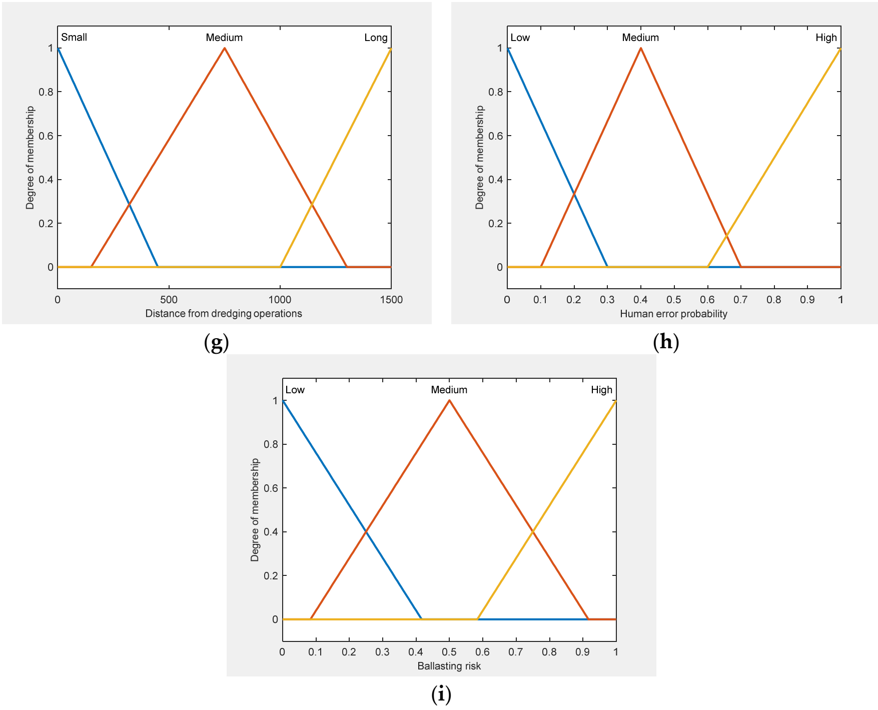

Figure 4. Membership functions for (**a**) tank capacity, (**b**) ballast receptor filter clarity, (**c**) harbor water turbidity, (**d**) ship construction date, (**e**) tank clarity before ballasting, (**f**) distance from sewage outfalls (nm), (**g**) distance from dredging operations (m), (**h**) human error probability, and (**i**) ballasting risk.

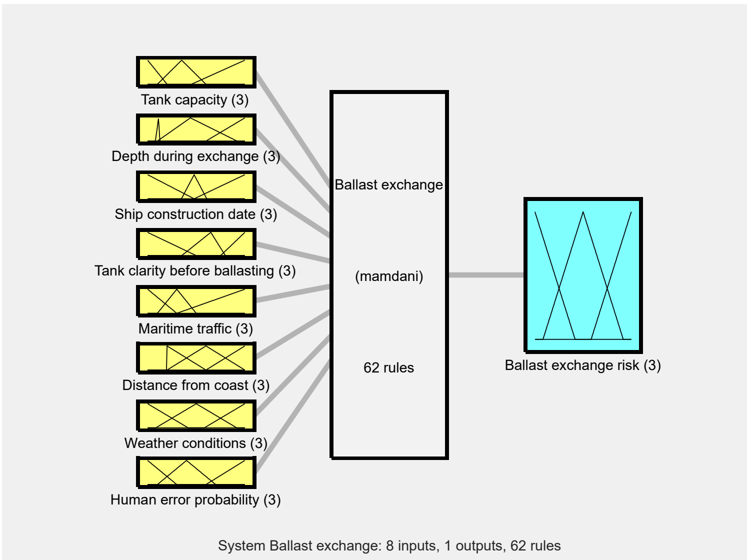

Figure 5. The fuzzy ballast exchange system.

4.2.2. The Fuzzy Ballast Exchange System

Ballast exchange is the process mandated through Regulation D-1, aiming at decreasing the organisms and sediment transported to the next port. For the ballast exchange to effectively mitigate the risk, it must be carried out under favorable conditions. The second fuzzy subsystem block is the fuzzy ballast exchange system that outputs the ballast exchange risk, as shown in Figure 5. It takes eight variables as inputs: (1) tank capacity, (2) depth during exchange, (3) ship construction date, (4) tank clarity before ballasting, (5) maritime traffic, (6) distance from coast, (7) weather conditions, and (8) human error probability.

The membership functions expressing the inputs are represented by triangular fuzzy sets. Most of them are represented in Section 4.2.1; the rest are omitted because of space limitations. It is noted that the linguistic terms for depth during exchange are Small–Medium–Long, for maritime traffic, they are Low–Medium–High, and for distance from the coast, they are Small–Medium–Long. A total of 62 fuzzy rules are generated for this system, and 9 of them are presented in Appendix B.

4.2.3. The Fuzzy De-ballasting System

De-ballasting is the release of the water contained in the ballast tanks at the discharge port. Throughout the de-ballasting process, certain circumstances may influence the survival rate of organisms in the water or potentially result in ecological impacts if not controlled on time. The third fuzzy subsystem block is the fuzzy de-ballasting system that outputs the de-ballasting risk, as shown in Figure 6. It takes the following 10 variables as inputs: (1) tank capacity, (2) harmful organisms concentration, (3) oxidant concentration, (4) salinity difference, (5) temperature difference, (6) ship construction date, (7) tank clarity before ballasting, (8) sailing days with ballast, (9) exchanged water amount, and (10) human error probability.

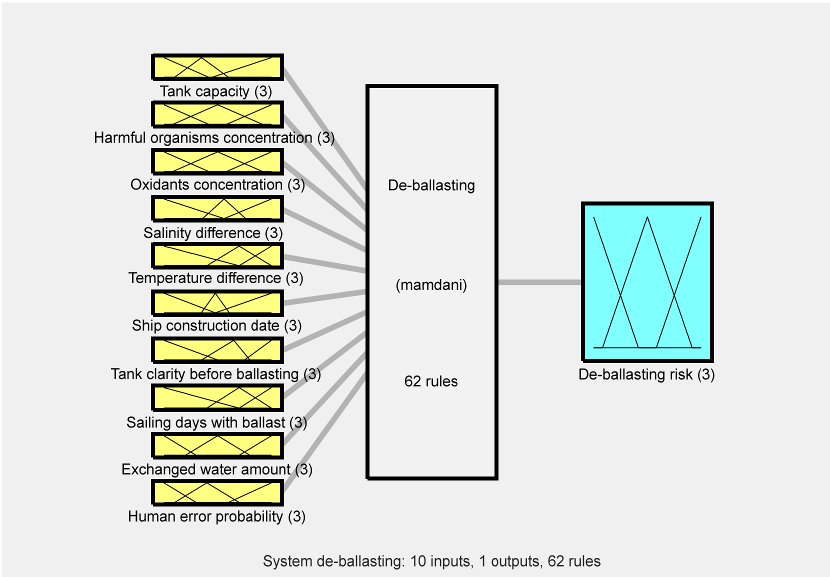

Figure 6. The fuzzy de-ballasting system.

The membership functions expressing the inputs are represented by triangular fuzzy sets, but they are omitted because of space limitations. It is noted that the linguistic terms for harmful organism concentration are Low–Medium–High; for oxidant concentration, they are Low–Medium–High; for salinity difference, they are Small–Medium–High; for temperature difference, they are Small–Medium–High; for sailing days with ballast, they are Few, Medium, and Many; and for exchanged water amount, they are Small–Medium–Long. A total number of 62 fuzzy rules are constructed for this system, and 9 of them are indicatively presented in Appendix C.

5. Simulation Results for the Ballast Water Risk Assessment System

To verify the effectiveness of the proposed fuzzy system, a test case for each subsystem is presented in the following subsections. This test case involves crisp values for the input variables and provides crisp values for the three outputs of the fuzzy control system.

5.1. Ballasting Results

In Figure 7, the fuzzy sets of inputs and outputs organized by rules are displayed. The resulting visualization is dependent on the given inputs. The final column reflects the fuzzy output, specifically the ballasting risk, while the bottom of the table presents a graphical representation of the outcome. For the test case including a tank capacity of 0.516 (=2580 m^3), ballast receptor filter clarity of 0.62, harbor water turbidity of 0.71, a ship constructed in 2017, a tank clarity of 0.826, 12.56 km away from sewage outfalls, 1210 m away from dredging operations, and a human error probability of 0.132, the attained ballasting risk is 0.62. Figure 8 presents 30 out of 62 fuzzy rules using these input data values. The yellow plots show the membership functions for the inputs and the blue plots show the membership functions for the output. Each fuzzy rule is represented by a shaded region expressing the activation for the specific input values.

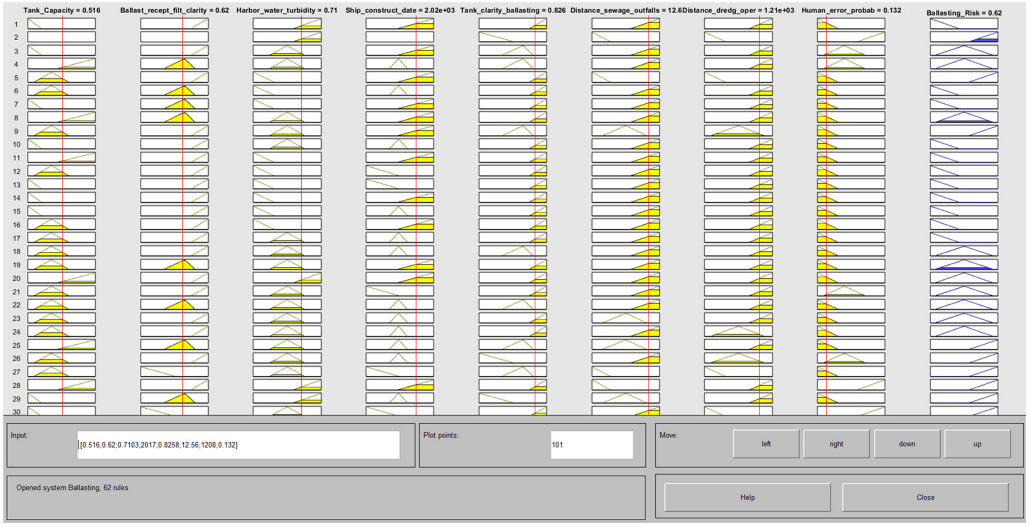

Figure 7. Fuzzy rule activation for ballasting.

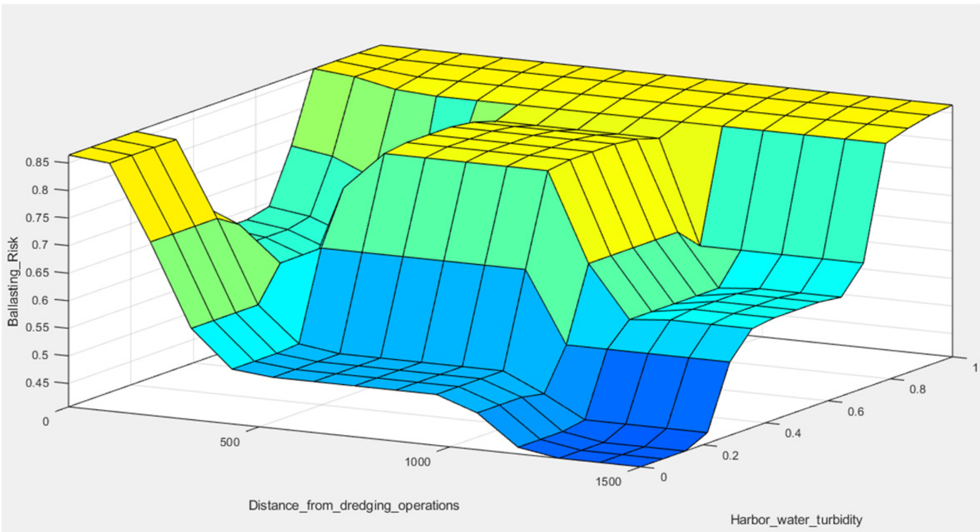

Figure 8. Surface plot indicative of the correlation between the inputs and the ballasting risk.

For the harbor's water turbidity, the given value belongs to "Medium" and "High". This value is associated with high turbidity in the recipient harbor. Water clarity is currently assessed through visual inspection by a ship's personnel. However, research suggests that clarity is a reliable indicator of sediment and the presence of certain organisms. Sediment increases the chances of blockage in the pumping and treatment systems; hence, it is considered a highly significant variable [34].

The tank's clarity before ballasting is set to a value belonging to "Clean". An uncleaned tank may contain additional microorganisms through which new organisms introduced will thrive or may contain residues from an undetected oil spill. It therefore significantly increases the risk [36]. In the case that a tank is clean, the risk is defined by the other variables.

Distance from sewage outfalls is set to a value belonging to "Long". If the ship is located near sewage outfall during ballasting, the ballast water is likely to contain viruses that infect humans and aquatic organisms, which leads to a significant risk increase [37]. In the case where there are no sewage outfalls near the ballasting area, the risk is defined by the other variables.

The value given to the distance from dredging operations is set to a value expressing both "Medium" and "Long". Dredging operations lead to increased sediment and harmful organism concentrations, making the ballast water harder to disinfect and creating harmful conditions for the ship's ballast management system. When in close proximity, the risk automatically increases to "High" [38]. In the case where there are dredging operations taking place somewhat far from the ballasting area, the risk is defined mainly by the other variables.

The human error probability is defined as belonging to both "Low" and "Medium". There are numerous consequences of potential human error during shipboard inspection and prevention procedures. As a variable, it largely determines the risk, as other conditions may be moderate to good, but may be reversed by a misjudgment or an oversight. In this case, it does not affect the risk drastically, but the medium part tips the scale towards a higher risk.

For these input values, the resulting output is 0.619, meaning that the risk is considered more "Medium" than "High". The input variables that led to this outcome are the "Medium Clean" ballast receptor filter's clarity and the "Medium to High" turbidity, while the distance from dredging operations and the human error probability affect the risk in a non-drastic manner.

Figure 8 shows the surface plot between the ballasting risk and the inputs, which indicates the correlation between the distance from dredging operations and the harbor's water turbidity in combination with the ballasting risk (expressed by different colors). Warmer colors like r yellow indicate higher activation levels, while cooler colors like blue indicate lower activation levels. As shown, as the distance from dredging operations increases, implying increased organisms in the ballast, and as the harbor's water turbidity increases, implying a high concentration of harmful organisms, the higher the de-ballasting risk becomes.

The results from the fuzzy ballasting system demonstrate the model's capability to capture the risks associated with the ballasting process, addressing our first research question on the application of fuzzy logic. This showcases the innovation of our approach in accommodating the uncertainties inherent in environmental factors and ship operations.

5.2. Ballast Exchange Results

Figure 9 illustrates the case consisting of a tank capacity of 0.044 (= 220 m^3), a depth of 2150 m during the exchange, a ship constructed in 2021, a tank clarity of 0.884, maritime traffic of 0.228, 211 m away from the coast, weather conditions set at 0.861, and a human error probability of 0.076. The ballast exchange risk provided is 0.182.

The depth during exchange is set to a value belonging to both "Medium" and "High" fuzzy sets. The relevant legislation imposes a minimum exchange depth of 200 m. In some cases, a depth of 2000 m is proposed as the ideal depth [5]. The value of the tank's clarity before ballasting belongs to the fuzzy set "Clean". An uncleaned tank may contain additional microorganisms through which new organisms introduced will thrive or may contain residues from an undetected oil spill. It therefore would increase the risk significantly, having a neutral presence for the outcome of this test case [36].

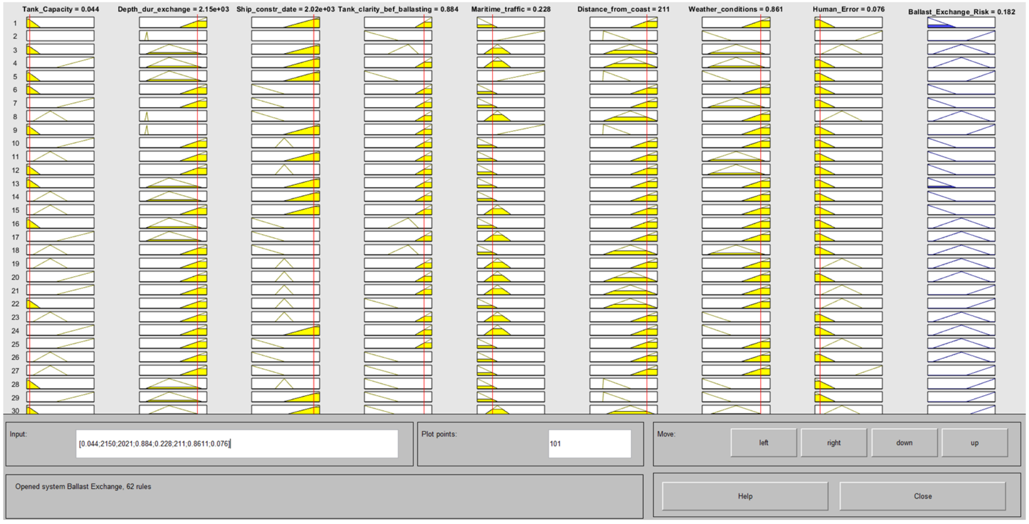

Figure 9. Fuzzy rule activation for ballast exchange.

The maritime traffic value is set to a value that belongs to "Low" and "Medium" since ballast exchange may be prevented for safety reasons when high traffic occurs. This instruction is often given in order to ensure the integrity of a ship.

The distance from the coast is set to a value that belongs to "Medium" to "High". As there are specifications for the legal ballast exchange distance from the coast, the value of "Small" would refer to a distance between the recommended 200 nm and the legal 50 nm, which is considered to be highly hazardous because of the microorganism and sediment content of the water [6].

The output value of this test case is 0.182, which is considered a "Low" ballast exchange risk. This result arises because of the absence of high-risk parameters. Those with some level of medium risk, when combined, do not significantly escalate the risk, particularly given the small capacity of the tank, which implies that its contents pose no substantial threat to the ecosystem.

Figure 10 shows the surface plot between the ballast exchange risk and the inputs, which indicates the correlation between the distance from the coast and the maritime traffic in combination with the ballast exchange risk. As depicted, as the distance from the coast decreases, and as the maritime traffic increases, implying more organisms due to higher exchanging ballast from other ships, the higher the ballast exchange risk becomes.

The findings from the ballast exchange analysis are linked to our second research question concerning the identification of key risk parameters. We discuss how these results highlight the importance of certain parameters, such as tank capacity and exchange depth, thus contributing to a more refined understanding of risk factors in ballast water management.

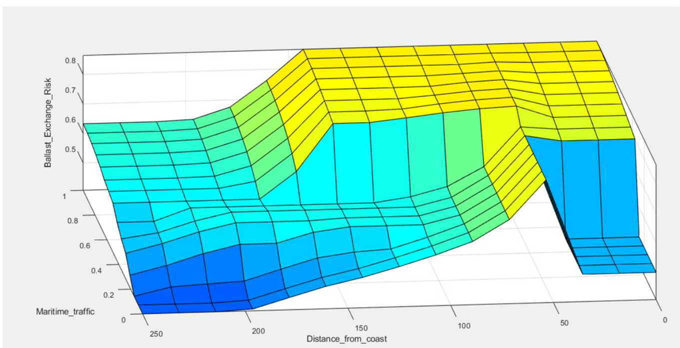

Figure 10. Surface plot indicative of the correlation between the inputs and the ballast exchange risk.

5.3. De-Ballasting Results

For the test case of a tank capacity of 0.947 (4850 m^3), a concentration of harmful organisms of 0.704, oxidant concentration set to 0.25, a salinity difference of 3.21 (=20,544 ppm), a 20.2 °C difference in temperature, a ship constructed in 2010, a tank clarity of 0.684, sailing 20 days with the same ballast water in the tank, having exchanged an amount of 0.40 (=122%) of the ballast water volume, and a human error probability of 0.378, the yielded de-ballasting risk is equal to 0.68 (Figure 11).

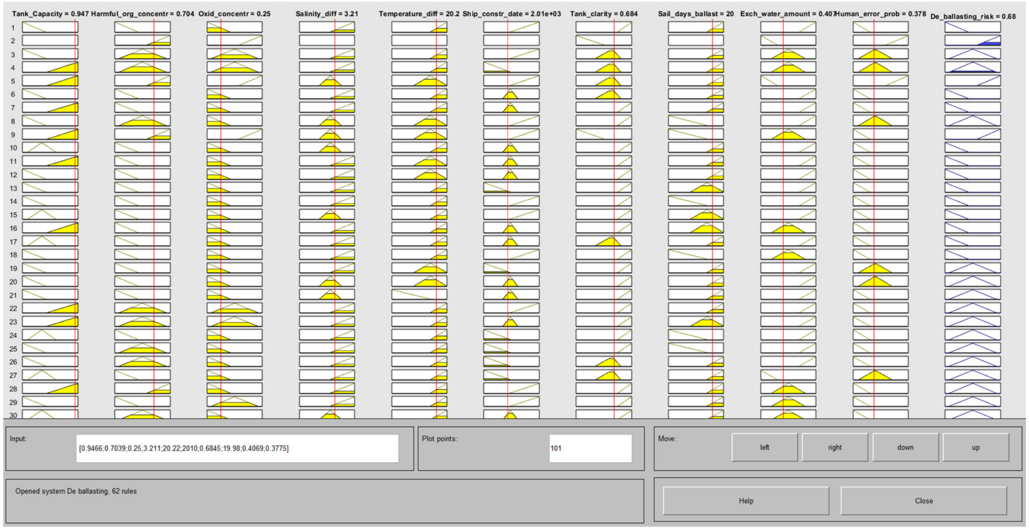

Figure 11. Fuzzy rule activation for de-ballasting.

Harmful organism concentration is set to a value corresponding to both "Medium" and "High" and concerns the content after chemical cleaning. If the organisms remain at a high concentration, ballast discharge is to be prohibited [7]. In this case, the contents are primarily considered as having a "Medium" concentration, which is lower than the suggested limits.

Oxidant concentration is set to a value linked with "Low" and "Medium" fuzzy sets. If the chemicals used to remove harmful organisms are discharged into the sea, the environment may be contaminated unless neutralization is carried out. Ships are required to carry out sampling before discharging ballast water [39].

The exchanged water amount is considered to be "Medium". Zero ballast exchange implies ballast teeming with microorganisms. In cases where it is not possible because of weather conditions, not exchanging ballast water is considered legal. However, the IMO considers 95% exchange of the volume to be necessary, while the 300% flow-through method is recommended [43,46]. In this case, the amount of exchanged water is at least the necessary percentage.

The de-ballasting risk of this test case is yielded equal to 0.689, which is considered to be "Medium" to "High". The variables that led to this outcome are the medium concentrations of oxidants and harmful organisms combined with the medium salinity and temperature differences. Reducing human error probability and utilizing smaller tank capacities would lower the risk level.

Figure 12 shows the surface plot between the de-ballasting risk and the inputs, which indicates the correlation between the human error probability and the exchanged water amount in combination with the de-ballasting risk. The surface confirms that as the human error probability increases, implying increased potential human error due to fatigue, and as the exchange water amount decreases, the higher the de-ballasting risk becomes.

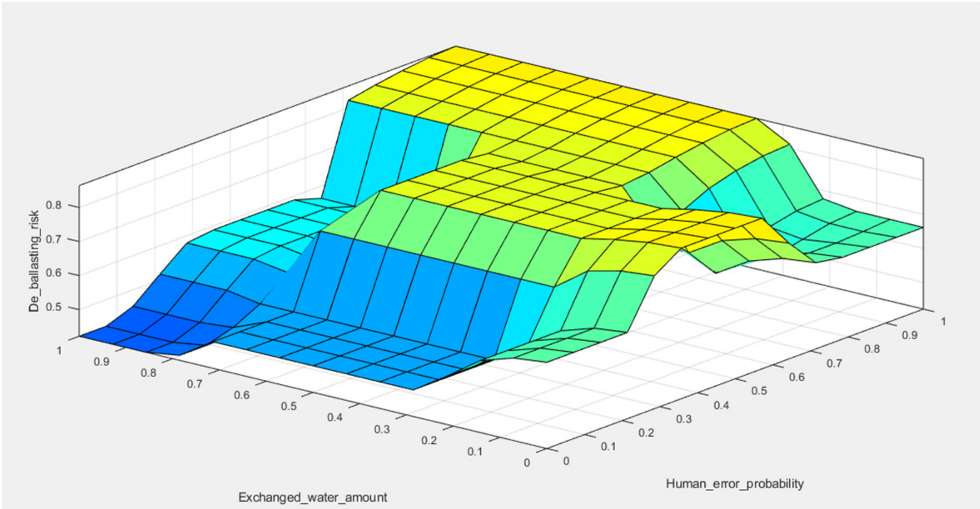

Figure 12. Surface plot indicative of the correlation between the inputs and the de-ballasting risk.

The de-ballasting results are connected to our goal of improving decision-making processes in maritime operations, as posed in our third research question. We elaborate on how these findings offer insights into the final stage of the ballast water management cycle and its implications for environmental sustainability in maritime transport.

5.4. System Validation

The proposed fuzzy logic-based model for ballast water risk assessment offers significant applicability in handling the complexities and uncertainties inherent in maritime environmental management thanks to its flexible and intuitive framework that can be tailored to diverse conditions and integrated with existing management systems. However, the approach is not without its weaknesses. For example, it relies heavily on the quality of input data, and the subjectivity involved in designing membership functions and rule sets can introduce variability. Additionally, the complexity of the rule base and the computational demands of the model may pose challenges, particularly for large-scale or real-time applications. Addressing these weaknesses requires careful calibration, validation, and possibly simplification of the model to ensure its practical utility in enhancing maritime environmental practices.

Table 2 presents nine cases of inputs and the corresponding estimated risk associated with the ballast water procedure. Test cases 1–3 indicate a relatively low calculated risk, while cases 4–6 are categorized as medium risk, and cases 7–9 exhibit high-risk outcomes. These results are considered representative of the study conducted, showing the expected increase in risk when high-importance variables are discredited. Particularly, in the first three cases, it is observed that the risk remains low when the distances from dredging operations and sewage outfalls are small, the probability of human error is reduced, the harbor water is relatively clear, and the tank along with the filter has been cleaned. Although the values of the tank capacity and the construction date have been set at various levels, the risk remains low since the most decisive variables are at optimal levels. For test cases 4–6, corresponding to moderate risk, variables such as the turbidity of the water in the harbor, the probability of human error, and the size of the tank (cases 4 and 5) were set to moderate values. Although distances from dredging operations and sewage outfalls are not considered to be of increased risk, the moderate risk example shows the contribution of the other variables to the system. Finally, in the high-risk cases (cases 7–9), it appears that only two variables of high significance are needed to influence the result, regardless of whether other variables received the optimal value.

Table 2. Input–output data for the fuzzy ballasting system.

S/N	INPUTS								OUTPUT
	Tank Capacity	Ballast Receptor Filter Clarity	Harbor Water Turbidity	Ship Construction Date	Tank Clarity before Ballasting	Distance from Sewage Outfalls	Distance from Dredging Operations	Human Error Probability	Ballasting Risk
1.	0.108	0.924	0.21	2018	0.828	12.06	1220	0.076	0.177
2.	0.388	0.84	0.29	2003	0.924	10.74	1089	0.1	0.202
3.	0.82	0.794	0.123	2012	0.884	14.34	1106	0.04	0.197
4.	0.54	0.804	0.425	2009	0.836	9.82	1173	0.148	0.448
5.	0.132	0.836	0.528	2014	0.628	10.86	1256	0.268	0.521
6.	0.612	0.732	0.274	2013	0.868	9.18	1113	0.244	0.588
7.	0.78	0.18	0.488	2020	0.38	3.06	363.1	0.14	0.818
8.	0.148	0.652	0.71	2017	0.092	10.26	886.9	0.316	0.86
9.	0.396	0.748	0.54	2010	0.639	5.68	446.4	0.516	0.795

Table 3 illustrates various data combinations and the outcomes of the fuzzy system regarding ballast exchange processes. The cases are categorized into three levels of risk as follows: low, moderate, and high, each comprising three instances. Within the low-risk scenarios, it can be observed that the optimal values of the high-risk variables determine the outcome. More precisely, when tank clarity is combined with distance from the coast, exchange depth, ideal weather conditions, and low probability of human error, the risk does not increase. However, in test case #2, human error could be considered at low to moderate probability, but the risk is mitigated by the small tank capacity and reduced traffic flow. In moderate-risk cases 4–6, there is some variance in the input values. In particular, in test case #4, although exchange depth and distance to shore are relatively low to moderate, the risk is also accounted for by the small tank size and the modern construction date of the ship, accounting for the other variables, some of which are at favorable levels. Similarly, in test case #2, with a relatively higher probability of human error and increased traffic, the risk is partially mitigated by optimal values of other inputs, yet it remains elevated because of the significance of these variables. Finally, in the last three cases, the ballast discharge is considered to be avoided since even with low-risk values for many variables, inputs with the highest contribution to the system are considered to pose potential harm to the environment.

Table 4 presents the results of de-ballasting with nine cases categorized as low, medium, and high risk, each comprising three instances. In test cases 1–3, low risk is determined by the optimal values taken by most of the variables, since all inputs except tank capacity and ship construction date are determinants for the result. In moderate-risk cases, even slight deviations from ideal values can escalate the risk, particularly when these deviations occur in combination with other variables. In case #4, the combination concerns the concentration of harmful organisms and chemicals with relatively moderate values of tank capacity and salinity and temperature differences. In case #5, the presence of a moderately clean ballast tank, coupled with a slightly elevated probability of human error, contributes to a higher difference compared with cases 4–6. Case #6 is primarily influenced by factors such as a larger tank, the likelihood of human error, and the ship's construction date. Lastly, the last three high-risk cases show that despite optimal values elsewhere, when certain high-importance inputs are assigned high-risk values, the discharge is considered dangerous.

Table 3. Input–output data for the fuzzy ballast exchange system.

S/N	INPUTS								OUTPUT
	Tank Capacity	Depth during Exchange	Ship Construction Date	Tank Clarity before Ballasting	Maritime Traffic	Distance from Coast	Weather Conditions	Human Error	Ballast Exchange Risk
1.	0.092	2190	2015	0.836	0.084	235	0.89	0.028	0.174
2.	0.138	2310	2007	0.923	0.124	221	0.93	0.24	0.186
3.	0.108	2270	2011	0.844	0.116	241	0.75	0.11	0.224
4.	0.236	1750	2019	0.838	0.172	209	0.79	0.084	0.398
5.	0.668	2010	2009	0.884	0.31	213	0.65	0.14	0.552
6.	0.788	2130	2013	0.82	0.428	159	0.877	0.22	0.576
7.	0.556	1710	2020	0.292	0.612	129	0.837	0.108	0.863
8.	0.14	542	2008	0.9	0.244	135	0.337	0.7	0.819
9.	0.58	1590	2014	0.828	0.172	107	0.647	0.404	0.729

Table 4. Input–output data for the fuzzy de-ballasting system.

S/N	INPUTS										OUTPUT
	Tank Capacity	Harmful Organism Concentration	Oxidant Concentration	Salinity Difference	Temperature Difference	Ship Construction Date	Tank Clarity before Ballasting	Sailing Days with Ballast	Exchanged Water Amount	Human Error Probability	De-Ballasting Risk
1.	0.15	0.131	0.123	4.19	21.94	2005	0.85	21.69	0.858	0.125	0.273
2.	0.383	0.18	0.074	4.63	22.67	2013	0.92	22.67	0.927	0.064	0.198
3.	0.413	0.23	0.191	4.34	23.65	2022	0.801	20.22	0.661	0.24	0.215
4.	0.5	0.267	0.23	3.70	17.77	2008	0.82	23.9	0.838	0.16	0.414
5.	0.36	0.35	0.65	3.64	18.26	2017	0.57	20.47	0.78	0.19	0.632
6.	0.606	0.18	0.26	3.06	20.22	2009	0.801	19.73	0.808	0.23	0.443
7.	0.79	0.38	0.49	1.35	14.34	2018	0.45	15.07	0.61	0.103	0.804
8.	0.69	0.60	0.378	3.11	18.01	2003	0.75	4.78	0.112	0.75	0.849
9.	0.59	0.93	0.33	2.57	19	2014	0.47	13.11	0.103	0.89	0.86

6. Conclusions

This research work introduces an innovative risk assessment model for ballasting operations within the maritime sector, incorporating fuzzy systems to mitigate pollution risks inherent in the crewing process. The primary objective of this work is to develop a fuzzy ballast water risk assessment system to account for environmental pollution. Information and empirical insights from actual conditions were acquired and utilized in constructing the system with the objective of accurately determining the real risk level.

By employing fuzzy logic, our approach offers a more effective and flexible framework that can accommodate the imprecise and variable nature of environmental and operational data in maritime settings. Partitioning the overall fuzzy model into three fuzzy subsystems (ballasting, ballast water exchange, and de-ballasting) makes the model more operational and representative of the processes. The proposed fuzzy model provides outputs including the ballasting risk, the ballast exchange risk, and the de-ballasting risk to assess the ballast water risk. The simulation results are generally satisfactory, affirming the reliability of the fuzzy logic architecture. The practical application of this system can prevent ballast water from being discharged into the sea when the environmental risk is high and can instead be safely discharged into dedicated facilities in port.

Our research contributes to the field by providing a detailed examination of key risk parameters within the ballast water management cycle, enhancing the understanding of how various factors contribute to environmental risks. This insight is crucial for developing more effective strategies for mitigating the introduction and spread of invasive species through ballast water discharge.

Addressing a relatively unexplored domain of marine pollution, our research delves into consolidating the risk factors associated with ballast water, drawing on studies predominantly published in the last six years amidst escalating ecological threats. Despite existing laws lacking the stringency to curb this environmental crisis, the imperative to adopt and enhance sustainable practices remains, with the ultimate cost being human well-being and our legacy.

Our findings validate the efficacy of a fuzzy logic-based model in navigating the complexities of ballast water risk assessment. The implementation of fuzzy subsystems for ballasting, ballast exchange, and de-ballasting processes highlighted the model's capability to navigate the complexities and uncertainties in maritime environmental risks. This aligns with our aim to apply fuzzy logic innovatively in this domain. Furthermore, the insights gained from analyzing key risk parameters underscored their impact on maritime operations, enriching our understanding and contributing to more informed decision-making in ballast water management. These findings collectively affirm our research's significant theoretical and practical contributions to the field.

Future research in the field of ballast water management presents exciting opportunities to advance environmental protection and maritime sustainability. By exploring the integration of real-time environmental and operational data, researchers can enhance model responsiveness and accuracy. Additionally, the application of advanced machine learning techniques alongside fuzzy logic could offer deeper insights and more predictive capabilities in identifying and mitigating risks associated with ballast water management. Investigating the scalability and applicability of the model across different maritime contexts, including various vessel types and geographic regions, would also provide valuable contributions to global maritime sustainability efforts. These opportunities not only promise to extend the boundaries of our current understanding but also to innovate practical solutions for the ongoing challenges in maritime environmental management.

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Appendix A

Appendix A indicatively presents 9 out of 62 fuzzy rules for the ballasting system.

Table A1. Fuzzy rules for the ballasting system.

S/N	Connection	Tank Capacity	Ballast Receptor Filter Clarity	Harbor Water Turbidity	Ship Construction Date	Tank Clarity before Ballasting	Distance from Sewage Outfalls	Distance from Dredging Operations	Human Error Probability	Ballasting Risk
1.	And	Small	Clean	Low	New	Clean	Long	Long	Low	Low
2.	Or	-	-	High	-	Unclean	Small	Small	High	High
3.	And	Small	Clean	Medium	New	Medium Clean	Long	Long	Medium	Medium
4.	And	Large	Medium Clean	Medium	Medium Old	Medium Clean	Long	Long	Medium	Medium
5.	And	Medium	Clean	High	New	Clean	Small	Small	Low	High
6.	And	Medium	Medium Clean	Medium	Medium Old	Clean	Long	Long	Low	Low
7.	And	Small	Medium clean	Low	New	Clean	Long	Long	Low	Low
8.	And	Large	Medium Clean	Medium	New	Clean	Long	Long	Low	Medium
9.	And	Medium	Clean	Medium	New	Medium Clean	Medium	Medium	Low	High

Appendix B

Appendix B indicatively presents 9 out of 62 fuzzy rules for the ballast exchange system.

Table A2. Fuzzy rules for the ballast exchange system.

S/N	Connection	Tank Capacity	Depth during Exchange	Ship Construction Date	Tank Clarity before Ballasting	Maritime Traffic	Distance from Coast	Weather Condition	Human Error Probability	Ballast Exchange Risk
1.	And	Small	Long	New	Clean	Low	Long	Good	Low	Low
2.	Or	-	Small	-	Unclean	High	Small	Bad	High	High
3.	And	Small	Long	Medium Old	Medium Clean	Medium	Long	Medium	Medium	Medium
4.	And	Large	Medium	New	Clean	Medium	Medium	Medium	Low	Medium
5.	And	Small	Medium	New	Unclean	High	Small	Bad	Low	High
6.	And	Medium	Long	Old	Clean	Low	Long	Medium	Low	Low
7.	And	Large	Long	Medium Old	Clean	Low	Long	Medium	Low	Low
8.	And	Medium	Long	Old	Clean	Low	Medium	Good	Medium	Medium
9.	And	Small	Small	New	Clean	Medium	Small	Good	Medium	High

Appendix C

Appendix C indicatively presents 9 out of 62 fuzzy rules for the de-ballasting system.

Table A3. Fuzzy rules for the de-ballasting system.

S/N	Connection	Tank Capacity	Harmful Organisms' Concentration	Oxidants Concentration	Salinity Difference	Temperature Difference	Ship Construction Date	Tank Clarity before Ballasting	Sailing Days with Ballast	Exchanged Water Amount	Human Error Probability	De-Ballasting Risk
1.	And	Small	Low	Low	High	High	New	Clean	Many	High	Low	Low
2.	Or	-	High	High	-	-	-	Unclean	-	Small	High	High
3.	And	Small	Medium	Medium	High	High	New	Medium Clean	Many	Medium	Medium	Medium
4.	And	Large	Medium	Low	High	Medium	Old	Clean	Medium	Medium	Low	Medium
5.	And	Medium	High	High	Small	Medium	New	Medium Clean	Medium	Small	Medium	high
6.	And	Medium	Low	Low	High	High	Medium Old	Medium Clean	Many	High	Low	Low
7.	And	Large	Low	Low	Medium	High	Medium Old	Clean	Many	High	Low	Low
8.	And	Small	Medium	Low	Medium	Small	New	Clean	Few	High	Medium	Medium
9.	And	Large	High	Medium	Small	Medium	Old	Unclean	Medium	Medium	Low	High

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