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Sustainable Solutions to Safety Risks on Frozen Lakes Through Effective Risk Mitigation Using Crisis Management Logistics

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Abstract: This article addresses the critical safety risks posed by the use of frozen lakes, risks which are increasingly exacerbated by the impacts of climate change. In Slovakia, where numerous water reservoirs are legally designated for year-round recreational and sporting activities, safeguarding public health and safety necessitates innovative and sustainable approaches to risk mitigation in emergency management. Using the Jazero water reservoir as a case study, this paper demonstrates that the integration of comprehensive risk assessment, the strategic selection of rescue methods, and the deployment of advanced technical equipment for rescue teams are fundamental to ensuring a robust and efficient crisis management response. Through a comparative analysis of nine access routes, validated by tactical exercises and a detailed evaluation of three distinct rescue methods combined with different equipment types, this study reveals the critical role of optimized rescue strategies in reducing response times. Rescue operations were accelerated by at least 4.5 s, a significant reduction that could be the deciding factor between life and death in real-world scenarios. The proposed sustainable strategies for the Jazero reservoir are applicable to similar natural water bodies, underscoring the vital importance of proactive, data-driven, and adaptive crisis management systems in enhancing both immediate and long-term public safety.

Keywords: sustainable risk management; security; endangerment; rescue operation; saving a person; environmental impacts; climate changes; frozen lake; ice

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1. Introduction

Climate change presents one of the most pressing environmental challenges of our time, profoundly influencing ecosystems and human safety alike. The impact on frozen lakes is especially significant, as their freezing patterns are becoming increasingly unpredictable, posing serious risks for both environmental and human systems. Lakes play a vital role in our planet's natural cycle, providing irreplaceable habitats for countless species and supporting essential human activities. Yet, as the climate warms, these delicate systems are under threat, demanding a reimagining of our approach to safety and crisis management.

Woolway et al. [1] have emphasized that as these changes accelerate, understanding and monitoring the freezing processes of lakes become critical to safeguarding both ecosystems and the communities that rely on them. Rising global temperatures, as documented by Hewitt et al. [2], Wang et al. [3], and Sharma et al. [4], lead to milder winters, delaying the freezing of lakes and significantly reducing the duration of ice cover. Even when lakes do freeze, the ice is often perilously thin, increasing the likelihood of accidents during winter activities. Thinner ice poses not only an environmental risk but also a profound challenge to the safety of those who venture onto frozen lakes for recreation and transportation, necessitating a rethinking of traditional rescue methods.

The loss of ice cover further disrupts the invaluable cultural ecosystem services these lakes provide. Knoll et al. [5] and Košová et al. [6] illustrate how seasonally ice-covered lakes and rivers serve as cultural landmarks, offering both recreational and societal benefits.

However, as Guerra et al. [7] and Molokáč et al. [8] highlight, the use of these natural resources comes with risks that must be carefully managed to protect both human lives and the integrity of the ecosystems themselves.

Despite these escalating dangers, seasonally frozen natural water bodies continue to be popular for winter recreation and sports. However, these activities carry significant risks that require thorough attention. Szpilman and Orlowski [9], Garzón-Garnica et al. [10], and Jarosova [11] have underscored the importance of systematically evaluating the potential hazards associated with frozen lakes. The critical questions we must ask ourselves are as follows: (1) What factors contribute to the danger? (2) Can these risks be mitigated? (3) What preventive measures are necessary to ensure the safety of those who use these lakes?

The scope of the problem becomes clear when we consider the global toll of drowning. According to the World Health Organization, 236,000 people lost their lives to drowning in 2019 alone, making it one of the top causes of unintentional injury-related deaths worldwide [12]. Effective public education on first aid and water rescue is essential to preventing such tragedies. Quan et al. [13] and Moutafi and Petridou [14] eloquently argue that knowledge of basic rescue techniques can make the difference between life and death, reducing panic and empowering individuals to act decisively in critical moments. Similarly, Claesson et al. [15] have demonstrated that specialized training in water rescues can dramatically improve survival outcomes.

However, there remains a significant gap in understanding what happens on-site, during those critical moments before emergency medical teams arrive. Isin et al. [16] bring much-needed attention to the role of bystanders in these situations, although they caution that untrained intervention can sometimes lead to further tragedy. Piepho et al. [17] and Tipton and Golden [18] emphasize the need for advanced training, not only for rescue professionals but also for emergency medical personnel, given the unique challenges posed by water-related incidents. Idris et al. [19] have further highlighted the importance of high-quality resuscitation and its impact on long-term recovery, particularly in cases of drowning.

At the heart of any effective crisis management strategy is a well-coordinated, timely response. Successful rescues depend on far more than the bravery of individual responders; they require a system that integrates planning, communication, and the deployment of resources. Re and Veitch [20] have examined how the specific environmental conditions of ice-covered waters complicate rescue operations. Their work, along with the contributions of Motylewski et al. [21], emphasizes the myriad factors that can determine the success or failure of a rescue mission. Techniques and methods for water rescue have been meticulously detailed by Kaca and Siermontowski [22], while Karpun et al. [23] offer invaluable insights from real-world rescue operations. Kruke et al. [24] have provided case studies that deepen our understanding of search and rescue procedures, and Clark et al. [25] have connected environmental variables with rescue outcomes, emphasizing the need for adaptive strategies.

The peril of rescuing someone from a frozen lake—where time, temperature, and terrain conspire against even the most seasoned professionals—remains one of the most dangerous rescue scenarios imaginable. Yet, with meticulous preparation, rigorous training, and the integration of cutting-edge crisis management techniques, we can improve the outcomes of these life-or-death situations. This article draws upon the collective expertise of researchers and practitioners to propose a forward-looking, sustainable crisis management framework that seeks to not only reduce response times but also preserve the most precious resource of all: human life.

2. Materials and Methods

Frozen lakes, while offering opportunities for various sports and recreational activities, present significant safety challenges due to the inherent risks of ice instability. Activities on frozen lakes often take place in remote areas lacking formal safety rules or professional supervision, such as dedicated water rescue services. This study emphasizes Effective Risk

Mitigation for Frozen Lakes Using Crisis Management Logistics, aiming to reduce risks and enhance safety during rescue operations. The increasing frequency of unstable ice conditions, influenced by climate change, underscores the need for sustainable approaches to crisis management that can adapt to these evolving challenges, ensuring that every rescue operation is both safe and swift.

2.1. Challenges and Risk Factors in Rescuing Individuals on Frozen Water Surfaces

Rescuing individuals trapped beneath the ice is a race against time, testing physical endurance and mental resilience to their limits. The effects of climate change—warmer winters, irregular freeze–thaw cycles, and thinner ice—transform what was once predictable into a landscape of uncertainty. As ice behavior becomes less reliable, our approaches to crisis management must evolve, emphasizing flexibility and rapid adaptation.

Crisis management logistics play a pivotal role in planning for such emergencies, integrating real-time assessments of risks such as ice thickness and climatic conditions to ensure timely and effective interventions. This proactive approach ensures that rescue teams are not caught off guard but are instead prepared to face the myriad challenges posed by the volatile nature of frozen lakes. Understanding the demographics of drowning incidents is also crucial for designing targeted rescue protocols. For instance, Table 1 provides a detailed breakdown of the age distribution of drowning victims in Slovakia from 2010 to 2016, based on data provided by the Ministry of the Interior of the Slovak Republic [26]. These data highlight the vulnerability of different age groups and help to focus efforts where they are most needed.

Table 1. Statistics of drowned victims in Slovakia for the period from 2010 to 2016 divided by age categories.

Age Composition of Drowned Persons	Year						
	2010	2011	2012	2013	2014	2015	2016
Up to 10 years	6	6	4	2	2	1	1
Up to 20 years	14	21	8	13	6	14	5
Up to 30 years	13	17	13	18	8	11	8
Up to 40 years	16	18	13	17	12	8	9
Up to 50 years	27	10	18	23	20	17	18
Up to 60 years	32	26	20	28	22	31	20
Over 60 years	21	26	16	25	26	18	28

While more recent data could have enriched this study, repeated requests to the Ministry of the Interior of the Slovak Republic for updated statistics have not been successful. This issue reflects broader challenges in the systematic collection and public accessibility of such data at the national level, where records of water-related incidents are often not updated regularly or centralized. Despite these limitations, the available dataset remains valuable for identifying long-term trends, which provide important insights into risk factors and the demographics of drowning incidents. Improving the availability of recent data would enhance the ability to design more effective and timely rescue measures in the future.

In addition to age-specific data, it is crucial to analyze the types of water bodies where these incidents occur. Table 2 illustrates the occurrences of drownings across various water bodies, allowing crisis management teams to better understand the environments that pose the greatest risks and direct their efforts accordingly.

Table 2. Statistics of drowning victims in Slovakia for the period from 2010 to 2016, divided by water bodies.

	Year						
Water Bodies	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Running waters	79	73	40	62	60	51	49
Running waters	21	20	22	28	13	21	21
Swimming pools	2	0	2	6	0	0	3
Dams	2	12	16	17	13	16	9
Wells	4	2	3	1	1	2	1
Waste pits	4	2	1	3	1	1	2
Uncovered pits	1	3	2	0	2	2	1
Other places	16	12	6	9	6	7	3
Total number of drowned persons for individual years in Slovakia	129	124	92	147	122	122	109

A key element of effective risk mitigation is understanding the variability of ice thickness, which directly impacts the safety and feasibility of rescue operations. While studies by Murfitt et al. [27] and others have extensively explored the properties of ice, this study aims to bridge theory and practice, integrating these findings into practical rescue guidelines. Table 3 outlines the recommended minimum ice thicknesses for various winter activities, providing essential benchmarks for determining when and where it is safe to proceed.

Table 3. Approximate recommended minimum thickness of (new) ice for various winter leisure and sports activities.

Recommended Minimal Thickness of the Ice	Ice Load Capacity in the Context of Leisure Activities
Up to 5 cm	It is very low, so an adult (with an estimated weight of 80 kg) often falls over.
From 5 to 10 cm	It can support an adult person or several persons walking with a distance of at least 3 m between them (e.g., ice fishing, walking, and cross-country skiing).
From 10 to 20 cm	It can support a group of adults who walk without gaps.
From 20 to 35 cm	It is safe for organizing recreational sports where there is a large accumulation of people and dynamic loads on a frozen surface, and it is also strong enough to support snowmobiles and small passenger vehicles (e.g., one car or a small pickup truck).
35 cm and above	It will support a medium-sized truck (e.g., pickup truck or van).

In addition to ice thickness, understanding the survival time of a person immersed in cold water is critical for informing the urgency of rescue operations. Table 4 provides estimates of survival time based on water temperature, highlighting the rapid decline in survival chances as the temperature drops. This information is essential for crisis management teams to prioritize speed and efficiency in rescue efforts, particularly when dealing with icy waters where even a few minutes can mean the difference between life and death.

Table 4. Estimated survival time of a drowning person depending on temperature and time.

Water Temperature	An Organism Exposed to Exhaustion	Estimated Survival Time
21–27 °C	3–12 h	3 h—without limit
16–21 °C	2–7 h	2–4 h
10–16 °C	1–2 h	1–6 h
4–10 °C	30–60 min	1–3 h
0–4 °C	15–30 min	30–90 min
<0 °C	up to 15 min	below 15–45 min

Water temperature significantly affects both the physical condition of the victim and the strategy employed by rescuers. For instance, in water temperatures below 0 °C, the survival time can be as short as 15 min, underscoring the need for immediate action and well-prepared response plans. These data emphasize the importance of minimizing delays in the arrival and rescue times, as even minor delays can drastically reduce the chances of a successful rescue.

In practical terms, the knowledge of ice thickness directly informs the choice of rescue method, i.e., whether to proceed with a crawling method, use a ladder, or employ other specialized equipment. By having a clear understanding of ice conditions, rescue teams can make informed decisions that reduce the risk of accidents, such as rescuers themselves breaking through the ice. This adaptive approach to managing ice conditions is a fundamental aspect of modern crisis management logistics, aimed at minimizing human risk while ensuring a swift and effective response.

2.2. Selection and Justification of Rescue Methods and Equipment

The selection of rescue methods and equipment in this study—specifically, the crawling method, the crawling method with ice picks, and the ladder method with ice picks—reflects a deep understanding of the practical realities of ice rescue. These methods were chosen not only because they are frequently used in real-world rescue missions but also because they can effectively respond to specific conditions typical of frozen lakes in Slovakia. The selection of methods was also informed by results from studies and practical experience, demonstrating their effectiveness across varying ice thicknesses and changing climatic conditions.

The crawling method is a tried-and-true technique that allows rescuers to distribute their weight evenly across fragile ice, minimizing the risk of breaking through thinner sections. It is the method of choice when approaching victims across unstable ice, offering a balance of caution and control. When combined with a ladder, this method gains an additional layer of safety, enabling rescuers to reach further distances without compromising stability on the ice.

Ice picks are invaluable tools that provide rescuers with secure grip and stability on slippery surfaces. The crawling method with ice picks is therefore ideal for environments where ice thickness varies, offering rescuers increased stability when moving across unpredictable surfaces.

The ladder method with ice picks is suited for the most precarious conditions, where rescuers require maximum stability. By spreading the rescuer's weight across the ladder, the risk of breaking through the ice is minimized, while the ice picks offer the necessary control and secure anchoring during the approach to the victim.

These methods were selected not only for their proven effectiveness but also for their ability to be adapted to changing conditions, minimizing human risk while reducing environmental impact, which is crucial for sustainable crisis management. The Results Section (Section 3) will provide a detailed comparison of these methods and their performance under different conditions, revealing their advantages and limitations in practical scenarios.

2.3. Risk Factors and Their Weight in Ice Rescue Operations

Ice rescue operations present a challenging area where theory meets practice in situations where every minute can determine the outcome between life and death. Successful interventions require not only technical skills but also a deep understanding of the risks that influence the course of rescue actions. Understanding the relative importance—or weight—of each factor is crucial for optimizing rescue strategies. This section provides a detailed analysis of key risk factors and their assigned weight, highlighting their role in influencing decision-making during rescue operations.

To systematically evaluate these factors, Table 5 lists the primary risk factors encountered during ice rescue operations, alongside descriptions and assigned weights. These weights were determined through a combination of practical field experience, expert consultations, and analyses of significant studies, including the research of Golden and Tipton [28] on survival in cold water, the findings from Zartman [29] on handling worst-case scenarios in ice rescue, and guidelines provided by the Ministry of the Interior of the Slovak Republic from 2003 [26]. A study by Kälin et al. [30] emphasizes the critical importance of rapid temperature assessment and appropriate protocols when dealing with victims of hypothermia, further supporting the necessity of understanding these risk factors. This structured approach offers valuable insights into selecting the most appropriate rescue methods and assessing the risks associated with ice rescue.

Table 5. Overview of key risk factors in ice rescue operations with assigned weights.

Risk Factor	Description	Weight (1–5)	Justification
Ice Thickness	The strength and stability of the ice, which affects the choice of rescue method and approach.	5	Thin ice presents a high risk of breaking during rescue, requiring special methods such as ladders or crawling. Field observations often highlight that unpredictable ice thickness is a decisive factor in the success of interventions.
Water Temperature	Determines the victim's survival time and the urgency of the rescue operation.	5	Lower temperatures reduce survival time, necessitating a faster response and affecting the condition of the victim. According to Golden and Tipton (2002) [28], hypothermia can set in within minutes, making every minute critical.
Distance from Shore	The distance between the shore and the location of the victim affects the time required for the rescue.	4	Greater distances increase travel time, which can delay reaching the victim and increase the risk of hypothermia. In practice, this factor has often been critical in determining the success of a rescue operation.
Weather Conditions	Includes factors such as wind, snowfall, and visibility, which can complicate rescue operations.	4	Adverse weather can reduce visibility and cause ice instability, complicating rescue logistics. Snowstorms and sudden drops in temperature have frequently been factors that reduce the chances of a successful intervention.
Experience of the Rescue Team	The skill level and preparedness of rescuers, which influence the effectiveness of the operation.	4	Experienced teams are better equipped to handle unexpected challenges, minimizing risks during demanding operations. While technology plays a significant role, it is often the human factor that determines success or failure.
Quality of Equipment	Availability and reliability of rescue equipment, such as ice picks and ladders.	3	Quality equipment can improve safety and speed, but its effectiveness often depends on other factors. Practical experience shows that even the best equipment requires skilled use to deliver maximum impact.
Physical Condition of the Victim	The health status and consciousness of the victim, which affects the complexity of the rescue.	3	A conscious victim can assist in their own rescue, while an unconscious one increases the difficulty of the intervention. Field experience has shown that a conscious victim significantly improves the chances of a successful rescue.
Variability of Ice Conditions	The degree of uniformity in ice thickness on the lake, which affects safe access routes for rescuers.	3	Variations in ice thickness require constant adjustments to the rescue approach, impacting the safety of the intervention. Sudden cracks and changes in ice stability have often dramatically altered the course of operations.

This table highlights the most critical factors influencing rescue operations on frozen lakes. Ice thickness and water temperature carry the highest weight (5) due to their direct impact on the chosen approach strategy and survival time. Distance from shore and weather conditions are rated slightly lower (4) but remain crucial as they directly affect the time required for the rescue and the stability of the environment during interventions. For example, situations where the ice is thin and water temperature is extremely low (below 0 °C) require a rapid response using methods that minimize pressure on the ice, such as the ladder method combined with crawling [31]. Conversely, if the ice is thicker but weather conditions are unfavorable, the rescue team should focus on maintaining visibility and safe access routes [32].

This structured approach to weighing risk factors ensures that rescue operations are tailored to the specific conditions of each emergency, allowing for more effective decision-making and resource allocation.

2.4. Explanation of Calculations and Simplified Context

Time is a critical factor in rescue operations, especially when hypothermia can set in within minutes. To optimize response times, this study uses a straightforward yet essential formula, adapted from the methodology of the fire and rescue corps [33]:

$$t_a = t_f + t_t \text{ (min)} \quad (1)$$

where

t_a—arrival time of the fire brigade (min);

t_f—time for the firefighting unit to prepare and depart, varying by service type (e.g., 1 min for professional units);

t_t—travel time, calculated as

$$t_t = (60 \times l)/v_a \text{ (min)} \quad (2)$$

where

l—represents the distance to the scene (km);

v_a—is the average speed of fire trucks (45 km·h^{-1}).

While this formula may appear simple, its implications are profound. Every minute saved in reaching the incident site significantly increases the chances of a successful rescue. Reducing the time by even 1 to 2 min can be critical, especially considering the rapid drop in body temperature of a person submerged in icy water. By optimizing the logistics and minimizing delays, such as through thorough route planning and equipment readiness, the overall efficiency of rescue operations is greatly enhanced. This methodology emphasizes that effective crisis management is about precision and preparedness.

Similarly, the time required by rescuers to reach a drowning individual on a frozen lake or river is equally critical. This duration is calculated using the following formula:

$$t_r = v_m/l_{ste} \text{ (min)} \quad (3)$$

where:

t_r—rescue time (s);

v_m—speed of movement on ice (m.min^{-1});

l_{ste}—length from shore to event (m).

In winter, when rescuing a person from an icy surface, every minute is essential. The entire intervention must be carried out as swiftly as possible to prevent freezing or drowning. Nearly two-thirds of ice-related incidents occur on lakes, with the remainder on rivers, highlighting the importance of rapid response in diverse aquatic environments.

The role of crisis management in such scenarios is undeniable. Its primary objective is to transform an imminent threat into a mitigated risk through prompt, efficient, and effective action. This requires careful preparation and planning for crisis situations, including specific strategies for rescuing individuals from frozen waters used year-round. The ability to coordinate resources, anticipate challenges, and execute a well-prepared plan directly impacts the success of such operations. By focusing on logistical efficiency and strategic preparedness, crisis management ensures not only a timely response but also a sustainable approach to addressing these life-threatening events.

2.5. Overview of Methods for the Results Section

The following Results Section (Section 3) will delve into a detailed comparison of the selected rescue methods and their performance under different conditions. The analysis will focus on the time differences between using a ladder, ice picks, and other methods, highlighting the specific advantages of each approach. It will examine how each method contributes to faster response times and increased safety during ice rescue operations, especially in scenarios where speed is critical. The results will demonstrate how the choice of method directly influences the overall success of the intervention, providing insights into their real-world applications.

3. Results

The Jazero water reservoir was chosen as a case study. It is a dominant feature of the Nad Jazerom district and is part of an important recreational area of the city of Košice. Originally, it was an ordinary gravel pit, but the lake is a popular recreational area today. This recreation includes a water area, a rope park, a boat rental, a sandy beach, and multifunctional children's playgrounds. The Jazero water reservoir has a high number of visitors all year round.

The activities of people on frozen water surfaces are often associated with injuries and, in the worst cases, with drowning, which can be defined as death by suffocation due to the lack of air.

For professional firefighters (rescuers), one of the decisive moments of preparation for the progress of rescue work and the choice of rescue means is information on water flow if involved, in the case of a drowning person on a water surface under an ice cover. Rescuers need to know that lakes freeze differently than rivers. The freezing of stagnant water differs from flowing water, and the risk of people breaking through ice on stagnant water is several times smaller than on flowing water courses. Rescue on flowing watercourses is complicated by the current of a watercourse, which pulls the drowning person under the ice cover. Since we have chosen lake reservoirs for our case study, let us look at the freezing process of lakes, as shown in the following Figure 1.

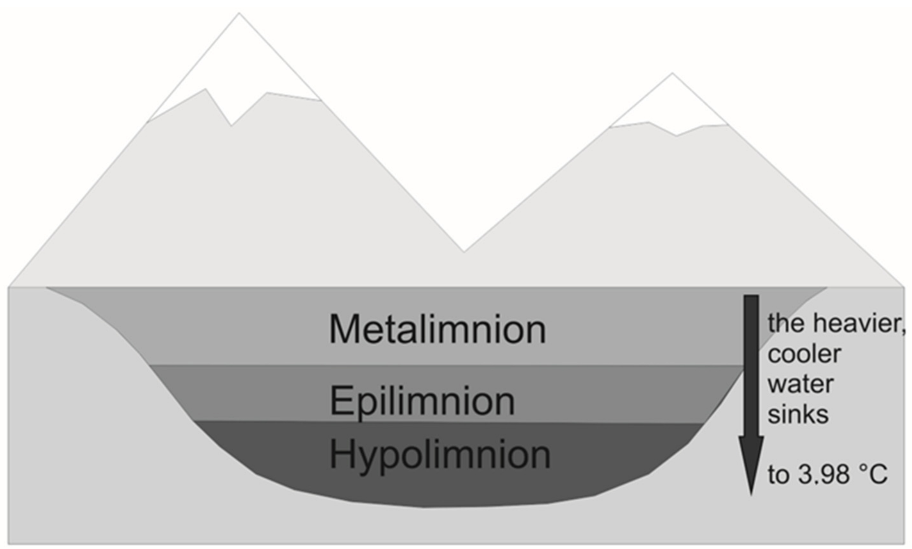

Figure 1. The process of a lake freezing.

Even before venturing onto a frozen lake, it is essential to consider the safety and potential risks of this decision. In the event of an extraordinary melting event, a well-prepared crisis management plan is invaluable. This plan should be designed to provide the necessary logistical support to address the crisis situation, allowing the affected individual(s) to navigate the extraordinary event with the assistance of integrated rescue services. The ultimate goal is to minimize the potential loss of life and health.

3.1. Implementation of Logistic Principles for Effective Risk Management on Frozen Lakes

Recent advancements in logistics principles for managing risks on frozen lakes have brought significant improvements in real-time decision-making and coordination among rescue teams. At the heart of these developments is the integration of predictive technologies and data-driven tools, which allow for optimized safety measures in dynamic and often unpredictable environments.

Predictive analytics, in conjunction with real-time monitoring systems, empowers responders to assess critical factors such as ice thickness, temperature fluctuations, and water currents. These insights play a pivotal role in shaping the strategies used during rescue operations, enabling teams to adapt their methods to ensure the highest levels of safety. The use of geospatial information systems (GISs) has further refined route planning, enhancing the efficiency and safety of reaching accident sites by accounting for potential hazards, such as unstable ice patches.

The rise of smart logistics solutions, incorporating automation and artificial intelligence (AI), has transformed the allocation of resources during emergencies. These advanced systems streamline response times, ensuring that rescue teams and necessary equipment are deployed with precision when emergencies arise. Such innovations are invaluable for maintaining operational safety on frozen lakes, even in the face of challenging and rapidly changing conditions.

To create a crisis management plan designed for fire protection units responding to emergencies on frozen lakes, a systematic approach has been developed and is illustrated in Figure 2. This flowchart visualizes the step-by-step intervention process, offering a structured overview of the coordinated response efforts required in these high-risk scenarios.

3.2. Model Situation of Environmental Burdens in the Jazero Water Reservoir

The frozen lake season, while offering opportunities for recreation, inherently carries a spectrum of risks that can range from minor injuries to life-threatening situations, such as breaking through the ice. Navigation of these natural ice areas is often carried out at one's own risk, emphasizing the critical need for a comprehensive and effective approach to risk mitigation. Crafting a successful rescue plan becomes paramount in this context, as every second counts when responding to emergencies.

Several challenges can hinder rescue interventions in such scenarios. These include inaccurate identification of the exact intervention site, insufficient reconnaissance of the area, inadequate rescue equipment, and suboptimal rescue procedures for individuals who have broken through the ice. A common thread among these challenges is the urgency of time; rapid response can be the difference between life and death.

Given the dimensions of the Jazero water reservoir, covering an area of 0.204659 km^2, a strategic division into seven sectors was implemented to enhance rescue efficiency and ensure systematic coverage of the entire lake area. This division, illustrated in Figure 3, was derived from field surveys and accounts for the conditions of access roads, year-round parking availability for rescue vehicles, and the distances that rescuers must traverse on foot with their equipment. Each sector was marked with visible signs to assist in identifying the specific location of an emergency. These markers allow bystanders or witnesses to report the exact location more accurately, even in high-stress situations. This improvement is critical as it minimizes delays caused by unclear or imprecise information.

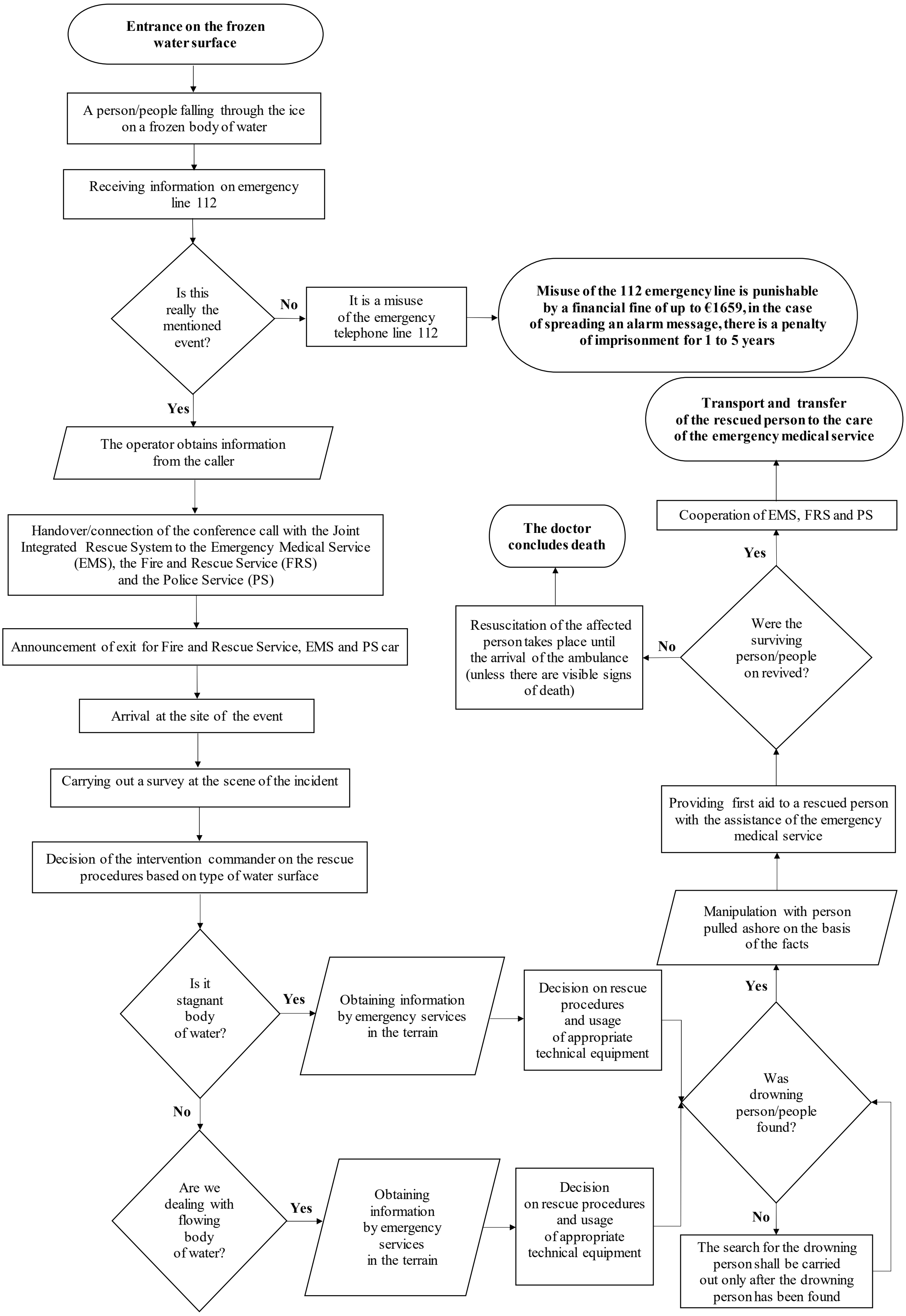

Figure 2. Effective resolution of a crisis situation on a frozen lake.

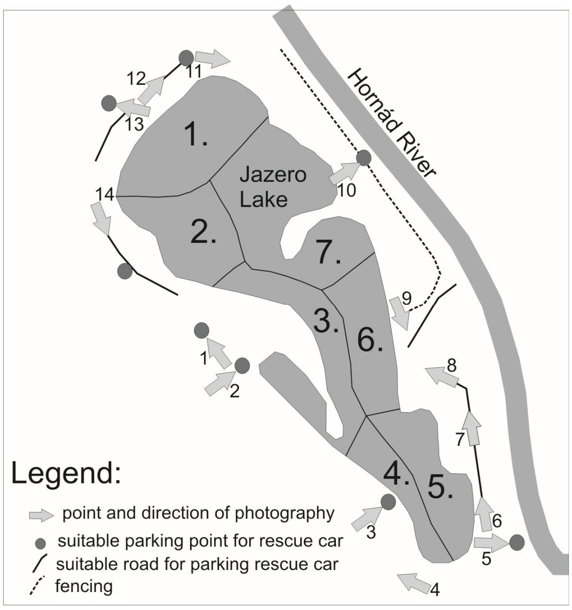

Figure 3. Adjusted satellite image of the Jazero reservoir showing the possibility of access roads and parking possibilities for emergency vehicles.

In cases of emergencies, the nearest rescue teams are mobilized, leveraging their familiarity with the local environment. Training responders within this known landscape not only reduces time spent on situational briefings but also ensures that the rescuers can navigate the area with precision. With this familiarity, combined with pre-established access routes, a team can efficiently reach the designated sector, minimizing critical response time. As emphasized, even a few saved seconds can be crucial when lives are at stake.

The Jazero water reservoir presents notable challenges for rescue service vehicles, particularly for fire protection units. The natural topography, characterized by an embankment, dense vegetation, and a partial fence surrounding the lake, restricts direct vehicle access to the shoreline. This limitation necessitates that rescuers cover a portion of the distance on foot, carrying essential rescue equipment to reach the emergency site. Detailed information on accessible routes for emergency vehicles and their proximity to the water area is depicted in Figure 3.

As shown in Figure 3, many of the identified staging areas are year-round public parking facilities, which provide suitable spots for fire trucks to park. These parking areas ensure that, under normal conditions, fire and rescue vehicles can position themselves relatively close to the lake. However, certain locations present unique challenges; for instance, at point 10, where a fence encloses the water surface, access is more restricted. Here, the terrain becomes particularly problematic during adverse weather conditions. If the access road is not adequately maintained or paved, the likelihood of a fire truck or rescue vehicle becoming immobilized increases significantly, potentially jeopardizing the entire rescue operation.

Given these constraints, the strategic planning of access routes and the pre-assessment of potential obstacles are critical for ensuring swift and effective response times during emergencies. Understanding the nuances of the terrain around the lake allows crisis managers to prepare alternative routes and develop contingency plans for situations where primary access points are blocked or compromised. The division of the lake into seven sectors not only facilitates efficient allocation of resources but also ensures that no part of the lake is neglected during a rescue operation. The addition of marked sectors contributes significantly to precise coordination and reduces critical response times.

Following a detailed assessment of the various roadway segments surrounding the Jazero reservoir, a strategic plan was developed to identify the most accessible and time-efficient routes for rescue operations. This plan prioritizes pathways that allow rapid access to critical areas, minimizing response times during emergencies. Figure 4 illustrates these optimized routes, taking into consideration the subdivision of the reservoir area into seven sectors as depicted in Figure 3. The integration of this strategic planning enables rescue teams to navigate the terrain with greater efficiency, thereby enhancing the overall effectiveness of crisis response efforts.

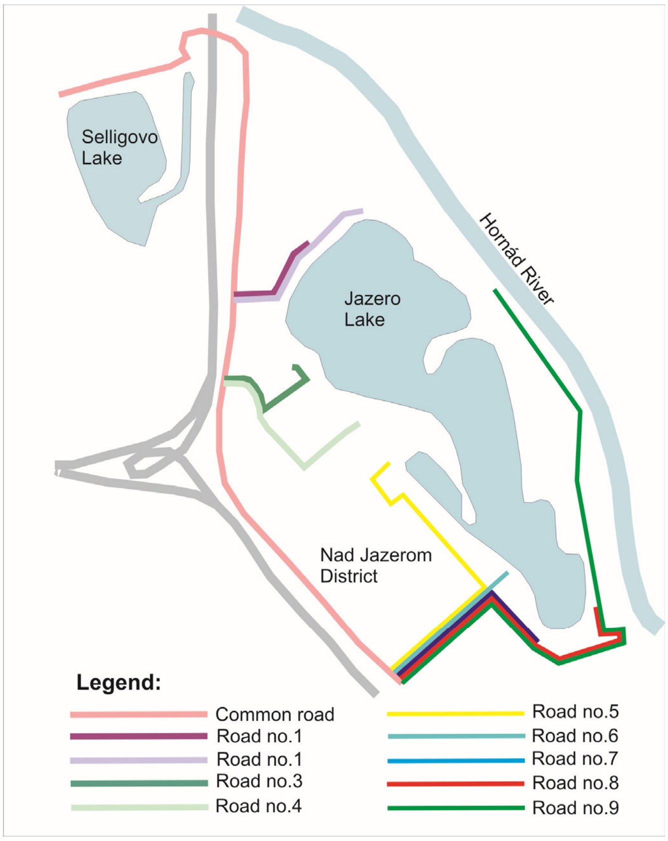

Figure 4. Adjusted satellite image of the Jazero reservoir showing available and fast routes for emergency vehicles.

A crucial aspect of any rescue operation is the prompt and accurate announcement of an emergency. During this phase, the emergency operator gathers essential information by asking targeted questions: Where did the incident occur? What type of frozen water body is involved (e.g., watercourse, lake, pond)? Is the incident site difficult to access (e.g., impassable roads) or exposed to additional risks? What exactly happened, and what is the mechanism of injury? How many individuals are affected, and what are their approximate ages and genders? Are there visible injuries? When did the incident take place? Is the caller able to see the individuals in distress? This information is critical, as it enables the rapid deployment of appropriate resources. The fire and rescue service alarm is triggered immediately upon receiving the call, with an emergency notification time of approximately 1 min.

For the specified routes displayed in Figure 4, calculating the estimated arrival time of the fire and rescue service (t_a) to the incident site was essential for tailoring the Crisis Management Plan to the Jazero water reservoir. Table 6 provides an overview of the calculated arrival times for professional fire and rescue units along various routes, considering an initial response time of up to 1 min.

Table 6. Endurance time to the site of the emergency for the individual routes.

Road Number	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9
Length of the route (km)	1.1	1.8	1.8	2.6	2.6	2.5	2.6	3.8	1.5
Endurance time (min)	2 min 28 s	3 min 24 s	3 min 24 s	4 min 28 s	4 min 28 s	4 min 20 s	4 min 28 s	6 min 4 s	3 min

Using Formulas (1) and (2), which determine the total response time by combining the preparation time and travel duration, the calculated endurance time for the professional fire and rescue service to reach the incident site via Route 1 is approximately 2 min and 28 s. These calculations highlight the importance of efficient route selection in reducing response times during emergencies, emphasizing the critical nature of rapid intervention in life-threatening situations on frozen water bodies.

The given endurance times for the different routes to the intervention site were verified through implemented tactical exercises. These simulations allowed the crisis management team to ensure that the theoretical calculations aligned with real-world conditions. Such exercises are critical for validating the planned response times, ensuring that the proposed routes remain viable under various circumstances, including adverse weather or unexpected obstacles.

Another important factor is the battle decision time, t_{bd}, which refers to the time required for the rescue team to make critical decisions upon reaching the site. In scenarios where there is direct access to the emergency location for the rescue vehicle, or the distance between the vehicle's stopping point and the incident site is within 20 m, this factor may be omitted from calculations. This approach aligns with the standards outlined in STN 92 0201 [34].

For our model scenario at the Jazero water reservoir, Area 2 was selected as the focus of analysis due to its challenging terrain and accessibility. Among all the areas considered, Area 2 presents the most difficult conditions for rescue operations, making it a key focus for testing the efficiency of different rescue methods. Rescue vehicles cannot approach the lake directly in this area due to a lack of accessible roads and parking spaces. Additionally, the steep drop-off to the water surface means that the rescue team must carry equipment, including a first aid kit, a footbridge, safety lines with ice picks, and two ladders, over a 200 m distance on foot.

Area 2 also experiences high visitation throughout the year, increasing the potential for accidents. As indicated in Table 6, the distance from the nearest authorized fire station to the emergency site is 1.8 km, resulting in an estimated arrival time of 3 min and 24 s for the nearest professional fire and rescue service.

The rescue team's approach time on the ice is a crucial component of the overall rescue time. As calculated using Formula (3), this time depends on the distance from the shore to the incident and the speed of movement on ice, emphasizing the importance of selecting the most efficient rescue method.

The subsequent analysis focused on the influence of the firefighting unit's material and technical equipment on the success and efficiency of the rescue procedure. The nearest fire station is equipped with essential tools such as a 10 m safety line and a Honda Marine Hon Wave lifeboat, weighing 54 kg and capable of carrying up to four individuals. Although this equipment is basic, it is sufficient for rapid intervention in cases where a person has broken through the ice. Safety lines, in particular, are a versatile tool in rescue operations and can be effectively combined with other safety measures.

In the first scenario, where the person is less than 10 m from the shore, the use of a safety line allows the rescue team to secure the individual and pull them to safety. This method is both efficient and straightforward. However, in cases where the person is more than 10 m from the shore, additional precautions are necessary to ensure the safety of the rescuer.

When the distance exceeds 10 m, throwing the safety line becomes impractical, particularly for a rescuer on an unstable ice surface. For instance, when a drowning person is 30 m from the shore and remains conscious, the rescue team must employ alternative methods to safely reach them. While the current equipment allows for rescue, the process is slower compared to scenarios where additional tools like ice picks and folding ladders are available.

For the second scenario, three potential solutions were evaluated, as summarized in Table 7 below.

Table 7. Comparative rescue times and efficiency of various methods.

Methods of Rescue Depending on the Material and Technical Equipment of Rescuers	Approach Time of the Rescuer to the Drowning Person on the Ice (s)	Acceleration Time Between Methods (s)	Walking Time for 200 m with Material and Technical Equipment (s)	Total Rescue Time for Area 2 and Route 3 (s)	Relevance to Crisis Management
The crawling method	72	0	180	7 min 36 s	This is the slowest method, which may increase the risk to both the victim and the rescuer due to prolonged exposure to cold conditions and potential complications.
The crawling method and fireman's axe	51	21	180	7 min 15 s	This method provides moderate improvements in speed, making it more effective at reaching the victim, but it still presents significant risks due to continued exposure to cold.
Ladder method and ice pick	46.5	4.5	180	7 min 10.5 s	This is the fastest and safest method, enabling quicker access to the victim while minimizing risk to the rescuer, thus significantly improving the chances of survival in cold-water emergencies.

Table 7 illustrates that the choice of rescue method significantly influences the overall response time and safety during the intervention. The ladder method, when used in combination with ice picks, emerged as the most effective approach, reducing the total rescue time to 7 min and 10.5 s. This method's efficiency lies in its ability to distribute the rescuer's weight evenly over the ice, minimizing the risk of breakthrough while allowing for a faster approach.

In contrast, the basic crawling method, while straightforward, results in a considerably longer approach time of 7 min and 36 s. This increased duration raises the risk of hypothermia for both the rescuer and the victim, making it less suitable for time-sensitive situations. The intermediate option, combining crawling with ice picks, offers a balance between speed and safety, yet it still lags behind the ladder method in terms of overall efficiency.

Ultimately, this comparative analysis highlights the importance of equipping rescue teams with the appropriate tools and training to adapt their approach based on the specific conditions of each incident. While simpler methods may suffice in less critical situations, investment in advanced equipment like ladders and ice picks can significantly enhance the effectiveness of rescue operations, especially in scenarios where time is of the essence.

3.3. Summary of Results

The effectiveness of a crisis management plan, particularly when responding to a drowning incident on a frozen lake in inland conditions, hinges on several critical factors. Foremost among these is the provision of timely and accurate information from the operation center, which enables rescuers to quickly orient themselves upon arriving at the emergency site. This rapid orientation is essential for the efficient execution of rescue operations. The skill and preparedness of the rescue team, characterized by their rigorous training and physical readiness, are central to the plan's success. Equally crucial is the availability of specialized material and technical equipment that aligns with the unique demands of the situation.

For the crisis management strategy developed for the Jazero water reservoir, a key recommendation is the division of the lake's surface into seven distinct areas. This strategic division, clearly marked and visible to both rescuers and bystanders, facilitates the swift localization of individuals in distress. Moreover, it enables a systematic assessment of the access routes, revealing potential challenges for emergency vehicle passage and parking near the water.

The detailed focus on Area 2 of the Jazero water reservoir, which spans 0.204659 km^2, highlights its challenging terrain for integrated rescue services, particularly for fire protection units. This study demonstrates that direct access to the lake's shoreline is obstructed by embankments, dense vegetation, and fencing around portions of the lake. As a result, rescuers are often required to traverse a 200 m distance on foot, carrying essential rescue equipment such as first aid kits, footbridges, safety lines with ice picks, and ladders. This logistical challenge underscores the need for precise planning in rescue scenarios where every second counts.

Given the proximity of the nearest fire station, integrated rescue system units are typically the first to arrive at the scene. For Area 2, using Route 3, the professional fire and rescue team can reach the incident location in approximately 3 min and 24 s. This rapid response time is critical in cold-water emergencies where the survival window is limited.

This study further analyzed how different types of rescue equipment impact response efficiency. The field exercises revealed that a well-prepared rescue team equipped with standard tools could reach a drowning person using the crawling method within 51 s. However, supplementing their equipment with additional items like two ladders and straightening spikes significantly reduced the approach time by at least 4.5 s, a crucial margin when a human life is at stake in freezing conditions.

The field exercises also demonstrated that the steep incline along the shoreline of Area 2 posed a considerable challenge during rescue operations. The uneven terrain and abrupt transition from land to the ice-covered water necessitate fundamental technical modifications. This study suggests constructing a year-round accessible pier to provide a safer and more stable transition onto the ice, ensuring that rescuers can more efficiently reach individuals in distress while minimizing the inherent risks posed by the terrain. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.4. Strategic Recommendations for Enhanced Safety and Risk Mitigation at the Jazero Water Reservoir

The insights gathered from the case study at the Jazero water reservoir underscore the necessity for a multifaceted approach to crisis management, particularly in environments where ice stability is increasingly compromised by climate change. In order to safeguard both recreational users and rescue personnel, it is vital to implement targeted interventions that adapt to the evolving risks of frozen lakes. These recommendations focus on bolstering physical infrastructure, improving response logistics, and leveraging advanced monitoring technology to create a more resilient safety framework.

A cornerstone of this enhanced safety strategy is the installation of strategically positioned SOS cabins around the perimeter of the Jazero water reservoir. These cabins should be equipped with essential life-saving tools, including throwing ropes, rescue wheels, and automated external defibrillators (AEDs), complemented by integrated real-time camera systems. Such equipment would not only facilitate immediate intervention but also enable continuous surveillance, providing critical visual data to the command center during rescue operations. Placing four cabins at key access points around the lake would ensure optimal coverage, allowing rescuers to deploy swiftly across different sections of the water body and minimize the time taken to reach the victim.

This proposal is grounded in the logistical analysis derived from the case study, where the location of rescue equipment significantly impacted response times. Given the unpredictable nature of ice conditions, the availability of readily accessible rescue gear can make the difference between a successful recovery and a tragedy. The implementation of these cabins should follow the principles of crisis logistics, ensuring that each unit is positioned to account for both the physical landscape and the observed patterns of lake usage during peak winter months.

In parallel with infrastructure improvements, raising public awareness remains a critical component of effective risk mitigation. The development of targeted educational campaigns can empower visitors to understand the inherent dangers of frozen lakes and the precautions necessary to navigate them safely. Emphasizing practices such as checking ice conditions, understanding safe load-bearing capacities of ice (as illustrated in Table 5), and carrying personal safety equipment like recovery spikes can significantly enhance self-rescue capabilities and reduce the burden on professional rescuers.

Another crucial recommendation is the adoption of a sector-based identification system for the lake, wherein the water body is divided into clearly marked zones. This zoning would streamline the process of communicating precise incident locations between bystanders and emergency services, drastically reducing the time taken for responders to pinpoint and reach those in distress. Such an approach is particularly valuable in large or complex lake environments like Jazero, where rapid localization can prevent critical delays in rescue operations.

Given the accelerating impacts of climate change on ice stability, a crisis plan must also embrace technological advancements to maintain effectiveness. Incorporating state-of-the-art monitoring tools, such as drones equipped with sonar for ice thickness measurement and thermal imaging cameras for identifying heat signatures, can provide real-time insights into the structural integrity of ice. These technologies enable rescuers to assess risk more accurately before deploying personnel onto uncertain surfaces, thus mitigating the likelihood of secondary accidents involving rescue teams themselves.

The integration of these recommendations into the crisis management plan at the Jazero reservoir is not merely a matter of procedural enhancement; it represents a paradigm shift towards a more adaptive and resilient safety strategy. By leveraging both traditional rescue techniques and modern technological solutions, the proposed measures aim to create a comprehensive safety net that evolves with the challenges presented by a warming climate. Such an approach ensures that rescue teams remain prepared and responsive, even as conditions on frozen lakes become more unpredictable.

Ultimately, the ongoing success of rescue operations on frozen lakes like Jazero hinges on a commitment to continuous improvement and adaptation. Future research should prioritize longitudinal monitoring of ice conditions, allowing for a deeper understanding of trends in ice thickness and their implications for safety. This data-driven approach will enable the development of refined protocols that align with the latest environmental conditions, ensuring that the lake remains a safe haven for winter recreation while preserving the readiness and safety of those tasked with rescuing others in perilous conditions.

4. Discussion

Experts in the field of crisis management unanimously agree that winter activities on frozen lakes carry inherent risks, but safety in such contexts is a relative and dynamic concept. As emphasized by Balog and Kovalenko [35], and Marticek and Knapcikova [36], the aim is to reduce risks to the lowest possible level, even though absolute safety can never be fully achieved. In the case of Jazero reservoir, achieving the required level of safety means managing risks so that the routine activities of responsible authorities are sufficient to address potential threats without the need for extraordinary measures [37]. Regional factors, such as large-scale climate patterns, can further influence ice stability, as demonstrated by Ptak et al. [38]. This highlights the need for localized assessments in understanding how broader climatic patterns impact specific lake conditions.

The influence of climate change on the stability of ice on lakes presents a significant challenge for crisis management experts. Studies, such as those by Woolway et al. [1] and Hewitt et al. [2], highlight how global warming is leading to warmer winters, resulting in more frequent freeze–thaw cycles. This leads to thinner and less predictable ice layers, posing new challenges for the safety and effectiveness of rescue operations. These insights align with our findings at Lake Jazero, where variations in ice thickness directly impact the choice and effectiveness of rescue methods. Sharma et al. [37] note that the reduction in lake ice is a global phenomenon, significantly increasing the risks associated with ice rescue operations and requiring new approaches to managing these situations. Similarly, Farp et al. [39] emphasize the need for the continuous monitoring of ice conditions, as changing ice thickness patterns can directly affect the safety and planning of activities on frozen lakes.

The case study conducted at Lake Jazero demonstrated that with a stable ice thickness ranging from 15 to 17 cm, traditional methods like the ladder technique with ice picks were effective, allowing for a quick and safe approach to victims. Under these conditions, the risk of breakthrough is minimized, and the response time is shortened, which increases the chances of successful rescue. However, in a hypothetical scenario where the ice thickness decreases by approximately 30%, reaching only 10 to 12 cm, the situation changes dramatically. The reduced load-bearing capacity of the thinner ice means that traditional access methods, like the ladder technique, become more challenging. Every movement on such thinner ice carries an increased risk of breakthrough, requiring extreme caution and a slower pace [40]. In this scenario, the time required for a safe approach to the victim could extend to around 70 to 75 s, which would simultaneously decrease the likelihood of a swift and successful rescue. As noted by Imrit et al. [41], similar trends in decreasing ice thickness across North America highlight the broader challenges faced by rescue teams dealing with increasingly unpredictable ice conditions.

In cases of extremely thin ice less than 10 cm thick, the situation becomes even more critical. Here, the use of flotation devices or special platforms for even weight distribution is necessary, prolonging the approach time to over 90 s. While this approach increases the safety of the rescuers, it also significantly lengthens the response time, potentially reducing the chances of a successful rescue. These differences are illustrated in Table 8, which shows how response times and the complexity of operations change under varying ice thickness scenarios. External factors like wind and waves can further reduce survival times during rescues, as highlighted by Power et al. [42], making the timing of these operations even more crucial.

Table 8. Comparison of rescue times and challenges in different ice thickness scenarios.

Scenario	Ice Thickness	Preferred Method	Approach Time	Challenges
Stable Ice	15–17 cm	Ladder method with ice picks	45–50 s	Stable conditions allow for a quick approach.
Reduced Stability	10–12 cm	Ladder method without ice picks	70–75 s	Increased risk of breakthrough; requires a slower approach.
Very Thin Ice	<10 cm	Flotation devices and platforms	>90 s	Extremely high risk of breakthrough; requires utmost caution.

While our study focuses on traditional rescue methods, such as the ladder technique, it is important to consider other approaches used worldwide. In regions like Canada and Scandinavia, inflatable bags and winches are often used, minimizing the need for direct contact between rescuers and thin ice. These techniques can be highly effective, but they are equipment-intensive, which may pose challenges for remote areas like water reservoir Jazero [43]. Advanced technologies, such as drones equipped with thermal sensors and sonar, are increasingly used to monitor ice thickness in real time [44]. Such technologies could significantly enhance the safety of rescuers and enable more effective decision-making during operations. However, our study considered methods that are accessible to local rescue teams without the need for substantial investment in new technology, providing practical solutions for regional needs.

The ongoing trend of thinning ice due to climate change represents a long-term challenge for the sustainability of rescue operations. Flexible and adaptive crisis management strategies, as well as regular updates to rescue protocols, will be crucial for maintaining operational effectiveness. Studies like those of Filazzola et al. [45] and Steiner et al. [46] emphasize the need for adaptation in response to climate-induced changes in ice cover, suggesting that monitoring and adapting to fluctuating ice conditions will be key to future safety measures. This approach would better prepare rescue teams for increasingly demanding conditions, ensuring the protection of lives even in the face of a changing climate [47].

5. Conclusions

This study focused on the challenges and strategies for rescuing individuals from ice-covered lakes, using the Jazero water reservoir as a case study. By comparing nine access routes, evaluating three rescue methods, and analyzing the impact of different combinations of rescue equipment, we made the following key conclusions:

1. Criticality of Response Time: Time remains a decisive factor that influences the success of rescue operations. Differences in routes and methods, confirmed through tactical exercises, demonstrated that even small time savings, such as the 4.5 s gained through optimized equipment, can be crucial in improving survival chances. This highlights the need for continuous training and adaptation of rescue procedures to maximize efficiency.
2. Importance of Proper Equipment: Among the evaluated methods—crawling, using ice picks, and the ladder method—the ladder method proved to be the most effective in balancing speed and safety. This underscores the necessity of equipping rescue teams with tools that allow them to adapt their approach based on the distance from shore and ice conditions. Providing such flexible equipment is vital for enhancing the ability of rescuers to respond swiftly and safely.
3. Strategic Planning of Access Routes: Detailed evaluation of nine potential routes around the Jazero water reservoir revealed that terrain and accessibility significantly impact the efficiency of rescue operations. Strategic route planning is essential, especially in areas with limited direct vehicle access. A thorough understanding of the terrain enables crisis managers to prepare for potential obstacles and ensure that, even under challenging conditions, rescuers can quickly reach those in need.
4. Recommendations for Improving Safety and Prevention: The findings of this study suggest that strengthening monitoring systems, raising public awareness, and improving infrastructure can significantly enhance safety on ice-covered lakes. We recommend the following:
   - ✓ Enhancing Monitoring Systems and Early Warning: Establishing a specialized team to monitor ice conditions and provide early warnings about weak spots could significantly improve the safety of visitors and local residents.
   - ✓ Raising Public Awareness of Safety: In line with global best practices, it is recommended to increase awareness of the risks associated with movement on frozen lakes through campaigns on social media, local media, and through informational signs around the lake.
   - ✓ Improving Infrastructure: In areas prone to freezing, it is important to improve safety measures, such as clear warning signs, anti-slip measures, and the availability of rescue equipment. In high-risk zones, heating technologies could be considered to prevent the freezing of critical infrastructure.
   - ✓ Strengthening Legal Framework and Policy Support: Developing clear regulations that define responsibilities for managing frozen lakes is essential.

Governments and local authorities should ensure financial support for the operation of monitoring and early-warning systems, thereby enhancing overall safety in the area.

5. Recommendations for Future Research: The findings of this study emphasize the importance of using more recent data (post-2016) to capture current climatic trends affecting frozen water bodies. Future research should focus on detailed assessment of the weight of individual risk factors during rescue operations, providing deeper insights into the influence of each factor on rescue outcomes. Such studies would provide valuable information for refining rescue techniques and strategies.
6. Application to a Broader Context: Although this study focused on the Jazero reservoir, its insights are applicable to similar inland water bodies that face variable ice conditions. The strategies discussed, such as optimizing equipment use and raising public awareness, are relevant for enhancing safety in other regions as well.

This study, combining local experiences with proven global practices, highlights the potential for continuous improvement in crisis management through openness to diverse approaches. Our analysis demonstrates that, by integrating technological advancements with adaptability in the field, the safety and efficiency of rescue operations can be enhanced, even under the most challenging conditions. We believe this model will serve not only as a foundation for further research but also as a practical guide for those involved in crisis management, both in Slovakia and beyond.

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