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When Maritime Meets Aviation: The Safety of Seaplanes on the Water

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Abstract: The water environment is a dynamic domain critical to global transportation and commerce, where seaplanes operate during take-offs, landings, and ground operations, often near maritime traffic. Canada's vast remote regions and unique geography increase reliance on seaplanes, especially for private and recreational purposes. This article examines the intersection of aviation and maritime operations through a mixed-methods approach, analyzing seaplane safety on waterways using quantitative and qualitative methods. First, data from 1005 General Aviation (GA) seaplane accidents in Canada (1990–2022) are analyzed, revealing 179 fatalities, 401 injuries, and 118 destroyed aircraft—significant given that seaplanes comprise under 5% of GA aircraft. Of these, 50.35% occurred while the seaplane was not airborne. Second, insights from interviews, focus groups, and questionnaires involving 136 participants are explored through thematic and content analysis. These capture pilot concerns that are not evident in accident data, such as hazards from jet ski interactions and disruptive boat wakes. The findings highlight risks like limited visibility and maneuverability during waterborne take-offs, worsened by seaplanes' lack of priority over maritime vessels in shared spaces. This article concludes with recommendations for both the seaplane and maritime communities, including increasing awareness among boaters about the presence and operations of seaplanes, as well as regulatory adjustments, particularly considering the right of way.

Keywords: seaplane; safety; take-off; landing; collision; water operations; maritime safety; aviation safety

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Academic Editors: Andrea Maternová, Andrej Dávid, Nermin Hasanspahic, Lucia Švábová, Grzegorz Karoń and Ayeley Tchangani

Received: 21 March 2025
Revised: 9 May 2025
Accepted: 14 May 2025
Published: 22 May 2025

Citation: Manole, I.; Majumdar, A. When Maritime Meets Aviation: The Safety of Seaplanes on the Water. *Appl. Sci.* **2025**, *15*, 5808. https://doi.org/10.3390/app15115808

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1. Introduction

Hazards, whether natural or human-made, present potential threats to individuals, equipment, and operations [1]. Reducing these and mitigating associated risks are essential objectives in transportation safety to protect lives, goods, and the environment. However, systematic hazard analysis is often constrained by reporting limitations, as incidents that do not result in significant damage or harm may go unreported. Public accident databases frequently lack critical contextual details, such as environmental factors or pilot decision-making processes, leading to incomplete insights. A comprehensive safety analysis must therefore go beyond traditional accident data to incorporate both qualitative and quantitative methods.

The maritime industry is considered to be the most complex and dangerous worldwide [2,3]. Canada is a nation that boasts a rich maritime heritage and vast coastal regions, with major ports such as Vancouver, Halifax, and Montreal playing critical roles in international trade and commerce. Maritime safety is crucial due to its role in providing a protective refuge for vessels, facilitating the transfer of people and goods, promoting trade

and economic growth, and serving as a significant source of employment. Recent studies, such as that by Cao et al. [4], have emphasized that maritime accidents are influenced by multiple interconnected risk factors, highlighting the need for robust analytical frameworks to better manage operational safety. In particular, ports represent dynamic environments with a complex set of safety challenges.

Canada is also a global leader in seaplane operations. However, the unique operational environment of seaplanes, combining maritime and aviation hazards, requires pilots to navigate risks associated with both sectors. This poses specific safety management challenges that are currently underexplored. Canada, with its vast and rugged geography, is a global leader in seaplane operations, supporting both commercial and recreational activities. While commercial seaplane operations are subject to stringent regulatory oversight, private and recreational seaplane pilots often operate under more relaxed regulatory frameworks. This increases their exposure to safety risks. Unlike land-based aircraft, seaplanes must contend with additional hazards, such as water conditions, limited maneuverability, and interactions with maritime traffic. The dual nature of seaplane operations further complicates their safety management, as regulatory distinctions exist between aircraft and vessels.

Seaplanes are generally defined as aircraft that can take off and land on water. The International Civil Aviation Organization (ICAO) defines a seaplane as "An airplane on floats (amphibious or non-amphibious) or a flying boat (water-only or amphibious)" [5]. There are two main categories of seaplanes in use in Canada:

(i) Floatplanes—these have floats but no wheels;
(ii) Amphibious—these are planes that have floats and retractable wheels, so they have the capability to land and take off from both the land and the water.

In addition, according to the 1972 International Regulations for Preventing Collisions at Sea (COLREGs), a seaplane is regarded as a vessel when it is on the water, whether it is landing, anchored, or being launched from a water slide. However, when the seaplane is out of the water, it is treated as an aircraft [6].

Research relating to the safety of ships and seaplanes sharing the water environment is scarce, but there are a few studies that mention both. These have revealed several key areas of concern and methodological approaches. Gao [7] conducted an extensive risk analysis of seaplane operations in Sanya Port in China, comparing the maritime traffic environment of seaplanes to that of other vessels, and emphasizing unique safety challenges. Similarly, Vidan et al. [8] explored the operational and environmental safety of seaplane traffic in Croatia, noting differences in waste management between seaplanes and traditional vessels. These studies emphasize the need for customized safety protocols that consider the specific dynamics of seaplanes on water.

In complex socio-technical systems, the safety issues of smaller communities within a transport sector can often be overlooked. General safety measures designed for larger communities or transport sectors, outlined in safety management systems (SMSs), may be ineffective for those that are smaller, requiring tailored safety strategies to address their unique challenges. For example, seaplane operations are part of both the aviation and maritime sectors and require specific safety measures due to their dual operational environments. Additionally, safety in commercial operations is more thoroughly addressed due to the greater scrutiny and regulations needed to protect larger passenger and cargo volumes. In contrast, private operations often fall under less rigorous regulatory frameworks, with fewer mandatory safety measures and oversight, leading to gaps in comprehensive safety standards. Consequently, private pilots may be indirectly affected by factors that are less prevalent in commercial aviation, such as less rigorous training and infrequent flying. Given the unique risks associated with recreational seaplane flying, such as varying pilot experience and diverse operating environments, a thorough sector-specific analysis is

imperative. Analyzing subsets of occurrences (referring to both accidents and incidents) is crucial to understand and address specific challenges for underrepresented communities in a transport sector. This approach aids in identifying specific safety issues and formulating targeted recommendations to enhance overall safety in complex transport systems.

This research addresses these critical gaps by conducting a comprehensive, mixed-methods safety analysis of private recreational seaplane operations on water. It contributes directly to the improvement of maritime and aviation safety management systems by providing an evidence-based understanding of safety risks at the intersection of these two domains. The potential benefits of this study include informing targeted regulatory adjustments, enhancing pilot training programs, promoting integrated reporting practices, and improving stakeholder collaboration between maritime and aviation authorities. Ultimately, by strengthening seaplane safety protocols, this research can contribute to safer waterways, reduce accident rates, and support broader efforts in transport safety governance.

In summary, the water environment is a complex and dynamic place where two transport sectors intersect. Even though the literature including both seaplanes and vessels is very limited, it remains important to study the interactions of these sectors and mitigate their specific risks. Both the maritime and aviation sectors benefit from tailored SMSs that incorporate both human factors and risk assessment methodologies. Therefore, this paper aims to address the above limitations by employing a mixed-methods approach of qualitative and quantitative analysis of seaplanes' safety on water. A holistic understanding of seaplane safety is sought not only through data collection and analysis but also through understanding the importance of minor incidents or near-misses and their reporting, the knowledge and expertise of different stakeholders and industry professionals, and finally, assessing how organizational aspects come into play and share safety knowledge.

2. Materials and Methods

This section outlines the methodology used to analyze the safety of private recreational seaplane operations in Canada, as shown in Figure 1. It includes details of the occurrence (accident/incident) database (Section 2.1), data categorization (Section 2.2), data analysis (Section 2.3), and survey proposal (Section 2.4).

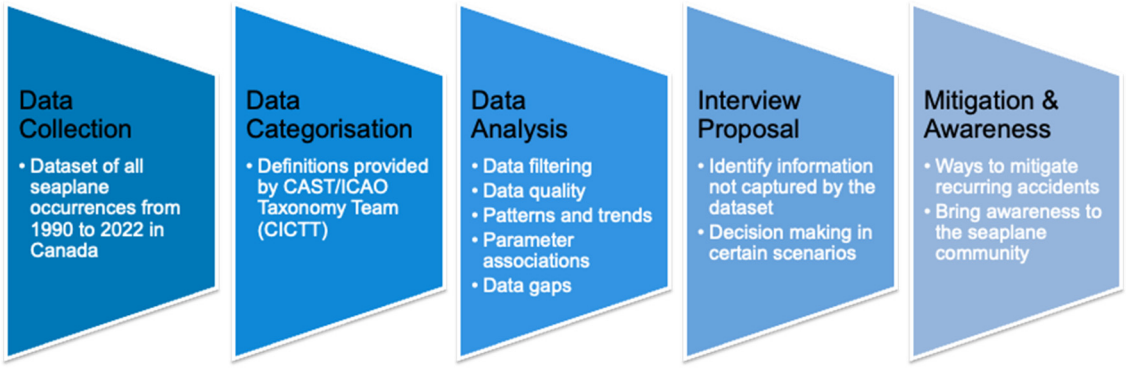


Figure 1. Methodology used for the study of seaplane safety on Canadian waters.

Firstly, as this paper considers only occurrences of seaplanes on the water, it is important to correctly categorize the phase of flight when an accident or incident occurs. For this purpose, Goblet et al. [9] provided a comprehensive list of possible safety events during each phase of flight and developed an algorithm to detect the phase of flight. However, these phases of flight are for commercial operations, and we have made changes below to reflect the phases of flight for General Aviation (GA) operations. It should be noted that, for seaplanes, a runway can also be on a body of water.

The phases of flight where an occurrence can happen for GA seaplane operations have been separated into 14 categories, as presented in Table 1. This is based on adaptation of the CAST/ICAO Common Taxonomy Team (CICTT) [10] definitions of phases of flight, so as to reflect the phase categories used by the regulator, Transport Canada, for its occurrence reports and for GA.

Table 1. Definitions for phases of flight during seaplane operations by adapting CICTT [10] definitions of phases of flight. The phases of flight in italics are subcategories of the phase of flight they follow (e.g., "Initial Climb" and "Cruise Climb" are subcategories of "Climb").

Phase of Flight	Definition
Standing	Stationary aircraft at dock before taxi.
Taxi	Aircraft unassisted in moving before take-off or after landing.
Take-Off	Starts when take-off power is applied, until either being airborne above 35 feet from the runway/water elevation, or when the gear is up. This includes rejected take-offs.
Climb	
Initial Climb	After take-off, until the aircraft either reduces prescribed power for the first time or reaches 1000 feet above the runway/water elevation.
Cruise Climb	Subcategory added to account for the period after the initial climb and prior to leveling off at cruise altitude.
Cruise	Level flight segment between the end of climb and the beginning of descent for landing.
Maneuvering	Intentional altitude changes during low altitude (not associated with take-off and landing).
Descent	Descent between level flight and 1000–2000 feet above the runway/water elevation. It includes emergency and uncontrolled descent.
Approach	Constant altitude decrease in preparation for landing, from 1000–2000 feet above the runway/water elevation until the beginning of the landing flare. It includes missed approaches and go-arounds for up to 200 feet above the runway/water elevation.
Landing	The phase that immediately follows the approach, where the aircraft transitions to the landing attitude, enabling the airplane to touch down on the landing surface at the slowest speed possible commensurate with safety. This transition is known as the flare. The flare is normally executed at 50 feet or less above the runway/water elevation. For touch-and-go landings, this phase ends the moment power is applied for take-off. Landing includes flare, touchdown, and aborted landings after touchdown.
Landing Run	The phase that immediately follows the water landing, when the aircraft slows down to taxi speed (normally with the engine at idle), until reaching the end of the landing runway or coming to a stop on the runway.
Docking	The transition from idle taxi to the safe securing of the seaplane to a permanent structure fixed to the shore. Docking is normally executed with the engine stopped.
Other	
En Route	After the initial climb, through cruise and controlled descent, until the initial approach. Often used when it is not clear in which of the airborne phases of flight the occurrence took place.
Post-Impact	Considers the segment of flight after impacting terrain, obstacles, people, or objects.
Unknown	For accident and incident data, when the phase of flight of the occurrence could not be determined.

Figure 2 was created to account for 10 out of the 14 phases of flight. It does not include maneuvering, en route, post-impact, and unknown.

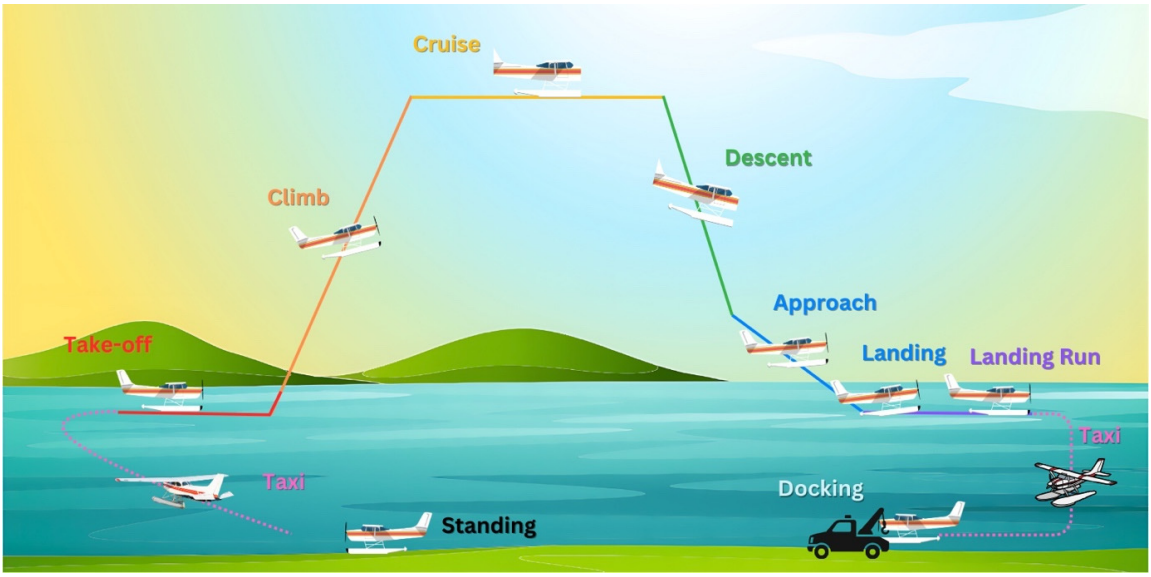


Figure 2. Illustration of the typical phases of flight of a seaplane, excluding maneuvering, en route, post-impact, and unknown.

2.1. Description of the Database of Seaplane Occurrences in Canada

Transport Canada (TC), the safety regulator, has collated a database that consists of 1771 seaplane occurrences (accidents and incidents) in Canada, from 1990 to 2022. In this database, there are 466 occurrences on water involving private recreational operations, during the following phases of flight: standing, taxi, take-off, landing, landing run (roll out), and docking (including parked).

While TC provided a comprehensive dataset, certain data fields had to be derived from the narratives, such as the cause of the occurrence (categorization), number of injuries and fatalities, and route. The data fields include general information (e.g., date, time, phase of flight), details of the surrounding environment (e.g., route, location), aircraft specifications (e.g., damage level, tonnage, landing gear), and environmental conditions (e.g., weather). To enhance the reliability of the data extraction process, an inter-rater verification method was applied, whereby a second reviewer independently coded a randomly selected subset of narrative-derived fields. Discrepancies were discussed and resolved through consensus to ensure consistent interpretation and minimize potential bias.

Details of the individuals affected (e.g., gender, age, injuries) were unavailable, as were any details about the pilot's performance. Complementary data collection methods such as interviews, focus groups, and decision-making studies, e.g., those by Irwin et al. [11], are considered in this paper. The underreporting of incidents, either due to minimal reporting requirements or fear of repercussions, further limits the dataset's accuracy, potentially skewing risk assessments. Comprehensive reporting and interdisciplinary approaches are therefore essential to address these limitations, ensuring a holistic understanding of seaplane safety and enabling meaningful recommendations for mitigating risks in shared waterways.

2.2. Categorization of Seaplane Occurrences

Hazards that can lead to an occurrence are categorized using the Hazards Common taxonomy [12], according to their type: human, technical, environmental, or organizational. Aviation occurrences are categorized using the Aviation Occurrence Categories from the Commercial Aviation Safety Team (CAST) and the International Civil Aviation Organization (ICAO), as of May 2021 [13], according to their contributory factor(s). These categories are grouped into the following: take-off and landing, airborne, ground operations, aircraft,

non-aircraft-related, weather, and miscellaneous [13]. The categorization is not part of the recorded data fields of reported accidents or incidents, and it is determined separately only for the few occurrences that require deeper investigation and have a published Canadian Transport Safety Board (TSB) report.

2.3. Analysis of Past Seaplane Occurrences on Canadian Waters

Descriptive statistics, frequency analysis, and distributions were used to analyze the trends of seaplane occurrences on Canadian waters. The TC dataset contains the following types of data:

- Continuous (e.g., number of injured people);
- Categorical (e.g., phase of flight);
- Textual (e.g., occurrence description).

Both continuous and categorical data were tested for normality using the Kolmogorov–Smirnov (sample > 50) and Shapiro–Wilk (sample < 50) tests [14]. Non-parametric statistical tests, such as Pearson's chi-squared test (χ^2), were applied for non-normally distributed data. For categorical variables, Pearson's chi-squared test (χ^2) was used to compare the actual frequencies with the corresponding expected frequencies in the categories of the variables [14]. The χ^2 statistic is calculated using Equation (1):

$$\chi^2 = \sum \frac{(observed\ frequency - expected\ frequency)^2}{expected\ frequency} \quad (1)$$

where the expected frequency refers to the expected count if there was no association between parameters, while the observed frequency is obtained from the dataset. Moreover, the data fields are adjusted such that the expected frequencies less than five are under 20% [15]. Otherwise, it is considered that there are not enough data to test the association.

The p-value indicates the statistical significance of the association, with lower p-values, meaning stronger evidence against the null hypothesis, for statistically significant relationships. The significance was set at $p < 0.05$ for the statistical test, meaning a 95% confidence level. Consequently, the phi value was used as a measure of the strength of the association, with higher phi values indicating stronger relationships. Based on this, the strength of the relationship was determined (weak, moderate, or strong). Table 2 shows the interpretation of the phi values.

Table 2. Interpretation of phi values [16].

Phi Value	Strength of Relationship
−1.0 to −0.5 and 0.5 to 1.0	Strong
−0.5 to −0.3 and 0.3 to 0.5	Moderate
−0.3 to −0.1 and 0.1 to 0.3	Weak
−0.1 to 0.1	None or very weak

2.4. Survey

While the analysis of accident and incident data is crucial for improving safety and ensuring accident prevention in the future, there are certain limitations that hinder a comprehensive understanding of all underlying safety factors. There are gaps in the available data that have been mentioned previously, especially related to the people involved in the occurrence, such as decision-making, concerns, and other contributory factors that can influence safety outcomes. Hence, additional data were collected to complement the

insights from accident and incident data analysis, by means of a survey that engaged with pilots and other safety professionals in the field.

This survey encompassed a wide range of scenarios that encourage pilots to critically consider their actions in different conditions, while bringing awareness regarding current safety issues. These scenarios were based around the most frequent occurrence categories and phases of flight when accidents and incidents occur. The methods used to gather qualitative data from recreational, private GA pilots in Canada were as follows: semi-structured interviews, phenomenological focus groups, and a phenomenological questionnaire. Thematic and content analyses were employed to identify key safety issues and develop an in-depth understanding of the processes and interactions affecting GA seaplane safety. The data were coded and analyzed iteratively, enabling themes to emerge naturally from the data. This approach ensured a comprehensive understanding of the participants' perspectives and experiences.

Participant confidentiality was preserved, and the study complied with the General Data Protection Regulation for health and care research. Additionally, approval from the Research Governance and Integrity Team (RGIT) was obtained for this survey. This study was conducted in compliance with the protocol, Data Protection Act 2018, and General Data Protection Regulations (Europe), along with other regulatory requirements as appropriate.

Multiple-choice or open-ended questions were used, which were structured into six parts. These are a subset of the questions asked that relate to seaplane operations on waters only:

1. Participant information and consent;
2. General details;
3. Information gathering—safety training and concerns;
4. Scenario discussion—take-off;
5. Scenario discussion—landing;
6. Ending questions.

The questionnaire, focus groups and interviews were based on the same questions and began with a short description of their purpose, after which the participants were assured of their confidentiality and explained their freedom to withdraw without giving a reason (Part 1). Informed consent was obtained from all participants prior to proceeding with the questions. Parts 2 and 6 contained questions about the participants' age group, experience, seaplane ratings, safety training, and preferred methods of safety awareness. Sections 4 and 5 consisted of scenarios that included the questions "What have you done to mitigate this?" and "What would you do to mitigate this?", regarding different hazardous situations that may happen during take-off and landing.

This survey was intended to gain information related to pilot decision-making during different scenarios, as well as other details about safety training and practices, and the ways in which pilots stay current and proficient. Pilots could express their current safety concerns and propose methods for safety prevention and awareness. All answers were anonymous, increasing the chance that the pilots would answer truthfully.

3. Results

Mixed methods of quantitative and qualitative analysis were used to analyze the safety of seaplanes on Canadian waters, as previously presented in Section 2. This section presents and interprets the results of the accident/incident data analysis (Section 3.1), as well as the responses obtained through the survey (Section 3.2). Table 3 summarizes the accident/incident dataset and the methods of analysis used.

Table 3. Summary of the accident/incident dataset and the reasons of employing different methods of analysis.

Dataset Description	Method of Analysis	Reason
- Canada - 1990 to 2022 - 466 private recreational GA on-water seaplane occurrences - Source: Transport Canada	Narrative analysis	To extract further information and improve the quality of the analysis. It includes the occurrence categorization.
	Trend analysis	Calculate trends and determine patterns.
	Contingency analysis	To detect potential associations and relationships between two and three variables.
	Three-way associations	
	Interviews	Engagement with industry professionals to discuss the data analysis results and assess mitigation methods.
	Focus groups	Engagement with seaplane pilots and industry professionals to determine potential factors not included in the database and bring awareness of current areas of concern.
	Questionnaire	

3.1. Analysis of Previous Accidents and Incidents

This section provides the quantitative analysis of the accident/incident dataset of past seaplane occurrences on Canadian waters. It includes an assessment of the narratives (Section 3.1.1), trend analysis (Section 3.1.2), contingency analysis and three-way associations (Section 3.1.3), and a summary of the results (Section 3.1.4).

3.1.1. Narrative Analysis

The occurrence narratives were used to identify their root causes from the following categories: airborne, ground operations, take-off and landing, aircraft-related, non-aircraft-related, weather conditions, and miscellaneous. Within these categories, factors such as visibility, wind, loss of control, mechanical errors, human errors in making decisions or in operating the plane, the reasons for pilots making certain decisions (such as abrupt maneuvers), missing emergencies, etc., were considered. This particularly timely task revealed that loss of control and abnormal runway contact led to the majority (59.23%) of seaplane occurrences on the water (Table 4).

Table 4. Five most recurrent types of seaplane accidents and incidents on the water.

Category Name	Category ID	Count	Percentage
Loss of Control—Ground and Inflight	LOC-G and LOC-I	152	32.62%
Abnormal Runway Contact	ARC	124	26.61%
System/Component Failure or Malfunction (Non-Power-Plant)	SCF-NP	42	9.01%
Collision with Obstacle(s) During Take-Off and Landing	CTOL	29	6.22%
Unintended Flight in IMC	UIMC	20	4.29%
System/Component Failure or Malfunction (Power Plant)	SCF-PP	18	3.86%
Abrupt Maneuver	AMAN	15	3.22%
Unknown	UNK	15	3.22%
Ground Handling	RAMP	10	2.15%
Other	OTHR	9	1.93%

3.1.2. Trend Analysis

The dataset of seaplane occurrences was analyzed around the following variables:

- Year;
- Landing gear;
- Phase of flight;
- Aircraft damage level;
- Injuries and fatalities.

In Canada, the number of seaplane occurrences has gradually decreased over the years (Figure 3). However, considering private recreational seaplane operations on the water in particular, the number of occurrences is showing an increase over the years (Figure 4). This indicates that, while general seaplane safety may be improving, especially in the commercial world, there are unique challenges and risks associated with recreational, on-water seaplane operations that need to be addressed. This subset of data is used for the subsequent analysis in this article. It should also be noted that COVID-19 restrictions impacted the number of flights in 2020–2021.

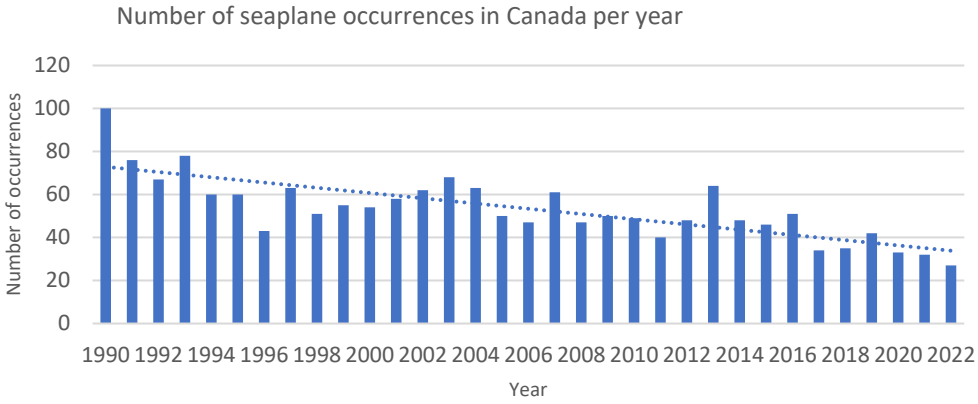


Figure 3. Distribution of the yearly number of seaplane occurrences in Canada.

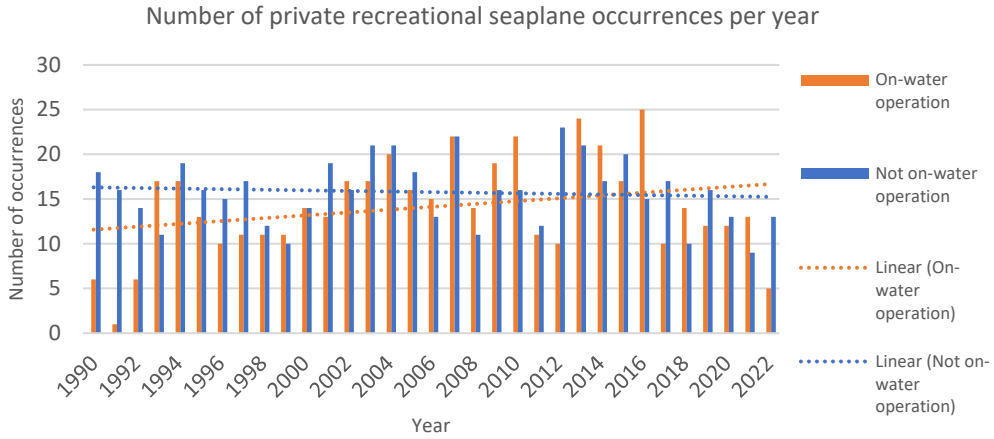


Figure 4. Distribution of the yearly number of seaplane occurrences in Canada for private, recreational, on-water operations.

The accurate calculation of occurrence rates for seaplanes presented a significant challenge due to the deficiency of data on seaplane movements, or on the yearly number of hours flown by seaplane pilots. This issue is particularly relevant in the context of recreational seaplanes in Canada, where specific data are not available. One of the primary issues highlighted by Ison [17] is the lack of detailed data on the seaplane fleet and the cadre of seaplane pilots in the US, which makes it difficult to calculate accurate accident/incident

rates because comprehensive records of flight hours, pilot experience, and operational contexts are often incomplete or unavailable. This is also the case for Canada.

Figure 5 shows how the number of injuries and fatalities fluctuated over the period, with the trendline ascending for the number of injuries and constant for the number of fatalities. The probable impact of COVID-19 restrictions on the number of flights in 2020–2021 should be noted. Also, it was not possible to determine the number of injuries and fatalities between 1990 and 1992 for a large number of narratives, so these three years have been removed.

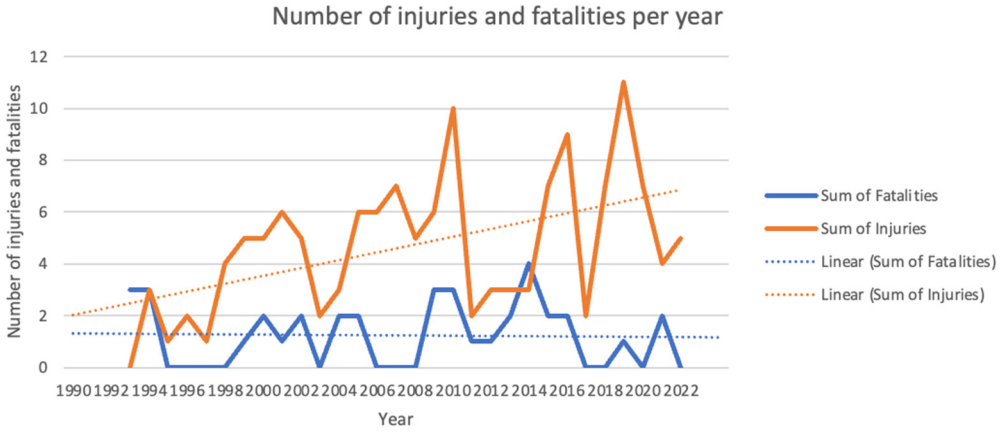


Figure 5. Numbers of injuries and fatalities per year, for private, recreational, on-water seaplane operations in Canada.

The number of occurrences annually for recreational seaplane operations on water involving amateur-built aircraft shows an increasing trend over the period, as shown in Figure 6, with the first amateur-built occurrence in 1998. From 2003, the numbers stabilize around a consistent average, which can be attributed to improved safety and a more experienced and knowledgeable community, along with regulatory enhancements. However, in recent years, a considerable percentage of occurrences have involved amateur-built aircraft. This highlights the importance of maintaining improvements so that, in the future, amateur-built aircraft become safer, to ensure a decreasing trend in their occurrences.

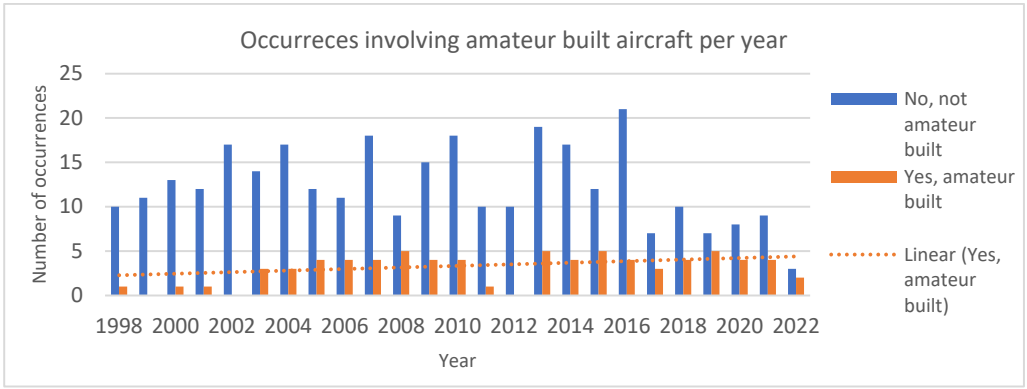


Figure 6. Number of occurrences per year for private, recreational, on-water seaplane operations using amateur-built aircraft, in Canada.

Exploring the relationship between different occurrence causes and the level of damage to the aircraft reveals whether there are significant differences in the degree of damage suffered by seaplanes under different causes, thereby providing information for safety management and flight operations.

Figure 7 illustrates the severity of aircraft damage resulting from the occurrences, with 94.62% leading to substantial aircraft damage, while 3.44% resulted in the aircraft

being destroyed. These figures show that, irrespective of the cause of occurrence, serious damage or even destruction of the seaplane is the likely result. The most notable trend is the fluctuation in the number of substantially damaged aircraft, which, in the past six years, while showing a gradual decline, nonetheless shows an increasing trendline over the period. Occurrences with less than major structural problems with the aircraft are not required to be reported unless there has been a death, injury, missing aircraft, or collision [18], which is reflected in the low numbers of occurrences where the aircraft had minor or no damage.

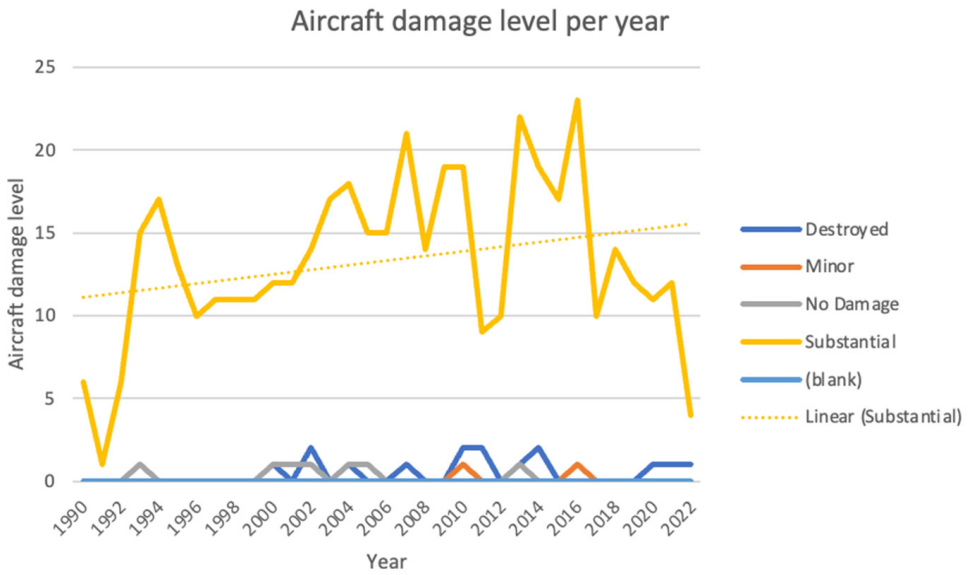


Figure 7. Aircraft damage level per year, for private, recreational, on-water seaplane operations in Canada.

Figure 8 indicates that the landing phase is the most hazardous for recreational seaplane operations in Canada, accounting for 51.5% of occurrences. It shows an increasing trend, with an average increase in the past decade, following a peak period between 2013 and 2019. The trendline for take-off (accounting for 22.75% of the occurrences) is slightly decreasing, with an increase in 2020–2021.

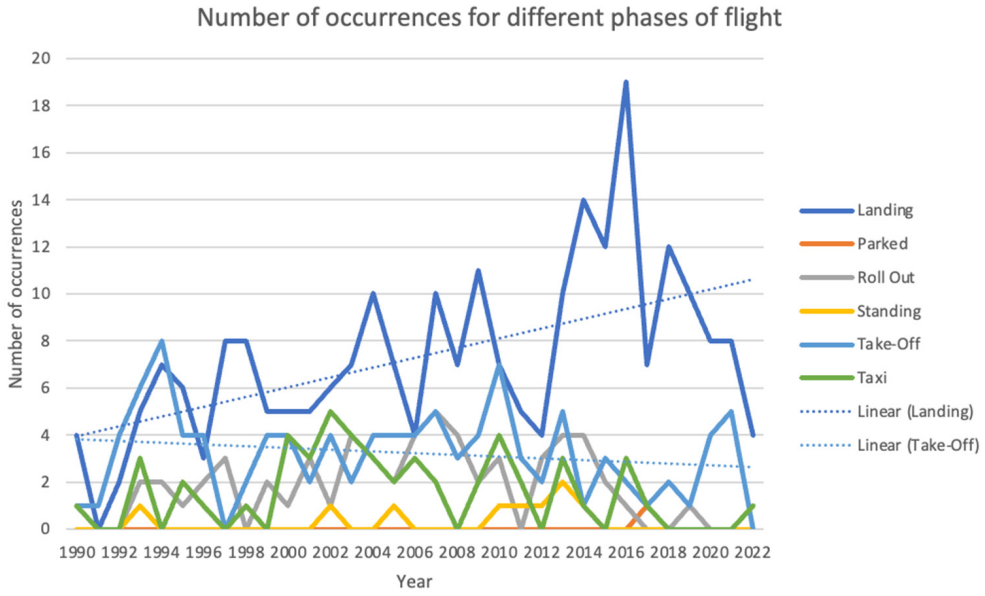


Figure 8. Number of occurrences during the top 5 phases of flight, for private recreational seaplane operations in Canada.

Figure 9 shows the number of occurrences during take-off for the studied period. It shows several peaks, indicating intermittent periods of increased risk. Despite a low profile for take-off in 2014–2019, the years 2020 and 2021 show the highest number of occurrences in the past decade, despite restrictions on the general population due to the COVID-19 pandemic in those years. The data for landing show an increasing trend in occurrences from around 2013 onwards, peaking notably in 2016. This indicates a possible shift in the underlying factors contributing to landing incidents, such as changes in operational procedures, increased seaplane activity, or variations in reporting practices.

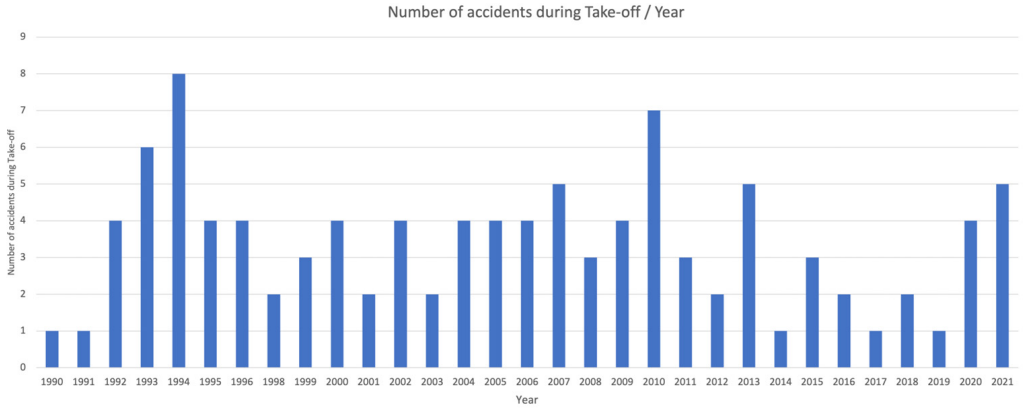


Figure 9. Number of occurrences during take-off per year, for private recreational seaplane operations in Canada.

The distribution of the type of landing gear of the seaplanes involved in occurrences is 62.23% float and 32.83% amphibious (float-wheel and hull-wheel). The number of float seaplanes in Canada is expected to be higher than that of amphibious aircraft, although exact numbers could not be obtained, hence the difference in the number of occurrences for these categories. Figure 10 illustrates the number of occurrences for different occurrence categories, per different landing gear. It shows that float-equipped seaplanes have the highest number of occurrences across all categories, particularly in "LOC-G" (loss of control on ground), with 28.62% of float occurrences. Amphibious float-wheel and hull-wheel configurations also show significant numbers of occurrences, albeit to a lesser extent. The most frequent type of occurrence for amphibious aircraft is "ARC" (abnormal runway contact), with 37.25% of amphibious occurrences.

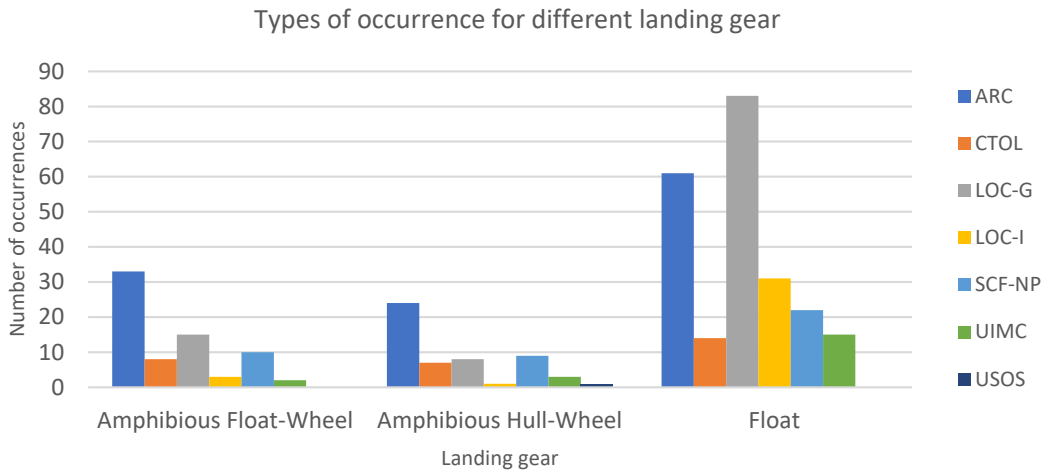


Figure 10. Number of occurrences for different categorizations, per different landing gear, for private, recreational, on-water seaplane operations in Canada.

Between 1993 and 2022, private recreational seaplane occurrences in Canada led to 179 fatalities and 401 injuries, out of which the on-water occurrences led to 37 fatalities and 140 injuries. Most of the injuries occurred after abnormal runway contact (31.43%), followed by loss of control on ground (15.71%) and engine failures (10%). When considering the number of fatalities, the majority occurred during unknown circumstances (35.14%), followed by abnormal runway contact and loss of control in flight (13.51% each).

The landing phase shows the highest number of injuries (62.14%) and fatalities (64.86%), followed by the take-off phase (23.57% of injuries and 16.22% of fatalities).

Figure 11 outlines the changes in the numbers of injuries and fatalities over the studied period, showing an increasing trendline in the number of injuries and a constant one for fatalities. Despite low numbers in 2021–2022, this figure indicates peak values every decade, each higher than the time period before, which is concerning for the safety of seaplanes on the water.

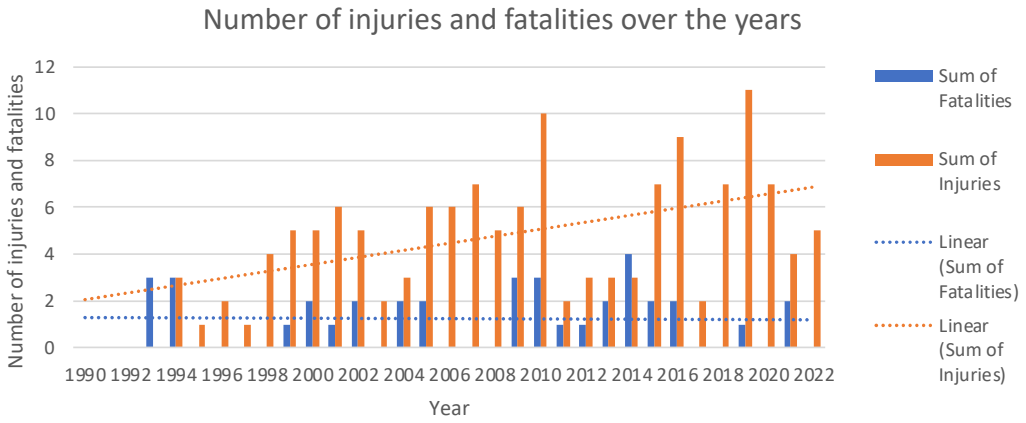


Figure 11. Numbers of injuries and fatalities per year, for private recreational seaplane operations on water in Canada.

3.1.3. Contingency Analysis and Three-Way Associations

Results were obtained at a 95% confidence level, for permutations of two or three of the parameters in Table 5. These were then recoded and converted into binary variables, as shown in Table 5, to help understand the meanings of the associations. In some cases, such as for the "Time" parameter, which had many possible outcomes, these were grouped to reflect the part of the day (morning and evening, daytime and night-time) and therefore have only three possible outcomes. In other cases, such as for the "Phase of Flight" parameter, some possible outcomes were grouped into an "Other" binary variable, so that the focus could be on the phases of flight deemed to be of interest during the trend analysis. This was generally done for the least frequent outcomes, to avoid binary parameters with a low expected count, as those would not provide accurate results.

Table 5. Parameters used for the contingency analysis and three-way associations.

Parameter	Binary Variables	Count	Description/Reasoning
Year	1990–2000	117	Separated the years into 3 groups of equal number of years.
	2001–2011	186	
	2012–2022	163	
Month	May–October	432	Grouped into flying season (May–October) and outside flying season (November–April).
	November–April	34	

Table 5. *Cont.*

Parameter	Binary Variables	Count	Description/Reasoning
Time	Daytime (11:00–17:59)	277	Grouped to reflect the part of the day.
	Morning and evening (05:46–10:59 and 18:00–21:59)	168	
	Night-time (10 p.m.–05:45 a.m.)	21	
Aircraft Amateur-Built Flag	Yes amateur-built	75	Unchanged.
	Not amateur-built	391	
Aircraft Landing Gear	Amphibious	153	"Amphibious Float-Wheel" and "Amphibious Hull-Wheel" were grouped into "Amphibious". Categories grouped into the "Other" category: "Hull" and "Water Landing Aircraft".
	Float	290	
	Other (landing) gear	23	
Aircraft Damage Level	Substantial	440	Categories grouped into the "Other" category: "Minor", "No Damage", and "Missing Aircraft".
	Destroyed	16	
	Other damage (level)	10	
Phase of Flight	Landing	240	Categories grouped into the "Other" category: "Parked" and "Standing".
	Roll-out	59	
	Take-off	106	
	Taxi	51	
	Other phase (of flight)	10	
Type of Occurrence (Occurrence Category)	ARC	124	Categories grouped into the "Other" category: "AMAN", "ATM", "BIRD", "CFIT", "FUEL", "GCOL", "LALT", "MAC", "MED", "OTHR", "RAMP", "RE", "TURB", "UNK", "USOS", and "WSTRW".
	CTOL	29	
	LOC-G	113	
	LOC-I	39	
	SCF-NP	42	
	SCF-PP	18	
	UIMC	20	
	Other (1st occurrence) category	81	

The results of this analysis are presented in Figure 12, which represents a heatmap of the relevant associations with a 95% confidence level. The blue shades indicate moderate relationships, while the red shades indicate strong relationships.

Some findings that are similar to the findings already presented in the previous sections were excluded. Moreover, the associations where one of the parameters was daytime, May–October, or non-amateur-built were excluded, as it was previously determined that the majority of accidents and incidents happen then. Moreover, the "Other" categories were also removed, as they include combinations of less frequent variables.

Taking these factors into account, the main findings for strong relationships with a 95% confidence level are shown in Figure 12. As an example, there is a strong association of amphibious aircraft being destroyed after occurrences during take-off or landing, or having substantial damage. However, occurrences of amphibian seaplanes during taxi are likely to not cause serious damage to the aircraft.

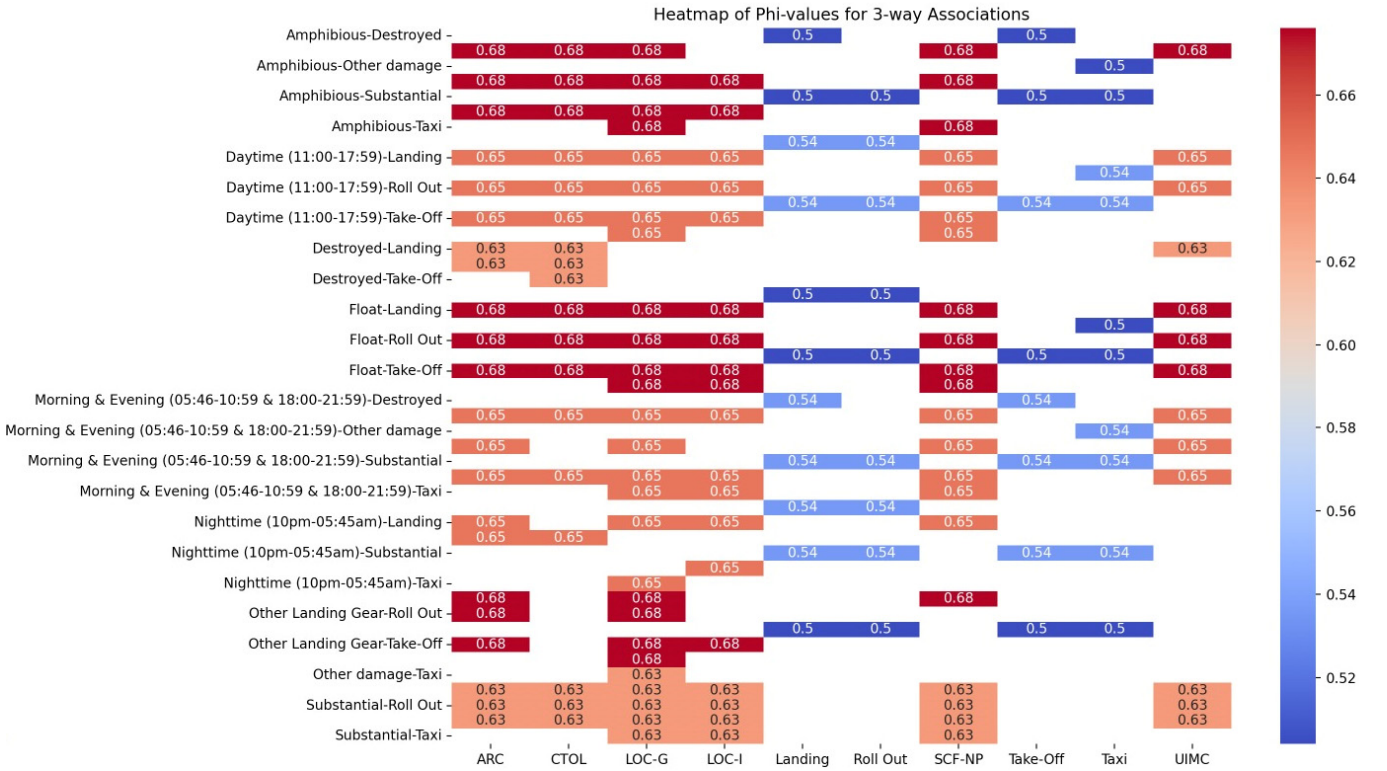


Figure 12. Three-way associations between 9 parameters for on-water occurrences of private recreational seaplanes.

3.1.4. Summary of Quantitative Analysis

This section presents the analysis of private recreational seaplane occurrences on the water in Canada, based upon the methods outlined in Table 3. The dataset and its limitations have been defined, and data quality checks were employed. For example, such limitations include the correlation between the number of occurrences and pilot experience, the inability to calculate accident or incident rates, or factors such as pilot experience, decision-making, and critical thinking in adverse scenarios that are not captured by the dataset. Potential solutions could include adding additional factors to be reported in case of an occurrence, or merging pilot logs with occurrence data. In addition, voluntary reporting apps could be promoted to minimize the underreporting of less serious incidents.

Despite these insights from the safety data analysis, it is still insufficient if we wish to understand why such occurrences happen in order to enhance the safety of this sector. The following section (Section 3.2) expands on this analysis and uses the results as the basis for collecting additional qualitative data from GA pilots.

3.2. Analysis of the Survey Responses

To supplement the quantitative analysis of the previous section, a mixed-methods approach based on qualitative data from interviews, focus groups, and a questionnaire is analyzed in this section.

This study recruited 80 recreational seaplane pilots with varying degrees of experience (in terms of both years and hours flown). The participants ranged from under 20 to over 70 years of age, with the majority being above 50. A possible explanation for this could be that the population of seaplane pilots is decreasing, while at the same time they are currently likely to be working and, thus, unable to attend the interviews or focus groups. Moreover, their experience in flying seaplanes is not directly proportional to their age and has a better distribution: 32% of the participants had over 30 years of experience flying seaplanes, indicating a highly experienced group. Other categories of seaplane flying

experience included the following: 20% of participants with 6–10 years, 18% with under 2 years, 12% with 21–30 years, and smaller groups with 2–5 years (9%) and 11–20 years of experience (9%). This reflects a broad range of experience levels among the participants. However, sampling bias should be noted, since there was a notable concentration of experienced pilots.

The data collection methods included online questionnaires, interviews, and focus groups, conducted both in person (22 participants) and online (29 participants). This study also engaged representatives from Canadian seaplane associations and Transport Canada to ensure diverse stakeholder representation. Ethical considerations excluded minors and vulnerable populations to prioritize participant safety and consent.

These qualitative data were analyzed using thematic analysis [19,20]. This method was employed to identify safety concerns by refining and analyzing codes and themes (patterns) within the data, with the themes redefined to be consistent for all three methods of data collection used. By identifying and analyzing these themes, the concerns and experiences of seaplane pilots can be better understood, and specific recurring issues can be addressed [21].

Before the start of the scenarios, the participants in the questionnaire were asked about personal safety concerns. The notable responses include concern over too many aircraft crashing and people killed, amphibious safety (including landing gear configuration on landing), and concerns about pilot attitudes in general. The key safety concerns identified through thematic analysis are summarized in Table 6.

Table 6. Summary of the main areas of concern (themes) identified by seaplane pilots and other safety professionals.

Theme	Key Findings
Training issues	Need for real-world flying experience; decline in basic skills due to overreliance on advanced systems.
Overreliance on technology	Excessive dependence on avionics (e.g., G1000) risks eroding fundamental flying skills.
Hazards from boats and jet skis	Unpredictable behavior creates collision risks; calls for regulatory right-of-way rules.
Misuse of radios during recreational operations	Lack of communication increases collision risks; “silent operations” culture persists.
Environmental and fauna awareness	Weather unpredictability, wildlife strikes, and challenges of glassy water conditions.
Mechanical reliability and safety	Concerns about engine failures; need for regular maintenance and high-quality equipment.

Pilots emphasized the importance of real-world experience, citing it as a critical complement to theoretical knowledge in preparing them for unexpected situations. However, concerns were raised about overreliance on advanced systems like the G1000 avionics system, which was perceived to erode fundamental flying skills. Participants highlighted the need for training programs to strike a balance between teaching traditional piloting techniques and incorporating modern technologies, as excessive dependence on technology could lead to problems if it fails. The interplay of these themes points to a decline in basic flying skills, with a call to adapt training methods to address this challenge effectively.

Regarding the hazards imposed by boats and jet skis, seaplane pilots expressed significant concerns about their unpredictable movements, with jet skis and boats towing tubes often changing direction erratically, creating dangerous situations during take-off and land-

ing. Pilots recounted near-collisions and emphasized that many boat operators are unaware of the risks that they pose to seaplanes, particularly during critical flight phases. To mitigate these hazards, pilots often delay landings or choose less congested areas, although these strategies are not always feasible. The presence of boats and jet skis adds considerable stress and anxiety to seaplane operations, leading to calls for regulatory adjustments to prioritize aircraft during take-off and landing. Additionally, pilots highlighted the importance of understanding maritime regulations to navigate busy waterways safely.

For seaplane operations on the water, the lack of consistent radio use among pilots poses significant risks. Pilots often fail to announce their intentions and positions, leading to missed communications and increasing the likelihood of misunderstandings and accidents. This issue is exacerbated by a culture of "silent operations", particularly among older pilots who are unaccustomed to relying on radios. The absence of proper radio communication heightens the risk of collisions, especially in areas with mixed traffic, as it becomes difficult to coordinate with other seaplanes and watercraft. Furthermore, the lack of radio use reduces situational awareness, with pilots recounting incidents where unannounced aircraft suddenly appeared during critical flight phases, endangering operations.

Environmental awareness also plays a critical role in ensuring the safety of seaplanes on the water. Unpredictable weather conditions pose significant challenges, requiring pilots to have strong forecasting skills and the ability to adapt to sudden changes. Wildlife hazards, including birds and marine animals, are another notable concern during take-off and landing, as wildlife strikes can be dangerous and demand constant vigilance. Additionally, glassy water conditions present unique difficulties, such as misjudging distances and visual references, which can lead to errors during landing. These environmental factors emphasize the need for heightened awareness, thorough training, and careful planning to mitigate risks in seaplane operations.

Finally, for mechanical reliability and safety, pilots highlighted that engine failures, especially during take-off, represent a significant hazard, emphasizing the importance of dependable engines. Maintenance lapses exacerbate safety risks, underscoring the need for diligent upkeep. Reliable equipment is essential, as failures can lead to severe consequences. To ensure safety and instill pilot confidence, the participants emphasized that operators must prioritize regular maintenance and invest in high-quality, dependable equipment.

4. Discussion

The findings of this study highlight critical safety challenges associated with private recreational seaplane operations on Canadian waters. These incorporate both quantitative data analysis and qualitative survey responses. By employing this mixed-methods approach, a nuanced understanding of the risks and contributing factors associated with seaplane occurrences has been provided. The implications of these findings are discussed in the context of previous studies and broader safety management systems (SMSs), emphasizing the need for targeted safety interventions and future research.

4.1. Interpretation of Results in Context of Previous Studies

The analysis revealed that loss of control and abnormal runway contact are the predominant causes of seaplane occurrences on Canadian waters, accounting for over half of the recorded occurrences. This aligns with findings from Gao [7] and Vidan et al. [8], which emphasized operational and environmental challenges unique to seaplanes. Recreational seaplanes often operate in less controlled environments with diverse pilot experience levels. This increases their risk of occurrences compared to commercial operations, which benefit from rigorous regulatory oversight and advanced training protocols.

Environmental hazards emerged as a significant contributing factor. The data indicate that landing remains the most hazardous phase of on-water seaplane operations, accounting for over half of all accidents and incidents. This corroborates international studies, including those focusing on Croatian seaplane operations, which identified landing as a critical phase due to its reliance on both waterway conditions and pilot proficiency [8]. However, this paper uniquely highlights an increasing trend in landing-related occurrences in recent years, suggesting that additional factors, such as operational changes or evolving reporting practices, may play a role.

In terms of human factors and training, the persistent challenge of obtaining detailed data, particularly for private recreational seaplanes, is consistent with Ison's [17] observations regarding the lack of comprehensive records on flight hours, pilot experience, and seaplane operations. This gap underscores the need for enhanced data collection mechanisms to support more accurate risk assessments and safety interventions. Furthermore, variability in pilot skill levels, particularly among recreational operators, points to the critical importance of standardized and comprehensive training. This has been highlighted in the prior literature as essential for reducing accident rates in under-regulated aviation sectors.

4.2. Broader Implications

From a broader perspective, this study highlights the intersection of maritime and aviation safety, where dual operational environments create unique challenges for seaplane operations. The increasing trend in private recreational occurrences, particularly those involving amateur-built aircraft, raises concerns about regulatory oversight and safety education in this sector. Addressing these gaps requires collaboration between aviation and maritime authorities to establish integrated safety management systems (SMSs) that consider the dual nature of seaplanes. The findings also underscore the importance of reporting near-misses and minor incidents, which often go unreported but provide valuable insights into potential hazards. Enhanced reporting frameworks could significantly improve the understanding of seaplane safety and inform the development of targeted interventions.

Mitigating risks from boats and jet skis requires raising boaters' awareness about seaplane operations through community outreach and collaboration with maritime authorities. Regulatory adjustments giving aircraft priority during take-off and landing, along with clear right-of-way rules communicated to both pilots and boaters, can reduce conflicts. Education on maritime regulations is essential for safer shared waterways. Thus, pilots should be trained to recognize high-traffic water areas and apply effective avoidance tactics using standardized protocols.

To address the issue of insufficient training quality, the minimum mandatory course durations could be extended, and mandatory proficiency checks could be implemented, as well as using detailed checklists to ensure that pilots meet required standards before flying solo. To combat any decline in skills due to overreliance on technology, training programs should balance advanced system use with manual flying techniques, emphasizing hands-on experience. Updating the Seaplane Rating document to cover unsafe scenarios and spreading training over diverse conditions would better prepare pilots. Incorporating real-world flying exercises, simulated emergencies, and theoretical–practical integration should be mandatory, as this could further enhance pilots' readiness. Additionally, offering insurance discounts for pilots completing extra safety-related courses could incentivize further training and improve overall safety standards.

To summarize the actionable recommendations proposed in this study, Table 7 presents the key areas for intervention, along with corresponding measures.

Table 7. Summary of proposed safety interventions for private recreational seaplane operations.

Area of Intervention	Proposed Measure
Regulatory oversight	Develop integrated aviation–maritime SMSs; enhance reporting requirements for minor incidents
Boater awareness	Community outreach campaigns; regulatory adjustments to clarify seaplane priority and right-of-way
Pilot training quality	Extend minimum training duration; implement mandatory proficiency checks; use detailed checklists
Skills maintenance	Emphasize manual flying techniques alongside technology use; simulate real-world scenarios
Incentivizing further training	Offer insurance discounts for pilots completing additional safety courses

4.3. Future Research Directions

While this study provides critical insights, several areas warrant further exploration. Future research on seaplane safety should prioritize comprehensive data collection, focusing on seaplane movements, pilot experience, and operational contexts, particularly in recreational activities. Incorporating GPS tracking and automated reporting systems could enhance data accuracy.

Studies relating to amateur-built aircraft are also essential, exploring design, construction, and operational practices through collaborations with manufacturers and pilot associations. Furthermore, expanding this research to other countries could provide a comparative analysis across different regions with established seaplane industries. Additionally, deeper exploration of human factors, including pilot decision-making, cognitive biases, and stress management, is crucial to address the role of human error in seaplane occurrences.

5. Conclusions

This study emphasizes the unique safety challenges associated with seaplane operations on Canadian waters, particularly in the private and recreational sectors. Unlike their commercial counterparts, private seaplane pilots operate in less regulated environments, increasing their exposure to risks related to pilot experience, water conditions, and interactions with maritime traffic. The findings underscore the need for a holistic approach to safety management that integrates both aviation and maritime principles.

Raising safety awareness within the seaplane community requires active engagement through in-person events like seminars, workshops, and focus groups, which have proven effective based on positive participant feedback. Encouraging community involvement in safety initiatives fosters a strong safety culture, supported by awareness programs sharing practical tips through social media, newsletters, and seasonal emails. Additionally, collaboration with industry stakeholders, including regulatory bodies, training organizations, and seaplane operators, is essential for developing standardized safety protocols and sharing resources to enhance safety education.

To make interventions more effective, specific measures such as tailored boater education campaigns, clearer signage at popular waterways, and formal agreements between aviation and maritime authorities can be implemented to strengthen awareness and compliance. Regulatory adjustments could include updating collision regulations (COLREGs) to explicitly address seaplane operations and establishing formal procedures for shared water use. These targeted strategies provide concrete avenues for enhancing safety beyond general recommendations.

Ultimately, addressing seaplane safety on the water requires ongoing research, policy adjustments, and proactive engagement with all stakeholders. Practitioners and decision-makers can use these insights to design region-specific safety initiatives, develop integrated regulatory frameworks, and prioritize resources for public education campaigns. Furthermore, the study design emphasizes a cross-sectoral approach to safety, and it offers a replicable model for regions outside Canada, including areas with different maritime environments, regulatory landscapes, and seaplane usage patterns. By implementing targeted safety interventions and fostering a culture of awareness and preparedness, future efforts can contribute to safer waterways for seaplane pilots, passengers, and the broader maritime community.

In conclusion, while the findings of this study are rooted in the Canadian context, the proposed safety strategies and methodological framework can inform international efforts to improve seaplane safety, making this study relevant to diverse operational environments.

Author Contributions: Conceptualization, I.M. and A.M.; methodology, I.M.; software, I.M.; validation, I.M. and A.M.; formal analysis, I.M.; investigation, I.M.; resources, I.M.; data curation, I.M.; writing—original draft preparation, I.M.; writing—review and editing, I.M. and A.M.; visualization, I.M.; supervision, I.M. and A.M.; project administration, I.M.; funding acquisition, I.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Lloyd's Register Foundation NEST Fund, grant number N21\100025.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of Imperial College London on 30 April 2024 (Application ID 7022702).

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The seaplane accident/incident data were made available by the collaborators at Transport Canada. Data about past aviation accidents and incidents in Canada can be found on Transport Canada's website.

Acknowledgments: The authors would like to thank Simon Garrett from Transport Canada and the Seaplane Working Group of Transport Canada for their invaluable help with the facilitation of interviews and focus groups, along with their support in shaping the online questionnaire. The authors would also like to thank Lloyd's Register Foundation for sponsoring this research.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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