Frequency of Spill Model for Area Risk Assessment of Ship-Source Oil Spills in Canadian Waters

David J. Creber[1], Yvonne Koldenhof [2], Dave Poole [3], Cornelis van der Tak [2]
[1]Dillon Consulting Ltd., Fredericton, New Brunswick, Canada
[2]Maritime Research Institute Netherlands, Wageningen, Netherlands
[3]Dillon Consulting Ltd., Calgary, Alberta Canada
dcreber@dillon.ca

Abstract

The purpose of this paper is to describe the SAMSON model that was used within Area Risk Assessment methodology, developed for Transport Canada, to determine the Frequency of Spill for four pilot areas in Canadian waters. The SAMSON model used AIS information model marine traffic and included various environmental data (currents and wind), preventative measures in place (tugs, traffic separation schemes, pilotage and VTMS) and volumes and types of oil being transported (including cargo oil and bunker oil). The vessel records contained in the AIS data were classified into one of 42 different ship types based on the design and purpose of the ship from small work boats or tugs to the largest super tankers and incorporated into a traffic database. The model was run in four pilot areas to determine the location and frequency of marine accidents that include: Collisions, Allisions, Groundings, Fire/Explosions, Hull Damages and Founderings.

Once the known locations and frequency of marine accidents were determined, the frequency and volume of oil spilled were modelled. The likelihood of spill was calculated using a model that determined the frequency of the hull being penetrated as a result of the accident. Then the frequency and volume of outflow were determined. The volume of outflow is divided into 8 spill size classes that range from spills $<0.01\text{m}^3$ up to the complete loss of the largest super tanker. The model gives both individual frequencies for all the accident types and oil spills for each of the 42 ship classes as well as the total frequency for the area under study. The results of the model are presented in a series of heat maps that illustrate the frequency and size of various ship-source spills. The results of the model were then validated against Canadian marine accident data.

1 Introduction

An Area Risk Assessment (ARA) Methodology was developed by the authors to assess the relative risk of ship-source oil spills in defined Study Areas in Canada south of the arctic (Dillon, 2017). The ARA was produced for Transport Canada, to fulfill the recommendation from the Tanker Safety Expert Panel (TSEP) November 2013 report (Tanker Safety Panel Secretariat, 2013) and to expand on the Pan-Canadian Risk Assessment for Oil Spills in Canadian Waters (WSP, 2013; WSP, 2014a and WSP 2014b). The ARA Methodology, as illustrated in Figure 1, is completed in four phases with this paper addressing Phase 1. The first step is to determine the frequency of a ship-sourced oil spills (Phase 1) within the prescribed Study Area, thereby focusing efforts to identify the oil spill volume and type at specific locations (Phase 2) to be selected as scenarios for modeling. Before the final phase, the Frequency of Exposure is determined (Phase 3). These phases enable the risk assessment (Phase 4) to be completed to better understand and evaluate the risks for the selected oil spill volume types at specific locations within the Study Area. Further information on each phase is available in the Guidance Document (Dillon, 2017).

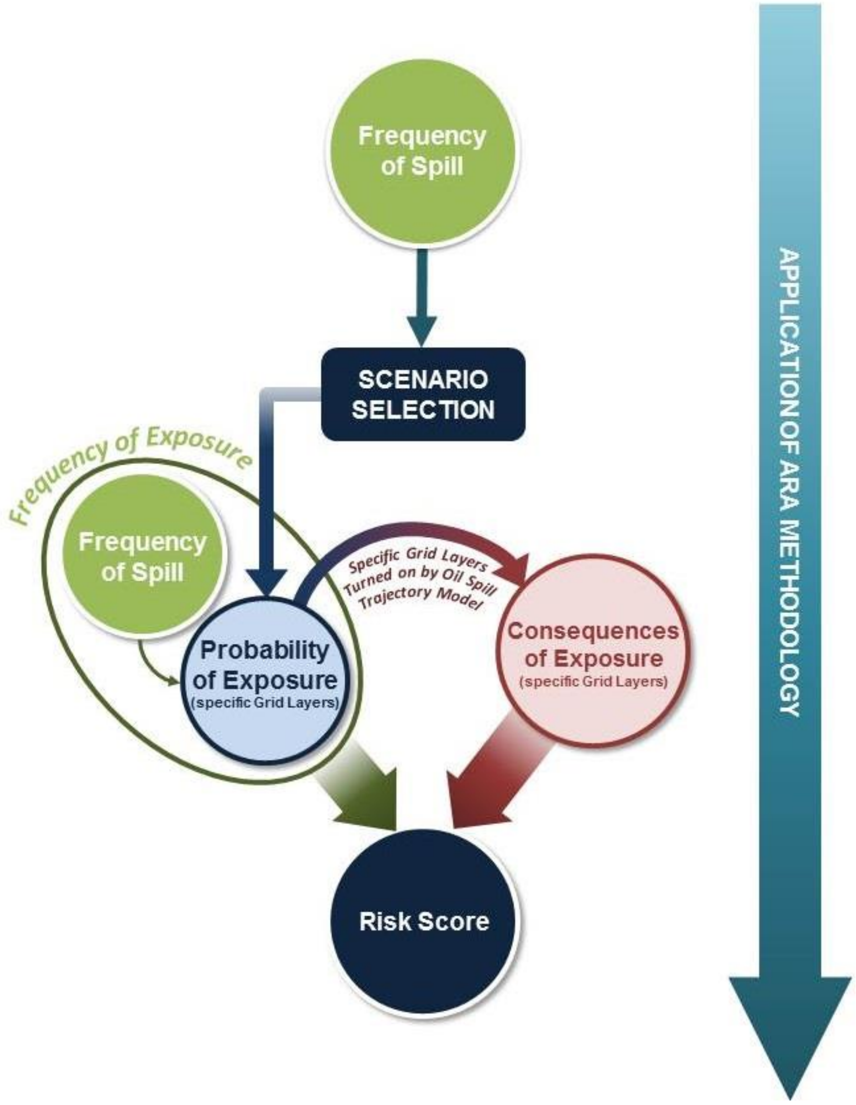


Figure 1 ARA Methodology flow chart

The ARA methodology was tested in four Pilot Areas that were identified as the four areas with the highest relative risk of an oil spill in the Pan-Canadian Risk Assessment (WSP, 2013). The four pilot areas were defined according to the Primary Area of Responses detailed in the Response Organization Standards (Transport Canada, 1995). The four pilot areas, illustrated in Figure 2, are: Saint John and the Bay of Fundy, Port Hawkesbury and Chedabucto Bay, St. Lawrence River (from Montreal to Anticosti Island) and Southern BC (including Straits of Juan de Fuca, Gulf Islands and Straits of Georgia).

Figure 2 Four ARA Pilot Areas

To determine the different frequencies of ship-sourced oil spills, the ARA Methodology used the SAMSON model, which is the acronym for Safety Assessment Model for Shipping and Offshore on the North Sea. During the last 30 years the model has been developed, extended, validated and improved by MARIN in various studies performed for Rijkswaterstaat, within European projects and other commercial parties (Koldenhof and van der Tak, 2006; Koldenhof and van der Tek, 2007; Koldenhof and van der Tak, 2010; and de Jong *et. al.*, 1998).

The model was developed for marine risk assessments to determine the probabilities, locations and consequences of various marine accidents within a defined study area taking into consideration various mitigation measures that could be used to reduce the likelihood of a marine accident (e.g.: pilotage). The parameters of the casualty models are derived from the worldwide casualty data of 1990-2012. Although the name suggests SAMSON is only applicable for the North Sea, it is a generic model can be used for any defined geographic location. The SAMSON model calculates the frequency, volume, location and oil type of potential ship-source oil spills from vessels greater than 100 GT.

The purpose of this paper is not to provide a detailed explanation of the SAMSON model, but instead to provide a cursory overview of the model and to describe how the SAMSON model is applied to determine the Frequency of Spills in the ARA Methodology. Finally, the predicted results from the SAMSON model were compared to actual marine accident data from the Transportation Safety Board (TSB)

2 Frequency of Spill Methodology

For the SAMSON model to be able to calculate the frequency, volume, location and oil type of a potential ship-source oil spill, it needs a number of data inputs as illustrated in Figure 3. The figure shows the system diagram of the complete SAMSON model, not all parts are used in the ARA-studies in Canada. The figure shows the main input of the model, the so-called "Maritime traffic system" which contains all the input data. The input data can be grouped into different categories: Traffic intensity and mix, Environmental Data (characteristics of the sea area), Preventive Barriers (traffic management measures), Incident Statistics, and Volumes and Types of Oil. Each of these inputs consists of several elements, of which a more detailed description is provided in the sections below. It is beyond the scope of this paper to provide a detailed analysis of the SAMSON model. Detailed descriptions of the SAMSON model can be found in van Iperen *et al.*, 2009, de Jong, *et al.*, 1998, and van der Tak and de Jong, 1996.

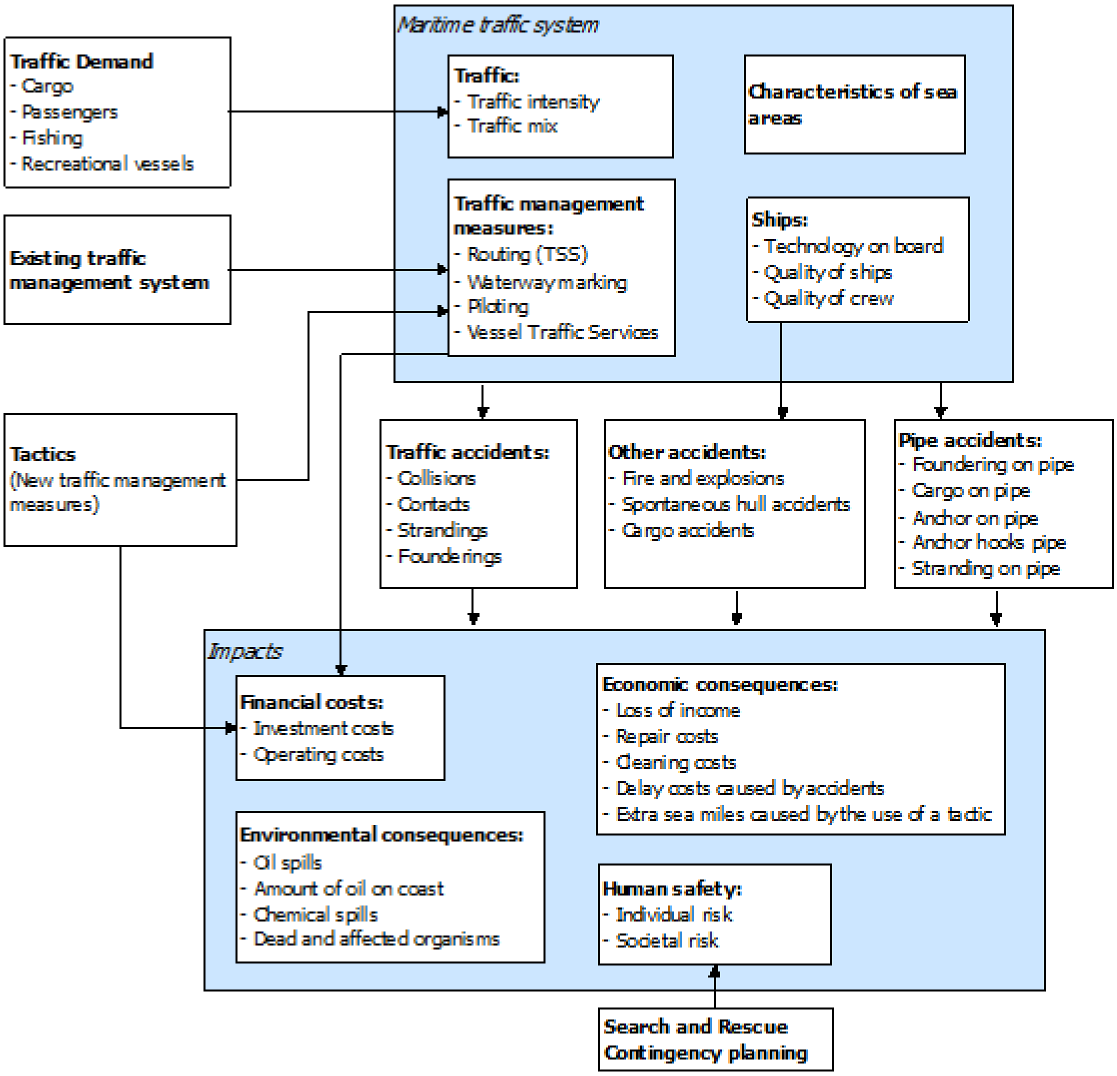


Figure 3 System diagram of SAMSON

2.1 Frequency of Spill Model Inputs

The SAMSON model requires several inputs as presented in Figure 3 with the details of these inputs explained herein.

2.1.1 Traffic Intensity and Mix

The basis of the SAMSON model is the traffic database, which describes the maritime traffic in density, intensity, composition, and behaviour. The maritime traffic is divided into two main groups: the route bound ships; and the non-route bound ships. The route bound traffic consists of merchant vessels and ferries sailing along the shortest route from one port to another. The non-route bound traffic contains vessels that mainly have a mission at sea, such as fishing vessels, supply vessels, working vessels and pleasure craft. The route bound traffic database in SAMSON consists of 36 ship types (Table 1) and the non-route bound database has six different vessel types (Table 2). For each ship type there are eight ship size classes presented in Table 3. This large number of classes is required for subsequent calculations, such as for the calculation of the kinetic energy when a ship strikes another vessel or goes aground. The non-route bound traffic database is also used for route bound traffic that deviates from the route network for some reason (e.g.: waiting for a pilot or anchorage area to free up).

Table 1 Ship Types (Classes) for Route Bound Traffic

No.	Ship Type	No.	Ship Type
1	Oil / Bulk / Combination Tanker	19	LNG
2	Oil/ Bulk/ Ore Combination Tanker DH	20	LPG Refrigerated
3	Chemical Tanker IMO 1	21	LPG Semi Pressured
4	Chemical Tanker IMO 1 DH	22	LPG Pressured
5	Chemical Tanker IMO 2	23	LPG Remaining
6	Chemical Tanker IMO 2 DH	24	Bulkers
7	Chemical Tanker IMO 3	25	Unitized Container
8	Chemical Tanker IMO 3 DH	26	Unitized Roro
9	Chemical Tanker	27	Unitized Vehicle
10	Chemical Tanker DH	28	General Dry Cargo
11	Chemical Tanker Water/Wine/Replenishment	29	General Dry Cargo with Containers
12	Chemical Tanker Water/Wine/Replenishment DH	30	General Dry Cargo Reefer
13	Oil Tanker, Crude Oil	31	Passenger
14	Oil Tanker, Crude Oil DH	32	Passenger Roro
15	Oil Product Tanker	33	Ferries
16	Oil Product Tanker DH	34	High Speed Ferries
17	Oil Remaining	35	Miscellaneous
18	Oil Remaining DH	36	Tugs

Table 2 Ship Types (Classes) for Non-route Bound Traffic

No.	Ship Type	No.	Ship Type
1	Work Vessels	4	Chemical Tanker
2	All route-bound ships outside route network, excluding oil and chemical tankers	5	Oil Tanker
3	Fishing from/to	6	Recreation

Marine traffic data for the four pilot areas were obtained from Automated Identification System (AIS) data provided by the Canadian Coast Guard for the pilot year of 2014. For the purposes of creating the traffic database for each of the four Pilot Areas the ARA methodology utilized one year of AIS data. However, it is recommended that multiple years of AIS data be used in future risk assessments to account for yearly differences in vessel traffic patterns. The AIS data was analyzed and the vessels were assigned to one of two traffic databases. A plot of the AIS data for 2014, plotted at 5 minute intervals for the Port Hawkesbury Pilot Area is presented in Figure 4. The position of the vessels is plotted every 5 minutes and the colour indicates the speed and/or the heading of the vessel. The red dots are the locations where the speed over ground is less than 0.01 knot (kn). A purple dot means a speed less than 0.2 kn, yellow less than 0.4 kn and blue less than 1 kn. When a vessel is sailing east the position is indicated with a black dot and when she is sailing west a brown dot is used.

Table 3 Definition of Ship Classes Based on Gross Tonnage

No.	Ship Type	No.	Ship Type
1	Work Vessels	4	Chemical Tanker
2	All route-bound ships outside route network, excluding oil and chemical tankers	5	Oil Tanker
3	Fishing from/to	6	Recreation

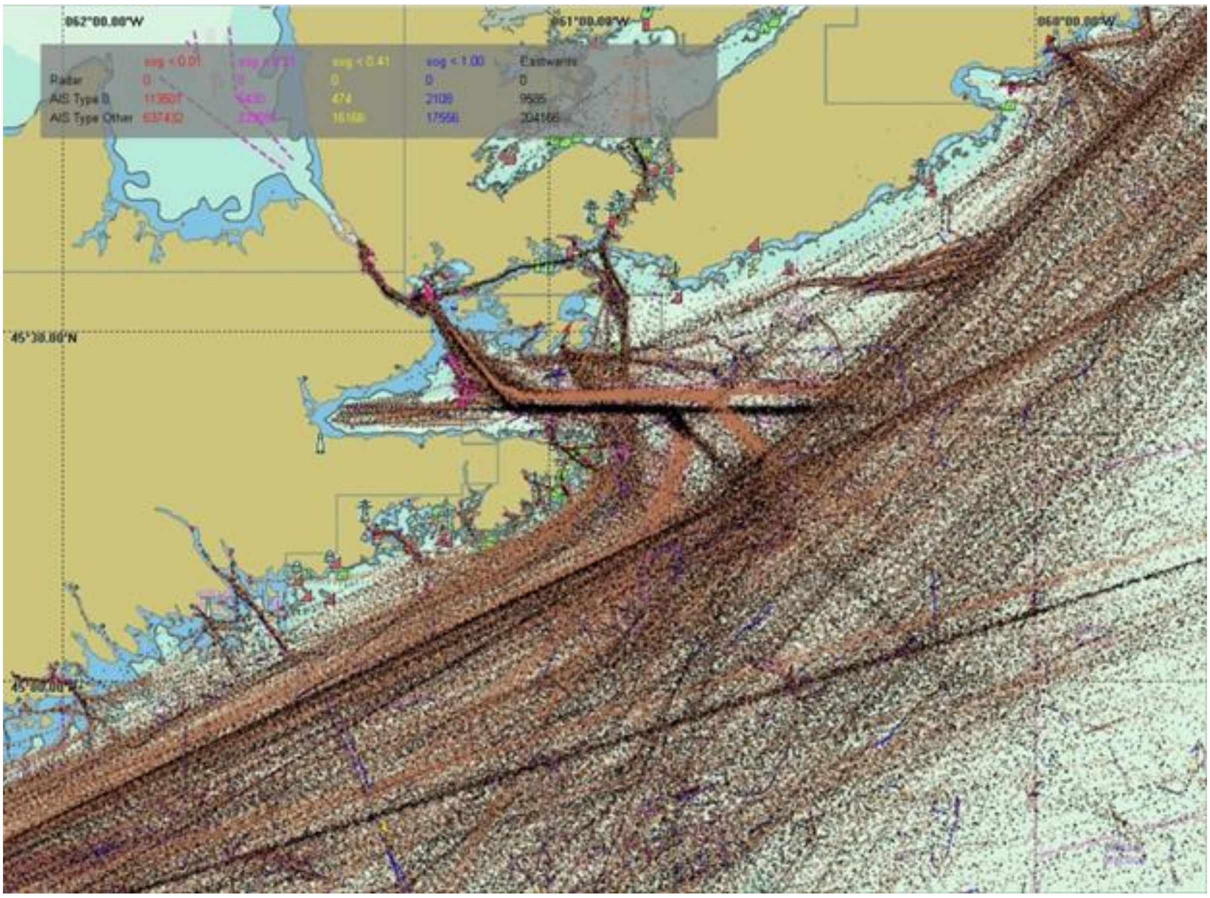


Figure 4 All AIS Signals for 2014 plotted at 5 minute intervals

2.1.2 Environmental Data

Within the context of the SAMSON Model, environmental data is used to determine the trajectory and speed of drifting vessels as well as to determine potential ship damage from extreme weather.

2.1.2.1 Wind Data

Simulating the trajectory and fate of drifting vessels requires a definition of a highly dynamic and variable wind field over the area where vessels may travel. There are public sources for wind data maintained by government agencies that provide the necessary inputs for the modeling required in a risk assessment. The data was obtained from buoys or fixed instruments (NOAA, 2016) where wind speed and direction have been recorded over multiple years and underwent a re-analysis or from output from long-term meteorological models (NOAA, 2014) that generate wind speed and direction on a regular grid from a multiple year simulation. Wind data for the SAMSON Model needs to have adequate spatial coverage to capture the spatial variability present in a region and it must cover a sufficient number of years (5 to 10 years is ideal) to capture the year-to-year variability. This data was then used to define various wind patterns at various locations throughout the study area as an input into the SAMSON model.

2.1.2.2 Current Data

Simulating the trajectory and fate of a drifting vessel requires a definition of the currents over the entire area where the vessel may potentially travel. Current observations such as those collected by instruments deployed in the field do not have sufficient spatial coverage to adequately drive the drifting model in SAMSON. In addition to complete spatial coverage a current field extending over a long time period is required in order to capture the variability that occurs on monthly, seasonal, annual or decadal time scales. A hydrodynamic model applied to the area of interest is the best solution for meeting the spatial and temporal requirements of the SAMSON model.

2.1.3 Preventative Barriers

There are two types of preventative measures used in the SAMSON model, namely 1) measures that reduce the frequency of the occurrence of an accident and 2) measures that mitigate the consequences of accidents (in this case the oil spill). Measures that reduce the frequency of the occurrence of an accident are presented in Table 4.

Table 4 Preventative Barriers for SAMSON Model that reduce the frequency of the occurrence of an accident

Built into the Model	Adjustable Elements	Not in the Model
Admission Policy	Pilotage	Dynamic Positioning System
AIS & Electronic Chart Display and Information System (ECDIS)	Traffic Separation Schemes	Fire Fighting Tug
Aids to Navigation	Vessel Traffic Management System (VTMS)	Safe Haven of Refuge
Anchoring Areas	Tugs (Tethered and Escort)	Emergency Anchorage
Marine Safety Info.		Emergency Tow Vessel
Waterways Management		
Safety Distances		

Not all preventive measures are or can be included in the SAMSON model. Some of the measures or barriers that are built into the model and are not adjustable, some of the measures are taken into account and are adjustable and some of the preventive measures are (not yet) included in the model (as indicated in Table 4). The barriers that are built into the model are partly represented by the traffic patterns from AIS and partly implicitly incorporated in the incident rates.

The adjustable barriers are ones that can be changed in the SAMSON model. Changing the adjustable barriers will result in a change in the frequency and locations of marine accidents predicted by the SAMSON model. Pilotage includes the areas in Study Area that require pilots, including where the pilots embark and disembark. The location of mandatory pilotage areas was obtained from the ENC charts, Annual Notice to Mariners (CCG, 2015), Port Information Books, Sailing Directions and local port authorities. Pilotage reduces the probability of a vessel colliding with another vessel and reduces the likelihood of a navigation error leading to a stranding by 62% (de Jong *et. al.*, 1998 and SSPA, 2012). The location of TSS was obtained from the ENC Charts. In areas where TSS are in place they act to reduce the number of encounters which reduces the number of incidents as traffic is separated laterally from each other. In the SAMSON model the reduction assigned to TSS is determined by the design of the TSS as the width of the lanes and the separation zone. The location of VTMS areas was obtained from the ENC Charts, Annual Notice to Mariners (CCG, 2015) and Sailing Directions. In areas where there is VTMS, vessel movements are being monitored and navigational safety is provided. VTMS is used in the SAMSON model calculations and the percentage effect it has on reducing the risk of collision is 30% (de Jong *et. al.,* 1998 and SSPA, 2012). In some areas it could be mandatory to have escort and tethered tugs. The locations where escort and tethered tugs are required, is obtained from the appropriate port authority, sailing directions and liaising with the OHFs in the Study Area. In addition to the locational requirement, the number and positioning of the tugs is obtained as well as the size and types of vessels that require tugs. Modelling of tugs in the SAMSON model calculations is dependent on area characteristics. The percentage effect that both escort and tethered tugs have on reducing the risk of groundings and allisions varies from 50% for an escort tug to 99% for a tethered tug; these numbers are based on expert opinion and are in line with what was used in other risk assessments (DNV, 2013 and DNV, 2016).

There were five preventative barriers, identified in Table 4, that were not included in the SAMSON model that was used in the ARA Pilot study. Dynamic Positioning System can be incorporated in the SAMSON model as a preventative barrier if vessels use the system during loading/unloading at OHFs. At the time of the pilot study none of the pilot areas had OHFs that used Dynamic Positioning Systems where vessels called. Fire Fighting Tugs can be included in the SAMSON model to look at the reduction in damage to a vessel from fire with a fire fighting tug present. However, the firefighting tug does not alter the frequency of fires/explosions nor the frequency and volume of oil spills therefore they were not included in the ARA methodology. Safe Havens of Refuge can be identified in the SAMSON model but were not included in the pilot study, as there are currently no designated places of refuge in any of the pilot areas. Designated emergency anchorage locations and emergency tow vessel locations (capabilities) can be included in the SAMSON model once these areas and locations have been designated.

Measures that mitigate the consequence of an accident include double hull tankers. The measure of mandatory double hull tankers is implicitly included in the traffic database as all oil tankers sailing in Canadian waters are required to by double hulled.

2.1.4 Incident Statistics

The SAMSON model uses an international collision database to calculate the frequency of vessel incidents when a vessel enters the domain of another vessel or object. The SAMSON model uses incident statistics available from the international IHS Fairplay collision database from 1990 to 2012. The international statistics obtained from the IHS Fairplay Database are used to determine the incident rates on the North Sea. The North Sea is mainly used by maritime countries with similar shipping regulatory regimes to Canada. This is an industry standard for completing marine risk assessments in Canada and this data has been used in marine risk assessment studies completed in BC (DNV, 2013) and NB (DNV, 2016). Although statistics from the IHS Fairplay database are used they are then compared to the Canadian incident statistics, obtained from the Transportation Safety Board of Canada website from 2004 to September 2015 (TSB, 2015).

2.1.5 Volumes and Types of Oil

In the event of an accident, the frequency and volume of oil outflow is calculated by the SAMSON model. Therefore information is required on the volume and type of oil carried as cargo by each vessel. The cargo oil data is not provided by one set of data, but can be determined by combining AIS Data with data from the Oil Handling Facilities (OHFs) in the Area. The data required from the OHF include: ship name, Port (OHF Name), arrival date, oil type, volume of oil and activity (loading, unloading or both). Once the oil data is obtained from the OHFs it can be linked with the vessel information from the AIS and the total volume of cargo oil carried by the oil tanker was determined.

In addition to cargo oil the SAMSON model predicts the frequency and volume of bunker oil spills. Bunker oil, in the SAMSON model, is defined as the petroleum product used/stored by the vessel for its own use. Based on the average layout of the various ship type/ ship size combinations the amount of bunker oil on board is estimated from MARIN's nautical database.

2.2 Frequency of Spill Model

The process used to calculate the frequency, volume and location of spill in the ARA methodology, using the identified input data is illustrated in Figure 5.

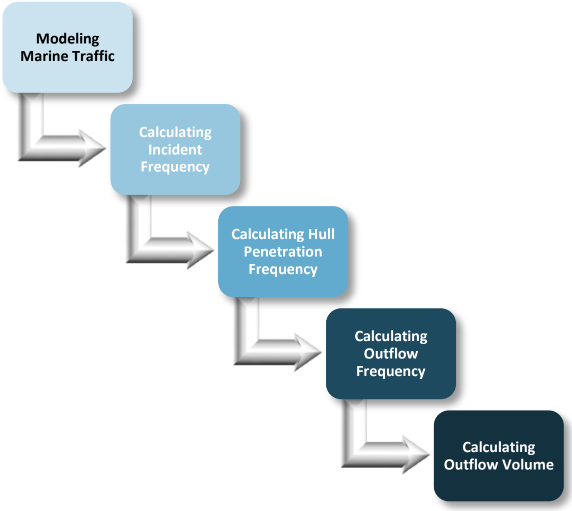


Figure 5 Frequency of Spill Model Calculation Process

2.2.1 Modelling Marine Traffic

The SAMSON model distinguished two main groups of ships: route bound ships and non-route bound ships. Each of these groups is modelled in a different way: The route bound traffic is modelled based on shipping routes, while the non-route bound traffic is modelled using vessel density.

The route bound traffic is modelled on the shipping routes. Because of the location of the different ports and the traffic separation schemes in the area, most of the route bound ships sail on a large network of links, comparable to the road network. It is assumed that ships sail along the shortest possible route to reach their destination. Ships have to comply with rules and regulations such as Traffic Separation Schemes. The route bound traffic database in SAMSON consists of 36 ship types (Table 1) and eight ship size classes (Table 3). This large number of classes is required for subsequent calculations, such as for the calculation of the kinetic energy when a ship strikes another vessel or goes aground. The shipping intensity on the different links is determined based on a combination of voyage data (Lloyd's List Intelligence) and AIS-data. The traffic database contains waypoints and links connecting these waypoints. On each link the traffic, in number of movements per year, is known for each of the 36 ship types and eight ship size classes.

The non-route bound database consists of vessels that have a mission at sea and don't necessarily follow a defined link. There are six different vessel types found in the non-route bound traffic database (Table 2) that reflect the types and sizes of vessel in the database. The non-route bound traffic database is generally constructed from three datasets. The first dataset is to assign any route bound traffic that could not be assigned a network to a density. The second dataset consist of the typical vessels found in the non-route bound database, vessels that have a mission at sea like fishing vessels, supply vessels and tugs that don't follow a defined network. The final dataset is to assign unknown vessels to the non-route bound database. Unknown, vessels are AIS signals, generally from small vessels, that don't provide any information on the type, size or mission of the vessel. Using the AIS signals of these three datasets, the non-route bound database is created which assigns a vessel density to each grid of the study area that is then subsequently used to calculate the frequency of an incident.

2.2.2 Calculating Incident Frequency

The SAMSON model determines the frequency of seven different incident types. The seven incident types are defined in Table 5. The frequency of incidents is calculated on the basis of exposures for the different type of incidents as presented in Table 5. Exposures can be described as *"possible dangerous situations that could lead to an incident"*.

Table 5 Relationship between Incident Type and Exposure

Incident Type	Exposure
Collision - contact between two vessels underway	Encounters
Allision - contact between a vessel underway and a vessel not underway (at anchor or terminal)	Stranding Opportunity (powered) and Danger Miles (unpowered)
Wreck/Stranding - ship runs aground or strikes the coast	Stranding Opportunity (powered) and Danger Miles (unpowered)
Foundering - sinks by circumstance (not as a result of another incident)	Nautical Miles (ship miles)
Fire/Explosion - on board of a vessel	Nautical Miles (ship miles)
Hull/Machinery Failure - Vessel starts drifting and ends in an allisions or wreck/stranding	Nautical Miles (ship miles)

The exposure for a collision between two ships is an encounter. Ships can only collide when they are within a certain range of each other. An encounter occurs when a ship enters the domain of another ship. This domain is defined as a circle with a radius of 0.125 nm around a ship. Only a small part of all encounters will actually result in a collision. The casualty rate, the relation between the number of exposures and the number of accidents, depends on the type and size of the ship.

The two causes for the incident types, allisions and wrecks/stranding, are navigational error and a technical failure, the later causes the ship to be uncontrollable. The exposure measure for an allision or wreck/stranding caused by a navigational error is called the stranding opportunity. An allision or wreck/stranding caused by a navigational error occurs more frequently when the ship sails closer to the stranding line or fixed object. The stranding opportunity is based on the location, sailing direction, speed and length of the ship and the location with respect to a stranding line or fixed object.

An allision and wreck/stranding caused by a technical failure will only take place when the ship drifts in the direction of the stranding line or object. The wreck/stranding or allision will only occur when the technical failure is not repaired prior to the vessel wrecking or stranding. The probability of successful emergency anchoring and thus stopping the vessel from wrecking or stranding is incorporated in the final incident probability. The exposure for this type of accident is called "danger mile".

The frequencies for remaining three types of incidents are calculated for each ship type and sized based on the international rates for the incidents. Then using the traffic databases the annual frequencies of each type of incident occurring is calculated based on the total nautical miles each ship type and size sailed in the study area.

2.2.3 Calculating the Frequency of Hull Penetration

Even if an incident occurs, this does not automatically mean that an oil spill will occur. Oil is only released from a vessel if the hull and the cargo or fuel tanks are penetrated. Therefore the next step is to calculate the frequency that the hull of a ship is penetrated. The probability that a hole in a cargo or fuel tank of a ship will occur as a result of an incident, is determined in the SAMSON model by:

- The tank layout of the ship (for each ship type and size some layouts are given); and
- Damage (penetrating) functions derived from casualty statistics combined with analysis completed by MARIN using the MARCOL Model (quantitative tool for analysing collision events) analysis.

To assess the expected damage to the tanks of a ship in case it is hit by another vessel, the MARCOL model has been developed (Bogaert and Boon, 2007). This analytical model, in contrast to the conventional method (finite elements), is capable of determining the penetration of the cargo tanks with a very rapid processing time. In order to achieve this reduction in calculating time, the model is based on analytical models with application of super elements. These analytical models describe the primary damage mechanics for typical structural components like shell plating and transverse webs. With this model it is possible to calculate the penetration depth into the hull of an tanker or other vessel, taking into account the large variation in size and bow shape of the colliding ship, its speed, collision angle and collision position. By applying the results of this model for damage to the oil tanker, covering the entire range of encountering ship types and sizes as relevant for a port, the probabilities of collision can be translated into probabilities of a hole in the cargo tankers of an oil tanker. Figure 6 illustrates an example collision in MARCOL in which the ship has penetrated the cargo tank of a tanker with the bow and bulb. A hole can only occur when the ship collides in the cargo part of the oil tanker, which stretches over approximately 65% of the side of the ship. Millions of collision scenarios have been run in other projects by MARIN to determine the probability of a penetration of cargo tanks. The following parameters can be varied:

- 36 different ship types with 8 ship sizes. Two loading conditions for some ship types and one average draught for the others;
- 7 different bow-bulb descriptions for each of the ship-size combinations;
- the collision angle;
- the contact point on the vessel receiving the collision, from half aft, to centre, to half front;
- the contact point on the hull plate between the web frames;
- 3 conditions for the vessel that received the collisions; sailing, manoeuvring in the vicinity of the terminal and when at the jetty; and
- different speeds for the ships.

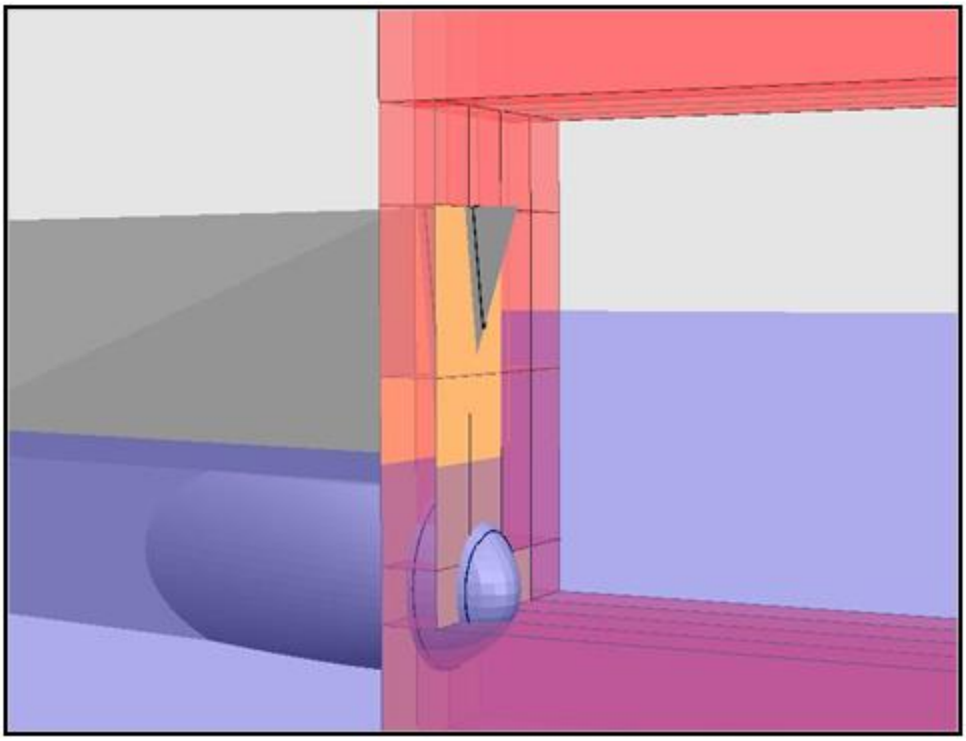


Figure 6 Result of MARCOL where a colliding ship penetrates the cargo tank (here membrane type cargo containment system)

2.2.4 Calculating Outflow Probability

Penetration of the hull of a ship and the cargo/fuel tanks during an incident does not automatically lead to an oil spill. For an oil spill to occur the tanks need to be loaded with oil. The frequency of an oil spill is determined by multiplying the frequency of penetration of a ship's tank with the frequency that the tanks are loaded. The probability of the cargo tanks being loaded and the volume of the oil in each tank is obtained from the traffic database and is calculated based on the ship class and from the data provided by the OHFs.

In the SAMSON model fuel oil is present in each ship, it is assumed that half of the fuel tanks are fully loaded and the other half of the fuel tanks are empty. The outflow of fuel tanks is determined by calculating the probability that a loaded fuel tank of the ship is holed.

2.2.5 Calculating Outflow Volume

When an incident will result in an outflow, the SAMSON model also calculates the volume of the outflow. The volume of oil that flows out of a penetration of a ship’s hull depends on the location of the hole in the tank and the probability that the tank has oil in it. When a hole in a cargo tank is located above the waterline, only the oil above the hole will flow out. If a hole in the cargo tank is located below the waterline, the model conservatively assumes that the entire volume of the tank is released. The volume of oil outflow can be calculated from equations (1) to (3).

$$N_{accidents} = N_{exposures} * CasRat \quad (1)$$
$$N_{outflow} = N_{accidents} * F_{hole\_in\_tank} * F_{oil\_in\_tank} \quad (2)$$
$$V_{outflow} = N_{outflow} * V_{tank} \quad (3)$$

Equation 1 determines the number of accidents per year ($N_{accidents}$) using the number of exposures ($N_{exposures}$) and the casualty rate (CasRat) which is the frequency that an exposure ends up in an incident. Equation 2 calculates the number of outflows ($N_{outflow}$) based on the number of accidents determined in equation 1, the frequency of a hole in the cargo tank ($F_{hole\_in\_tank}$) and the frequency of oil in the cargo tank ($F_{oil\_in\_tank}$). Finally the volume of oil that outflows ($V_{outflow}$) from the vessel due to the incident is calculated in equation 3 by taking the product of the number of outflows in equation 2 and the volume of oil in the damaged cargo tank (V_{tank}).

For ease of communication the volume of oil outflow is sorted into one of eight spill size categories that are summarized in Table 6. The classes were derived based on typical vessel types and the capacities and locations of their associated bunker tank and cargo tank (tankers only).

Table 6 Outflow Classes and Associated Vessel Types used in the SAMSON Model

Spill Volume Class	**Outflow - Spill Class**		**Vessel Type**	**Typical Spill Volume from Bunker or Cargo Tank (m^3)**	**Spill due to Total loss (m^3)**
	From (m^3)	**To (m^3)**			
1	0	30	Fishing, Recreation	Bunkertank <30	Fishing, Recreation (<150)
2	30	150	Small commercial	Bunkertank <150	
3	150	1,000	Medium commercial	Bunkertank <1k	Small commercial (<1k)
4	1,000	5,000	General purpose Med. range tanker	Bunkertank <5k 1x Cargo side 5k	Medium commercial (<10k)
5	5,000	15,000	Long range 1 tanker Panamax	1x Cargo side 12k	General purpose (<30k) Med. range tanker (<30k)
6	15,000	30,000	Aframax	1x Cargo side 10k + 1x Cargo centre 17k	
7	30,000	100,000	New Panamax Suezmax VLCC ULCC	1x Cargo side 17k + 1x Cargo centre 40k	Long range tanker (<60k) Panamax (<60k) Aframax (<100k)
8	> 100,000			NA (Spill exceeds volume of 2 largest) tanks)	New Panamax (100k+) Suezmax (100k+) VLCC (100k+) ULCC (100k+)

3 Results

The results of the SAMSON model are contained within a database that produces multiple outputs as presented in Figure 3. One of the first SAMSON model outputs are maps showing the route bound traffic database as well the non-route bound database. Examples of the route bound and non-route bound database from the 2014 Pilot Study completed for the Port Hawkesbury Area are presented in Figures 7 and 8 respectively.

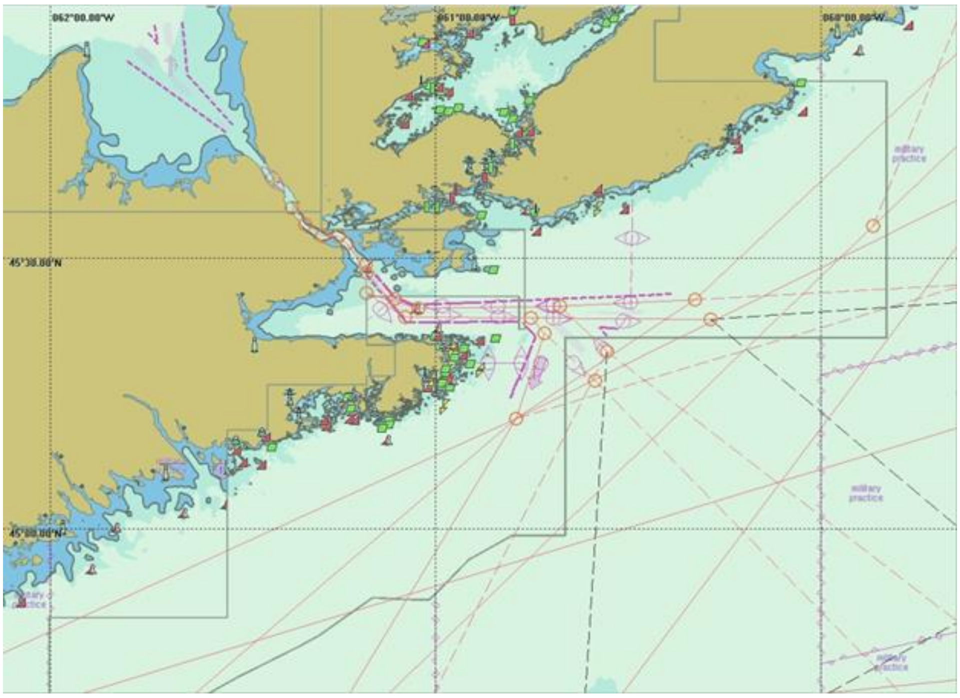


Figure 7 Route bound traffic database for Port Hawkesbury Pilot Area, the network of routes are illustrated by the orange lines.

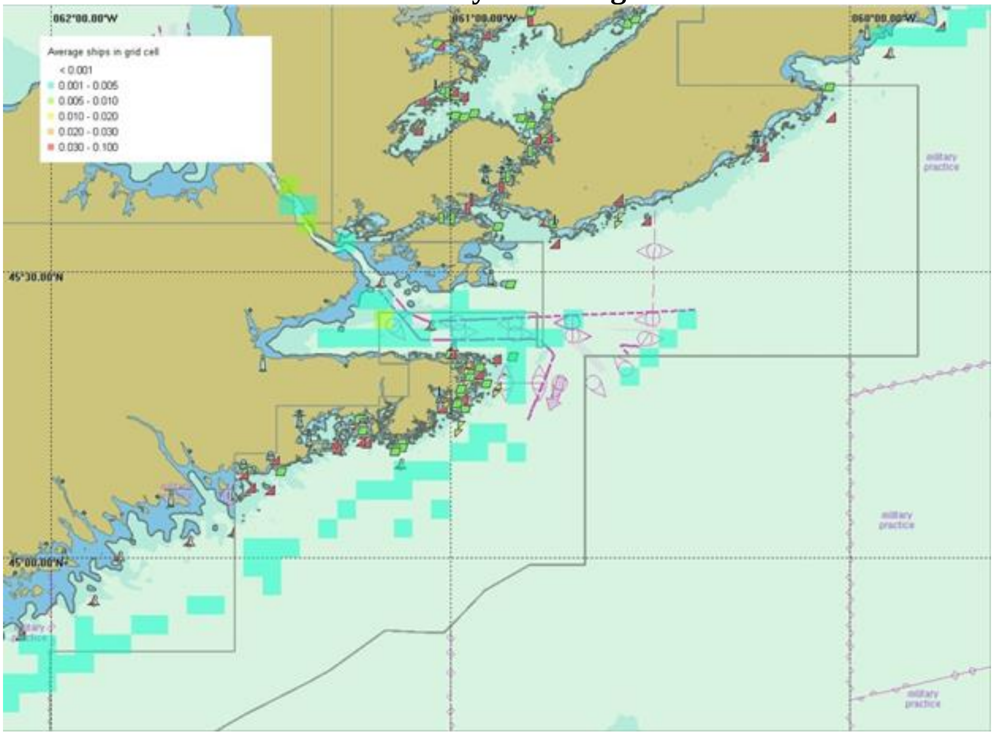


Figure 8 Non-route bound traffic database for Port Hawkesbury Pilot Area

To interpret and analyze the SAMSON outputs contained within the database, it is clear that the proper perspective and context is necessary to understand the various frequency values and how they can be utilized. There are three key frequencies that are provided in the SAMSON model that must be understood in order to properly interpret the results.

Aggregate Total Frequency (F) – reflects the frequency of all plausible ship-source scenarios across the entire Pilot Area. The magnitude of the Aggregate Total Frequency (F) is a function of a) intensity of shipping traffic within the geographic boundary of the Pilot Area and b) the size of the Pilot Area (geographic area being studied). Aggregated total frequency results for the Port Hawkesbury Pilot Study are presented in Table 7. Table 7 indicates that approximately 96 % of all spills predicted to occur in the Port Hawkesbury Pilot Area are in the smallest spill volume class of 0.01 m^3 to 30 m^3.

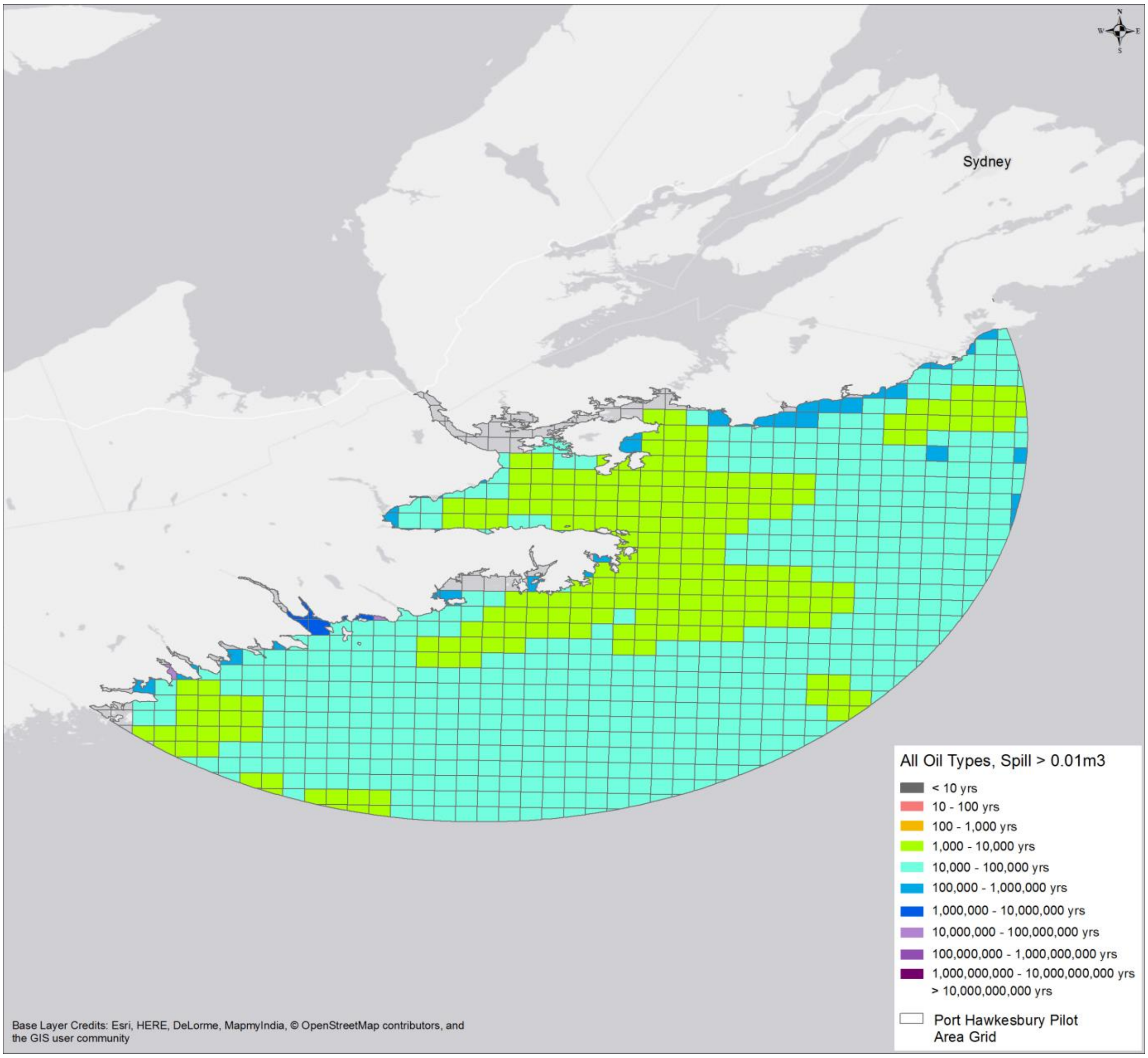
Table 7 Aggregate SAMSON Output leading to Oil Spills – Port Hawkesbury Pilot Area

Spill Volume Class	Vessel Type	Total Frequency (F) of Spill Volume Class + all Larger Spill Volume Classes (1/Year)	Total Return Period Per Spill Class in Years[1] (1/Total Frequency)	Average Spill Size (m^3)	% of spills in Spill Volume Class
1	Recreation	4.55×10^{-2}	22	3	96.45%
2	Small commercial	7.36×10^{-4}	1,358	93	1.57%
3	Medium commercial	6.50×10^{-4}	1,539	505	1.39%
4	General purpose Med. Range Tanker	1.54×10^{-4}	6,501	1,868	0.33%
5	Long range 1 tanker Panamax	3.46×10^{-5}	28,884	5,526	0.07%
6	Aframax	6.71×10^{-5}	14,897	16,121	0.14%
7	New Panamax Suezmax VLCC ULCC	1.89×10^{-5}	53,043	48,706	0.04%
8		1.84×10^{-6}	542,276	124,844	0.01%

Total Frequency (F) of Individual Grid Cell – reflects the frequency of all plausible ship-source scenarios within a specific grid cell (13.72 km^2), which can be plotted on a map for each of the 8 spill size classes. Given that the probabilities are calculated taking into consideration local shipping traffic and other factors, it highlights local conditions that influence the risk of a ship-source accident. It also stands to reason that since an individual grid cell is 2 nm x 2 nm (or 13.72 km^2) which is significantly smaller than size of the Pilot Area, the Total Frequency (F) of an individual grid cell is lower than the Aggregate Total Frequency (F) in a Pilot Area. Each Total Frequency (F) value is then classified and colour-coded based on the FOS Categories defined in Table 8. The pilot total frequency of individual grid cells for spill size class 1 (all spills greater than 0.01 m^3), for spill size class 3 (> 150 m^3) and for spill size class 6 (>15,000m^3) are presented for the Port Hawkesbury Pilot Area in Figure 9 through 11.

Table 8 Frequency of Spill (FOS) Categories, Description, Definitions and Colour Code

FOS Category	FOS Score (Annual Total Frequency)	Description	Definition (Total Return Period)	Colour Code
FOS-10	3.16×10^{-1}	Very High	<1:10 years	⬛
FOS-9	3.16×10^{-2}	High	1:10 - 1:99 years	🟥
FOS-8	3.16×10^{-3}	Medium	1:100 - 1:999 years	🟧
FOS-7	3.16×10^{-4}	Low	1:1,000 - 1:9,999 years	🟩
FOS-6	3.16×10^{-5}	Very Low	1:10,000 - 1:99,999 years	🟦
FOS-5	3.16×10^{-6}	Extremely Low	1:100,000 - 1:999,999 years	🟦
FOS-4	3.16×10^{-7}		1:1,000,000 - 1:9,999,999 years	🟦
FOS-3	3.16×10^{-8}		1:10,000,000 - 1:99,999,999 years	🟪
FOS-2	3.16×10^{-9}		1:100,000,000 - 1:999,999,999 years	🟪
FOS-1	3.16×10^{-10}		1:1,000,000,000 - 1:9,999,999,999 years	🟪



Base Layer Credits: Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 9 Return period for bunker plus cargo oil spills for spills > 0.01 m^3, excluding fishing vessels in the Port Hawkesbury Pilot Study.

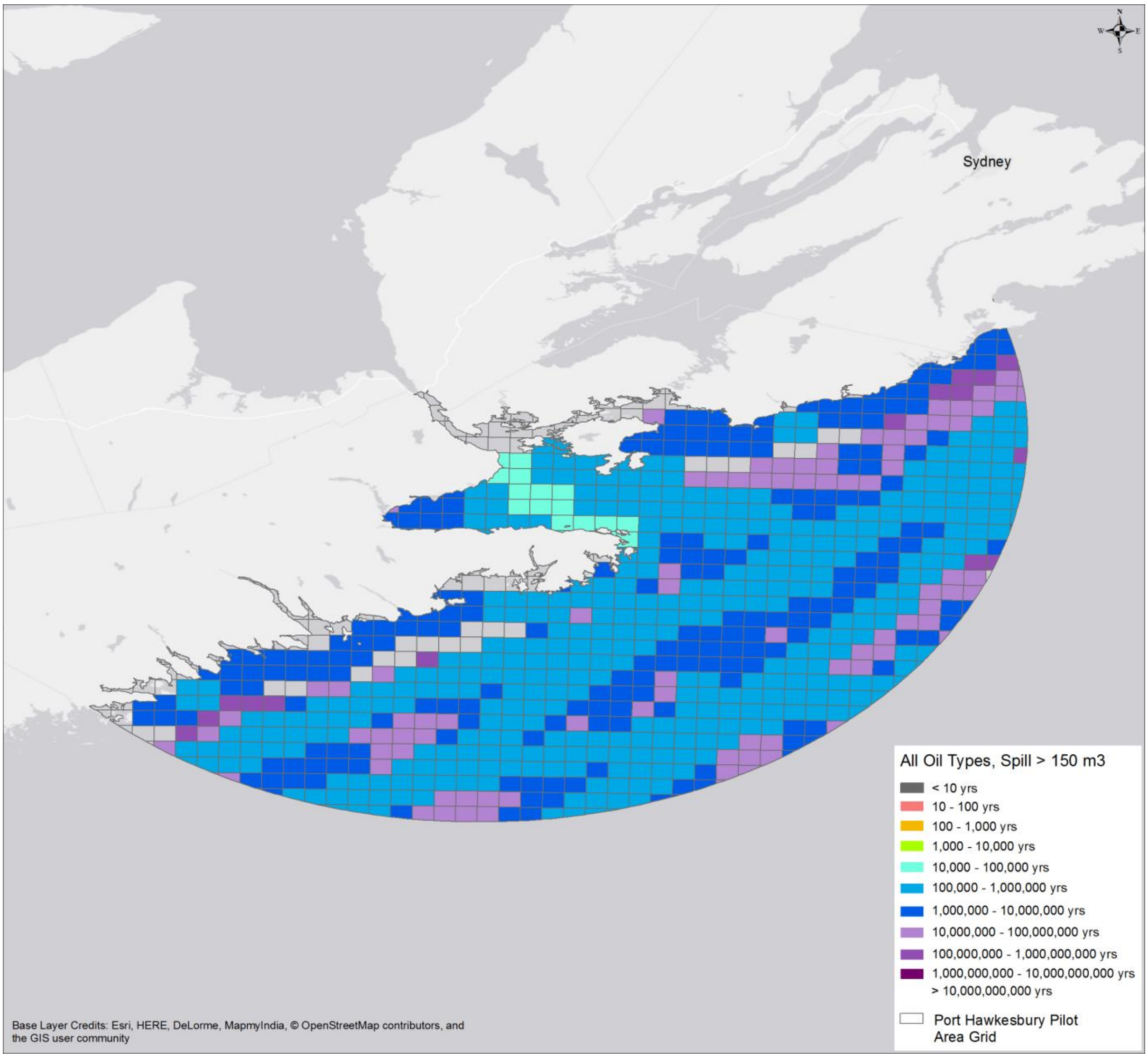


Figure 10 Return period for bunker plus cargo oil spills for spills >150 m^3, excluding fishing vessels in the Port Hawkesbury Pilot Study.

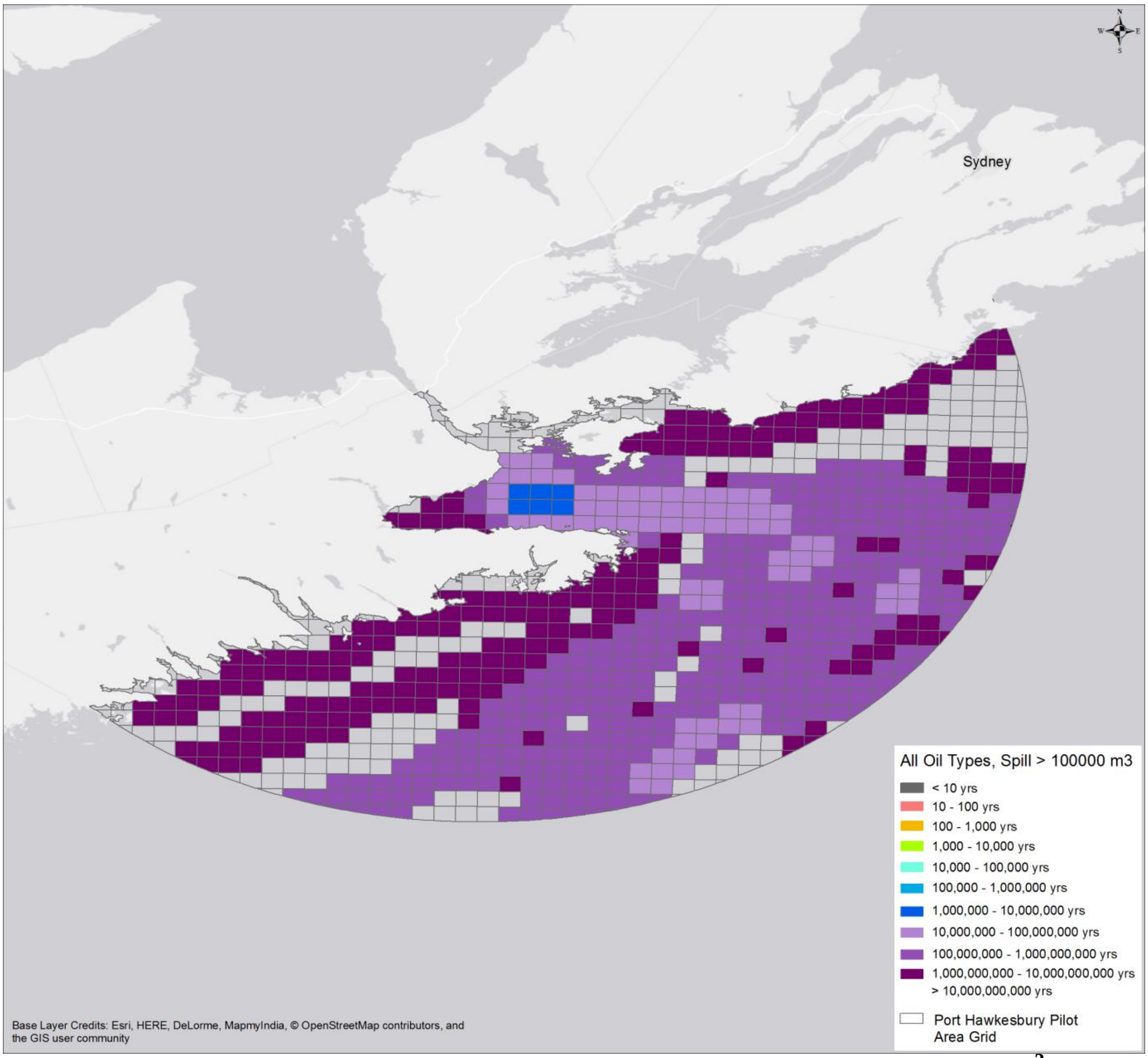


Figure 11 Return period for bunker plus cargo oil spills for spills >15,000 m^3, excluding fishing vessels in the Port Hawkesbury Pilot Study.

Individual Frequency (f) of a Scenario – reflects the frequency of a specific ship-source scenario within a specific grid cell (13.72 km^2), which can be used to focus analysis on specific circumstances that led to a specific accident. For example a the grid cell in the Port Hawkesbury Pilot Study that has the highest individual frequency of a scenario has, 90 individual ship-source oil spill scenarios generated by SAMSON and has corresponding Individual Frequencies (f) between 1.16×10^{-15} (or 1 in 862 trillion years) and 1.39×10^{-4} (or 1 in 7,194 years) for spill size class 1. The scenario with the highest individual frequency in the Port Hawkesbury Pilot Study is the grounding of a recreational vessel (individual frequency of 1.39×10^{-4}) and the release of 0.01 m^3 of marine diesel fuel.

3.1 Comparison of SAMSON Model to TSB data

The SAMSON model utilizes the LRF database to determine the casualty rates per ship type and size of ship for the accident types in the model. In essence the casualty rate is the probability that an encounter between two vessels will result in an incident (i.e. two ships colliding). The casualty rates in the SAMSON model vary over the ship types and ship size classes. The casualty rates are calculated by comparing the number of actual accidents with the number of exposures on a select portion of the North Sea. It is critical to note that the casualty rates are independent of the traffic intensity which allows them to be used in other jurisdictions as well.

The TSB is an independent agency, created by an act of Parliament, that is responsible for investigating marine incidents and accidents in Canada and Canadian registered vessels in international waters (TSB, 2016a). The TSB maintains a database for all marine incidents and accidents that occur in Canadian Waters as well Canadian Flagged Vessels in International Waters. The TSB generally defines an incident as an event that poses a threat to safety of the vessel but does not result in any negative ramifications (e.g. mechanical failure) where an accident is defined as when a vessel sinks, founders, collides or strikes another vessel, goes aground, has a fire/explosion aboard, or is rendered unseaworthy (TSB, 2016c). A marine occurrence refers to incidents and accidents together. An online database was accessed in March 2016 that contains record of incidents and accidents from 2004 until February 2016 (TSB, 2016b). During this time period there were a total of 8880 various incidents and accidents in Canada. Overall, oil tanker incidents and accidents in Canada only accounted for 3.3% of all marine occurrences with 80% of them occurring in the Central Region (Ontario, Quebec and Arctic). This database was filtered to only include the accidents types and vessels modelled in the SAMSON model as well only the accidents that occurred in the four Pilot Areas. The TSB database does not provide enough information in its publically available database to allow for the calculation of Canadian accident rates. During their assessment of the Risk of Marine Shipping in Canada, the Council of Canadian Academies (Council of Canadian Academies, 2016) attempted to determine an incident and accident rate for marine shipping in Canada. The Council used the total number of vessel movements in six different regions of Canada and combined it with the TSB incident and accident database from 2004 to 2011 to produce an incident and accident rate for marine shipping in Canada. However, one limitation of the study was that using vessel movement data only the number of arrivals and departures of vessels from Canadian Ports was used. Due to this limitation vessels that sail in Canadian Waters but do not arrive or depart from a Canadian Port are not included in the assessment potentially underestimating the accident rate.

Therefore the TSB database for marine incidents and accidents from 2004 until September 2015 was used, along with the 2014 AIS data to determine the incident and accident rates in each of the four Study Areas (Figure 13). The casualty rates in the four Study Areas deviate, but the incident and accident rate for the St. Lawrence Study Area at 15.5 incidents and accidents per million nm, is 1.6 times greater than the next closest Study Area. The rate is the lowest in Port Hawkesbury, with 2.5 incidents and accidents per million nm sailed. The rate for Bay of Fundy and Southern BC are close at 7.8 and 9.8 respectively, per million nm sailed. Caution should be used when interpreting these results as it was assumed that the AIS data used for 2014 is representative for the years 2004 until 2015.

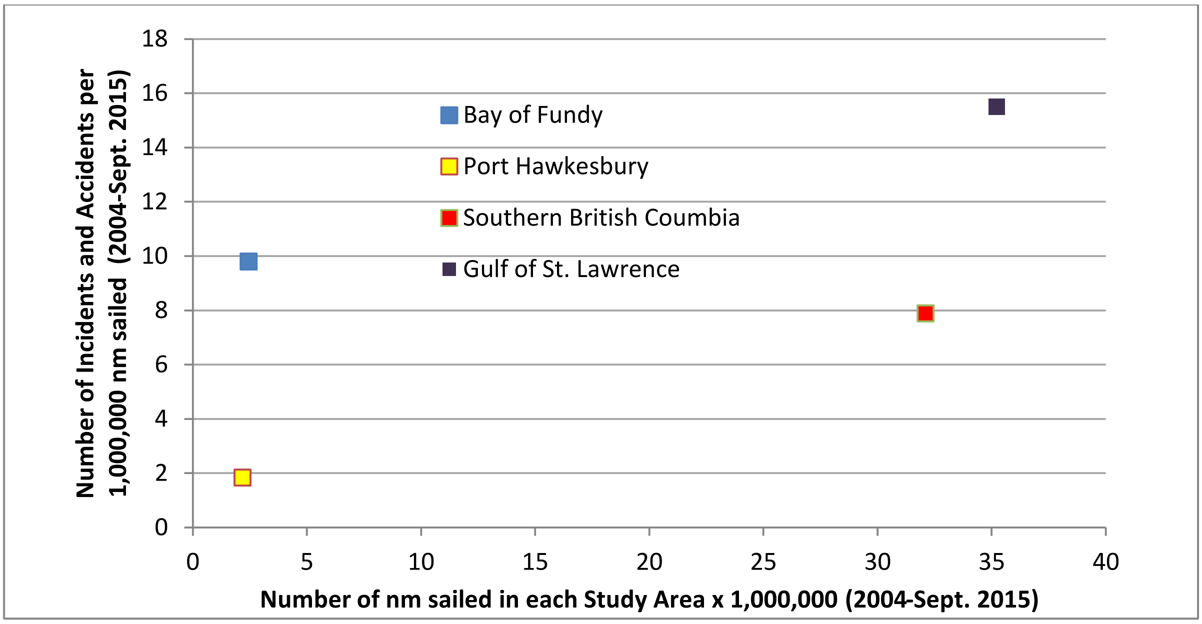


Figure 13 Calculated Incident and Accident Rate based on TSB data from 2004 until Sept. 2015 and 2014 AIS Data

A comparison of the SAMSON model predicted accidents and the TSB documented accidents from 2004 until September 2015 for all four Pilot Areas is presented in Table 9. The results presented in Table 9 are marine accidents that do not necessarily results in an oil spill and are therefore not comparable to the results presented in Table 7.

Table 9 Number of predicted marine accidents (not necessarily leading to an oil spill) predicted by SAMSON compared with the number of accidents recorded in the TSB database from 2004 until September 2015.

	Number of accidents predicted by SAMSON Model	Number of Accidents recorded in TSB Database	Variability
Collision/Allision	24	25	3%
Wrecked/ stranded	63	57	-10%
Foundered	13	24	47%
Fire/explosion	5	36	87%
Hull failure	89	87	-2%
Total	194	229	15%

There are notable differences between the predicted and actual number of accidents especially with the number of founderings and fire/explosions. The predicted number of ships involved in fire/explosion accidents is lower than the actual number of accidents of this type. The reason is presumably that a fire/explosion in the area of St. Lawrence, will be reported much earlier than somewhere on the ocean, out of sight of land. Since the purpose of the ARA project is to predict the probability of an outflow after a fire/explosion and the outflow is based on the observed fraction (of serious fire/explosions) at sea worldwide, it is not appropriate to change the fire/explosion rate because the reporting frequency in areas in close proximity to land is much higher. The SAMSON model under predicted the rate of founderings by 47% and is likely due to the differences in the definition of foundering between the SAMSON model and the TSB. The TSB definition of a vessel that sank includes vessels that partially sank, fully sank, foundered or capsized. Whereas the SAMSON model only considers vessels that founder and defines foundering as "the complete and total loss of a vessel for unknown reasons" and does not include partial sinking's of vessels. The underestimation of by the SAMSON model is due to the differences between the way the SAMSON model and the TSB classify foundering, therefore additional study of the TSB data would be required. Additional, analysis of the TSB data and the data used by the SAMSON model is required to confirm the reasons for the differences between the two sets of accident statistics.

4 Conclusions

The SAMSON model was used in a Pilot Study to determine the Frequency of Spills (FOS) within four Pilot Areas in Canada. The Pilot Study used the AIS data from each Pilot Area for the year 2014 along with other input data in calculating the FOS. The SAMSON results presented in the paper are from a Pilot Study and should not be used to draw conclusions about the safety of shipping in Canada without further analysis.

However, the FOS analysis completed by SAMSON provided a reasonable approximation of the inherent risks of shipping accidents occurring within the four Pilot Areas when compared to shipping accident statistics from the TSB. For an 11 year 8 month time frame, there were a total of 229 reported accidents and SAMSON predicted 194 – a difference of 15%. The main reason is that the coded description of the accidents available in the TSB database does not give enough information of what has really occurred during the accident. In fact you need a detailed description of each accident with all external conditions for a good comparison. Also the accident location is important, the location of a considerable number of accidents seem to occur in a port area.

Predictions made by the SAMSON model use standard casualty rates which were developed and validated over multiple years. As previously stated and confirmed by the Council of Canadian Academies (Council of Canadian Academies, 2016) there is not enough detailed data available from the TSB or the CCG to adjust the casualty rates. In order to develop statistically defensible, regional specific accident rates for use in the SAMSON model the Canadian Government will need to undertake a multi-year review of historical AIS data, along with a detailed review of accident reports from the TSB including detailed root cause analysis and accident avoidance action taken.

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