SHOAL'S EDGE CONSULTING

Modeling Alternative Fuel Spills in the Port of Vancouver

FINAL REPORT

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This report was prepared on behalf of World Wildlife Fund Canada.

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EXECUTIVE SUMMARY

World Wildlife Fund Canada (WWF) contracted Shoal's Edge Consulting (SEC), Environmental Research Consulting (ERC), RPS Group, Inc. (RPS), and Risknology, Inc. (Risknology) to perform a trajectory modeling study of hypothetical alternative fuel discharges from vessel activities in the Port of Vancouver, Canada. The Project team's approach for this study was to utilize advanced in-water and in-air transport modeling systems to evaluate the potential impacts of alternative fuel discharges on the water column, shoreline, and water surface, as well as potential atmospheric impacts from fire, explosion, and toxicity. This study was undertaken to better understand the potential ecological/socioeconomic impacts and trade-offs associated with the use of various alternative vessel fuels in Western Canada. Four types of alternative fuel were evaluated in this study: biodiesel, methanol, anhydrous ammonia, and liquified natural gas (LNG).[1] This study did not consider the future availability or commercial feasibility of these fuels, nor their baseline impacts (e.g., carbon emissions).

To develop the discharge scenarios for modeling, the largest credible discharge of each of the four alternative fuels of interest was calculated based on expected vessel traffic, existing and potential future designs of deep-draft vessels powered by the fuels of interest, the fuel volumes expected to be carried, and locations where discharges are more likely to occur within the Port of Vancouver. As the fuels evaluated in this study are still in development and are not yet in widespread commercial use, there is considerable uncertainty in the factors that influence the likelihood of a discharge, including mitigation measures like the design and protection of fuel tanks. The probability that a spill or discharge of alternative fuel might occur in the Port of Vancouver, or the most likely volume in the unlikely event of a discharge, were beyond the scope of this study.

The in-water discharge scenarios were simulated and analyzed using RPS's SIMAP and CHEMMAP spill modeling systems. The in-water modeling predicted that biodiesel would have the greatest impact on the water surface and shorelines. Biodiesel rises readily to the water surface and is transported by wind and currents as a surface floating slick. This results in a large area of water surface oiling. Due to the constrained geography of the Port of the Vancouver, this surface slick also reaches the shoreline very quickly, and results in a substantial amount of shoreline oiling. Biodiesel (B100) does not have the same toxicity as petroleum oil; however, it is known to smother organisms, kill birds, coat shorelines, and persist for several weeks. Anhydrous ammonia and methanol were predicted to have no impact on the water surface or shoreline. Anhydrous ammonia discharged under the water surface was predicted to completely dissolve in the water. Similarly, due to the properties of methanol, it does not float as a slick on the water surface. However, because of the solubility of anhydrous ammonia and methanol, these products can create large areas of water column contamination if discharged under the water surface. In the model simulations, ammonia resulted in the largest volume of water column contamination, followed by methanol. Biodiesel does not readily entrain into the water column, resulting in relatively small areas of water column contamination above the threshold of concern.

In-air modeling was conducted using the DNV PHAST Modeling Suite. The in-air modeling assessed three distinct hazards associated with the alternative fuels analyzed: fire, explosion, and toxic exposure. Dispersion distances were predicted to be the greatest for methane. The distance to

[1] In this study, LNG was modeled as 100 percent methane and biodiesel was modeled as B100 (soybean oil).

the lower flammability limit for methane was nearly 5 km, and more than four times the next largest distance, which was for ammonia. The distance to the lower flammability limit for methanol was an order of magnitude lower than for ammonia. For fires resulting from ignition of a spreading fuel pool (pool fires), the greatest distance to the threshold of concern was similar for ammonia and methanol, with methane having the smallest distance. The distance to the toxic threshold of concern for ammonia was extremely high, extending 43.8 kilometers from the discharge location. By comparison, the toxic hazard distance for methanol was minimal. The hazardous characteristics of biodiesel are not well known and open literature reports are inconsistent; thus, there was insufficient information to conduct in-air modeling for biodiesel. What is known about this fuel is that it has an extremely small vapor pressure, which would result in insignificant air dispersion to generate a hazard at a distance from the immediate discharge location.

To aid in the comparison of the relative potential impact of different types of fuel discharges on different components of the environment, coloring was assigned to the results based on exposure criteria developed for the water surface, shoreline, water column, and atmosphere. The colors reflect a relative impact level of “none” (green), “low” (yellow), “moderate” (orange) and “high” (red). To summarize the results into a single overall color for each environmental component, the highest relative impact level received in the modeling results for that component was assigned. Thus, the most conservative coloring is assigned to each fuel. The overall results are summarized in Table ES-1 below.

Table ES-1. Overall relative impact of “worst-case” alternative fuel discharges on different environmental components.

Overall Relative Impact	Biodiesel (B100)	Methanol	Ammonia	Methane
Water Surface Exposure				NA[a]
Shoreline Exposure				NA[a]
Water Column Exposure				NA[a]
Atmospheric Exposure – Flammability/Explosivity	NA[b]			
Atmospheric Exposure – Toxicity	NA[b]			
Atmospheric Exposure – In-air Hazards	NA[b]			

[a] Methane is a gas at ambient temperatures; therefore, in-water trajectory modeling was not conducted for this fuel type.

[b] The hazardous characteristics of biodiesel (e.g., Fatty Acid Methyl Esters) are not well known and open literature reports are inconsistent; thus, there was insufficient information to conduct in-air modeling for biodiesel.

The results of this study shed light on the potential impacts associated with worst-case discharges of various alternative vessel fuels in Western Canada. As the modeling results indicate, there is no “perfect” fuel that overall has a lower potential impact relative to other fuels. Rather, there are trade-offs between the potential impacts on different environmental components. For example, the potential impacts of methanol and anhydrous ammonia on shorelines and the water surface are very low, but these fuels are toxic and have substantial potential impacts on the water column and atmosphere. Overall, biodiesel was predicted to have the greatest impacts on the water surface and shoreline, ammonia and methanol were predicted to have the greatest impacts on the water column, and methane and ammonia were predicted to have the greatest atmospheric exposure impacts. Though the discharge volumes simulated were large, worst-case scenarios, this same pattern of impacts would be expected for smaller discharge volumes because the results are driven by the properties of the fuels and their behavior once discharged.

As more information about the designs and mitigation measures of deep-draft vessels powered by alternative fuels becomes available, future research should be conducted to refine the hypothetical worst case discharge volumes and assess the likelihood of discharges of the various types of alternative fuels. The probability of a discharge is a key component of understanding the true relative risk of each fuel, and the fuels could differ substantially from one another in this respect. Additionally, other issues, such as the feasibility of clean up and response for each fuel type, are important factors that should be considered in conjunction with the results of this study.

1.0 INTRODUCTION

World Wildlife Fund Canada (WWF) contracted Shoal's Edge Consulting (SEC), Environmental Research Consulting (ERC), RPS Group, Inc. (RPS), and Risknology, Inc. (Risknology) to perform a trajectory modeling study of hypothetical alternative fuel discharges from vessel activities in the Port of Vancouver, Canada. The Project team's approach for this study was to utilize advanced in-water and in-air transport modeling systems to evaluate the potential impacts of alternative fuel discharges on the water column, shoreline, and water surface, as well as potential atmospheric impacts from fire, explosion, and toxicity.

This study was undertaken to better understand the potential ecological/socioeconomic impacts and trade-offs associated with the use of various alternative vessel fuels in Western Canada. WWF requested the analysis of four types of alternative fuel identified as high priority: biodiesel, methanol, anhydrous ammonia, and liquified natural gas (LNG). This study did not consider the future availability or commercial feasibility of these fuels, nor their baseline impacts (e.g., carbon emissions).

This study specifically focused on worst-case discharges without any consideration of the lower probability of these magnitudes of events compared to smaller spills and discharges. To develop the scenarios for modeling, the largest credible discharge of each of the four alternative fuels of interest was calculated based on expected vessel traffic, existing and potential future designs of deep-draft vessels powered by the fuels of interest, the fuel volumes expected to be carried, and locations where discharges are more likely to occur within the Port of Vancouver. Note that the probability that a spill or discharge of any kind might occur in the Port of Vancouver is not considered in this analysis, nor is the most likely volume in the unlikely event of a spill or discharge.

The in-water discharge scenarios were simulated and analyzed using RPS's SIMAP and CHEMMAP spill modeling systems with the goal of assessing the potential impact on the nearby surface water, water column, and shoreline. In-air modeling was conducted using the DNV PHAST Modeling Suite, which is an interfaced group of models that compute mixture physical properties, discharge from containment, flashing, dispersion, thermal radiation from liquid pools, jet fires and flash fires, and explosion overpressure. In-water modeling was conducted only for the three fuels that are in a liquid state at ambient temperatures (i.e., biodiesel, methanol, and anhydrous ammonia). In the in-water modeling, biodiesel was simulated as B100 (soybean oil). In-air modeling was conducted for three of the four fuels: methanol, anhydrous ammonia, and LNG. Note that LNG is 85–95% methane along with a few percent ethane, even less propane and butane, and trace amounts of nitrogen. The exact composition varies by the source and processing of the natural gas. In this study, LNG was modeled as 100 percent methane, and is thus referred to as methane in the remainder of this report. However, in actual practice, vessels are/would be fueled by LNG. The hazardous characteristics of biodiesel (e.g., Fatty Acid Methyl Esters) are not well known and open literature reports are inconsistent; thus, there was insufficient information to conduct in-air modeling for biodiesel.

In-water modeling utilized a stochastic modeling approach, which uses multiple model runs under typical, yet varying environmental conditions (e.g., wind direction and speed, currents direction and speed) to characterize the probabilistic consequences of a discharge scenario. For each scenario, the model was run 300 times, each with a randomly selected historical start date and time, thereby sampling the variability of meteorological and oceanographic conditions in the study area. The stochastic model results were evaluated statistically and provide insight into the probable behavior of potential fuel discharges in response to varying environmental conditions in the study area.

In-air modeling utilized an integrated set of deterministic phenomenological models with inputs selected to represent site specific conditions and produce conservative results.

This report presents an overview of the scenario development (Section 2.0), a summary of the general modeling approach (Section 3.0), a description of the environmental, physical, and geographic input data utilized for modeling (Section 4.0), the methodology for assigning relative impact (Section 5.0) and the results and conclusions (Sections 6.0 and 7.0). Additional supporting information is provided in Appendix A, which contains a report compiled by ERC describing the discharge scenario development in detail.

2.0 SCENARIO DEVELOPMENT

This study specifically focuses on worst-case discharges without any consideration of the lower probability of these magnitudes of events compared to smaller spills and discharges. To meet this goal, the largest credible discharge of each of the four alternative fuels of interest—biodiesel, methanol, ammonia, and LNG (methane)—as well as their potential discharge locations were calculated. The probability that a spill or discharge of any kind might occur in the Port of Vancouver or the most likely volume in the unlikely event of a spill or discharge are not considered in this analysis.

Given WWF's stated objectives, a matrix was developed consisting of a focused set of four discharge scenarios (Table 1) that reflect highly damaging "worst-case" potential discharges (which have a very low likelihood of occurrence). Each modeled scenario was assumed to be completely unmitigated (i.e., there was no response to contain or remove the discharged substance). The methodology and assumptions of the scenario development are detailed in Appendix A.

Table 1. Matrix summarizing the discharge scenarios selected for modeling.

Location	Discharge Type	Fuel Type	Type of Modeling	Volume of Release (m^3)
Port of Vancouver	Surface discharge	Methane	In-air only	7,173
Port of Vancouver	Surface discharge	Methanol	In-water and in-air	10,311
Port of Vancouver	Surface discharge	Biodiesel	In-water only	4,931
Port of Vancouver	Surface discharge	Ammonia	In-water and in-air	13,001

2.1 Scenario Development Approach

The two components of the scenarios for each of the four alternative fuels are:

- Volume of the worst-case credible discharge or spill; and
- Location(s) of potential discharges or spills.

In order to develop scenarios for each of the four alternative fuels, the following factors were considered and analyzed:

- The types of deep-draft vessel traffic that might be expected in the Port of Vancouver in the next few decades based on current port visits;
- Existing or potential future designs of deep-draft vessels powered by each of these four alternative fuel types;
- The largest volume of each of the four alternative fuel types that might conceivably be carried by any of these deep-draft vessels in the Port of Vancouver based on vessel design for fuel capacity and/or an estimation of potential capacity based on volumetric energy density of the alternative fuels;
- The locations where spills or discharges of fuel might conceivably occur within the Port of Vancouver based on the current port configuration (i.e., as of 2023), existing

vessel traffic lanes, typical transit paths (based on current traffic), and the locations of docks/piers where loading or unloading of cargos might occur; and

- The locations where a hypothetical spill or discharge of fuel might have the greatest impact or cause the greatest harm to environmental and socioeconomic resources in the Port of Vancouver and surrounding area.

Ocean-going deep-draft vessels would generally include tankers, bulk carriers, container ships, cargo vessels, and cruise ships, as opposed to smaller tugs, ferries, fishing boats, and recreational vessels. These larger ocean-going deep-draft vessels were considered because they would be expected to carry the largest amounts of fuel even though there are more smaller vessels in the port than larger ones. For tankers, the vessel's bunker or fuel capacity would be of concern rather than its cargo. At this point, it is not known whether there would be any large-scale storage of alternative fuels at which tankers would load or unload alternative fuel cargos.

Since the probability of a spill or discharge of alternative fuel in general is not within the scope of this current study, the likelihood of a discharge in the event of an impact accident (collision, allision, or grounding) or for other reasons is not material to this analysis.

2.2 Key Assumptions in Scenario Development

Volumetric energy density refers to the amount of energy that can be contained within a given volume. If an alternative fuel has 1.5 times the volumetric energy density (in gigajoules per cubic meter) than a conventional fuel, it will require 1.5 times the space for fuel storage. To achieve the same vessel transport capacity (transporting the ship from Point A to Point B), the alternative fuel would be required at 1.5 times the volume of the conventional fuel. Therefore, a similar vessel with alternative fuel could be expected to spill 1.5 times the volume that a conventionally-fueled vessel would spill in the event of a worst-case discharge. Conversely, if a fuel has greater volumetric energy density than a conventional fuel, it will require less volume to provide the same energy to the ship to travel from Point A to Point B.

Important assumptions in this analysis included the following:

- Ocean-going deep-draft vessel traffic or the types of vessels that would be expected to enter the Port of Vancouver to load or unload cargo would generally be the same in future decades (i.e., there would still be container ships, tankers, and bulk carriers) and that beyond any currently-known port upgrades or development, there will not be any new categories of large vessels entering the port.
- The overall geography and layout of the Port of Vancouver would not change substantially in future decades so that the chosen locations for hypothetical discharges would still be credible in the future.[2]
- Volumetric energy density can be used to estimate the potential fuel capacity of a future deep-draft vessel design if there are no specific examples of current or future vessel designs upon which to rely for an estimate of fuel capacity.

[2] This is also an important assumption in the scenario modeling with respect to water and air effects.

- The total volume of fuel capacity of a vessel minus an assumed 15% would be the maximum amount of fuel with which the vessel would typically be loaded at the start of its journey. For the hypothetical discharge scenarios, it was assumed that the vessel would still have about 50% of its maximum likely fuel capacity at the time of entry into the Port of Vancouver given that it would have fueled elsewhere and would not be fueling inside the port. This also assumes that the outflow of this fuel would be complete.[3]

2.3 Assumption of Future Use of Alternative Fuels in Ocean-Going Vessels

Another assumption in this study is that the four alternative fuels evaluated in this study would actually be in widespread use based on:

- Reasonable availability and price for the maritime industry in global markets;
- Sufficient infrastructure and storage for vessels going to and from Port of Vancouver; and
- Maturity of the technology for use as fuel for ocean-going vessels of the type that would conceivably call at Port of Vancouver.

A number of shipping industry analysts have expressed concern about the availability of some of the alternative fuels evaluated in this study, as well as other practical considerations, as summarized in Table 2. Marine gas oil (MGO) and very-low sulfur fuel oil (VLSFO), which are currently in use by many large ocean-going vessels, are shown for comparison.

Table 2. Considerations for ship fuel options as seen in 2022 and possible for 2035.[4]

Fuel	Availability		Infrastructure & Storage		Maturity of Technology		Energy Density		Price	
	2022	2035	2022	2035	2022	2035	2022	2035	2022	2035
VLSFO/MGO	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
LNG	Green	Green	Yellow	Yellow	Green	Green	Yellow	Yellow	Yellow	Yellow
Methanol	Yellow	Yellow	Yellow	Yellow	Green	Green	Yellow	Yellow	Yellow	Yellow
Biofuels	Red	Yellow	Green	Green	Yellow	Green	Green	Green	Red	Red
Ammonia	Red	Yellow	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow

[3] No known outflow analyses on alternative fuel tank designs are currently available. For spills of conventional fuels, there are data on expected outflow volumes based on the naval architecture of the vessel, fuel type, and accident type and conditions (e.g., a T-bone strike from another vessel or a hard grounding).
[4] Based on a DNV presentation given in April 2022 (DNV 2022), DNV (2023), and DNV-GL (2020). Green indicates a positive picture, yellow indicates a moderate or cautious picture, red indicates a negative picture.

2.4 Discharge Locations

There are two approaches to selecting the locations of the hypothetical discharge scenarios for modeling:

1. The most likely sites for accidents that would result in the largest discharge (e.g., in busy vessel traffic lanes or where vessels are more likely to have cross-traffic); or
2. The locations at which the effects and impacts of the discharge would be greater.

Since the objective of the study is to compare the potential environmental effects of the different discharges, the second alternative is generally more appropriate. However, in considering the locations of the hypothetical discharges one needs to consider the different effects of each alternative fuel type. Within the Port of Vancouver, the discharge location at which the greatest effects may occur for one fuel may not be the same for another. Biodiesel will largely have in-water effects, methanol and ammonia will have in-water and in-air effects. Ammonia will form a toxic cloud and have human health effects. Methane will have in-air effects, including the risk of explosion, as would methanol and ammonia. The effects depend on the location of the discharge in addition to the properties of the fuel.

To capture the range of potential effects from varying discharge locations, five locations were selected as hypothetical discharge sites. The five locations were selected based on the current port configuration (i.e., as of 2023), existing vessel traffic lanes, typical transit paths (based on current traffic), and the locations of docks/piers where loading or unloading of cargos might occur. These locations are focused within English Bay going into Burrard Inlet, as this area has the greatest traffic congestion and vessel traffic with the largest fuel capacities.

Given that human health and safety effects will be of the greatest concern for three of the alternative fuels, a location that is dockside at one of the terminals is a credible location (e.g., accident during unloading) that might also cause the greatest effects as it would be close to port infrastructure and the local population. Thus, three of the release locations are assumed to be at terminal docks. The remaining two locations are in open water where traffic collisions could occur.

The selected discharge locations are shown in Figure 1 and listed in Table 3. In the modeling, individual releases were distributed between the five sites (see Section 3.0).

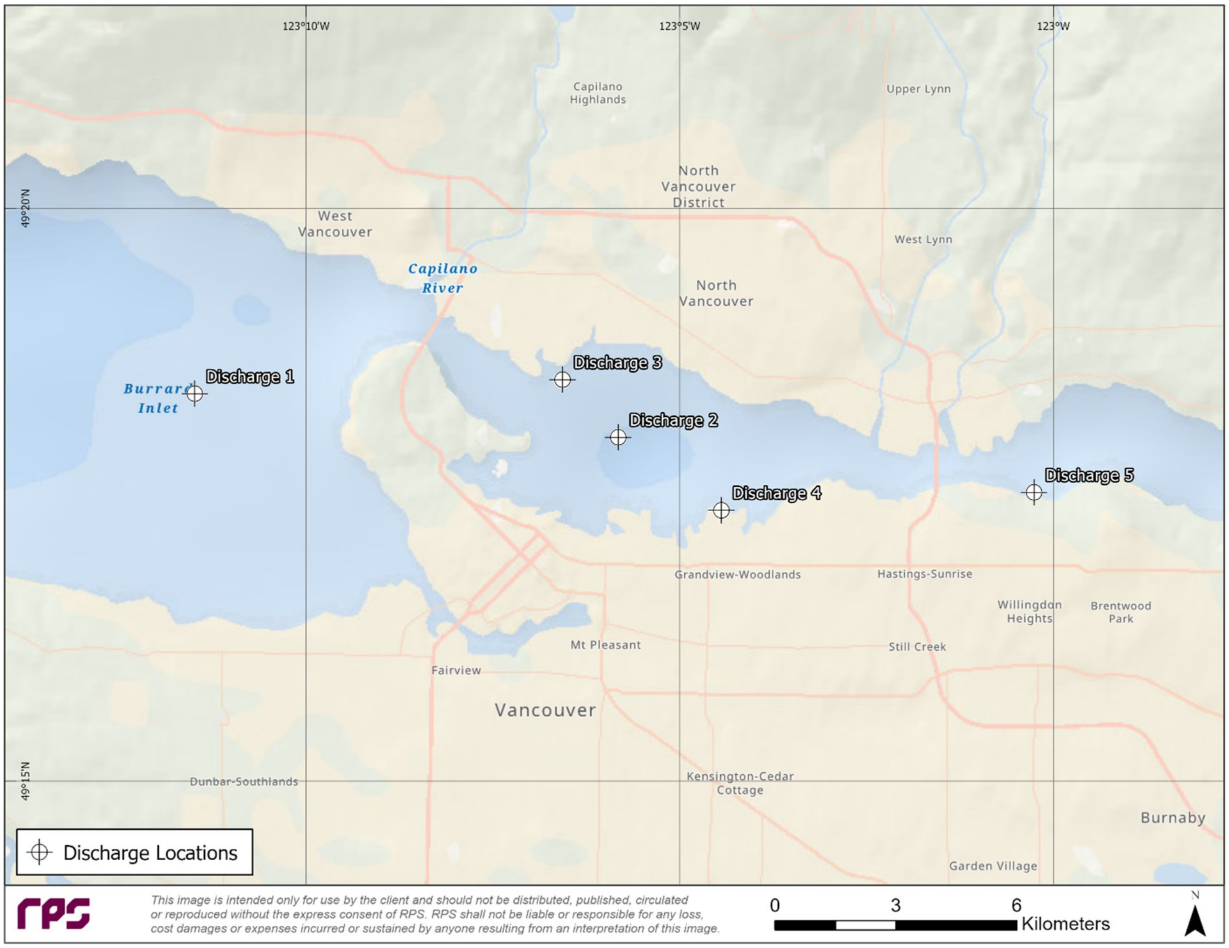

Figure 1. Locations for hypothetical discharges.

Table 3. Locations for hypothetical discharges.

Discharge Location Number	Location Description	Latitude	Longitude
1	Vancouver Anchorage in English Bay	49.306333	-123.191450
2	Middle of Burrard Inlet (potential collision location)	49.300000	-123.097033
3	Port of Vancouver Bulk Loading Dock	49.308367	-123.109467
4	GCT Vanterm Container Terminal	49.289400	-123.074050
5	Parkland Burnaby Refinery Dock	49.291983	-123.004317

2.5 Volumes for Hypothetical Discharges

There are two basic alternative approaches for estimating the fuel capacity of the vessels:

- Obtaining data on actual or proposed vessel designs specific for the alternative fuels and their actual fuel capacities; or

- Determining the amount of fuel that would be used on a particular type of vessel based on its volumetric energy density relative to conventional fuel (e.g., VLFSO or MGO).

There is limited information and only anecdotal examples of what deep-draft vessels powered by alternative fuels may look like in the future. Much of this information (ship designs, etc.) is proprietary and/or not available to the public or only with memberships that are prohibitively expensive. Many of the designs currently in progress or under consideration are for smaller vessels, such as tugboats or offshore supply vessels, or even small vehicles rather than larger cargo vessels or tankers. This presents a significant challenge for determining an appropriate and credible discharge volume for modeling scenarios for this current study. It was beyond the scope of this screening-level study to engage naval architects, structural engineers, or other experts that may be able to provide speculation on the likely design of future deep-draft vessels utilizing these alternative fuels, or the types of safety and discharge mitigation measures that might be incorporated into the vessel designs.

Since there were not enough data from current or planned future vessel designs to derive credible estimates of discharge volumes for the hypothetical discharge scenarios for Port of Vancouver, the discharge volumes were developed using the Volumetric Energy Density approach. As more information about the designs and mitigation measures of deep-draft vessels powered by alternative fuels becomes available, future research should be conducted to refine the hypothetical worst case discharge volumes and assess the likelihood of discharges of the various types of alternative fuels.

A sampling of 125 deep-draft vessels that called at the Port of Vancouver in the month of March 2023 and for which conventional fuel capacities were known was analyzed to develop distributions of vessel sizes and fuel capacities. Based on this dataset, the percentile volumes for capacity for conventional fuels was calculated, and the 95th percentile volume was selected to represent a “worst-case” discharge volume. This 95th percentile volume was multiplied by 85% to adjust for the fact that, for safety reasons, conventional bunker/fuel tanks are typically not filled beyond 85–95% of their capacity. This value was then multiplied by 50% to adjust for likely fuel tank content at the time of port entry. The fuel capacities were then translated into corresponding volumes of alternative fuels based on a conversion by relative Volumetric Energy Density. These conversions assume that a similar type of vessel traveling the same distance and carrying analogous cargo would require more of the alternative fuel than if it were carrying conventional fuel. Details of the analysis can be found in Appendix A. The resulting scenario discharge volumes for the four alternative fuels are shown in Table 4. Note that the Volumetric Energy Density calculations were made for LNG, but the actual modeling was conducted using methane, as LNG is composed mainly of methane.

Table 4. Hypothetical fuel discharge volumes for scenario modeling.

Units	Hypothetical Discharge Volume by Alternative Fuel			
	Methane	Methanol	Biodiesel	Ammonia
Volume in bbl	45,115	64,853	31,017	81,771
Volume in m^3	7,173	10,311	4,931	13,001

The volumes calculated for the hypothetical discharge scenarios, as shown in Table 4, vary from 31,017 bbl (4,931 m^3) for biodiesel to 81,771 bbl (13,001 m^3) for ammonia, a volume 2.6 times larger. The calculated volumes represent credible worst-case discharge scenarios for the different alternative fuels. Based on the analytical approach described above, these would be the volumes that the environment, including ecological resources, and the port and surrounding city infrastructure and population could be exposed to in the unlikely event of a worst-case discharge from a deep-draft vessel in the port. The modeling of the respective hypothetical scenarios simulates the potential behavior of the discharged fuels and the effects that might occur.

In comparing the fuels with regard to harmful effects, the question may arise as to whether the volumes of the discharge should be held constant (e.g., all discharges at an average volume of 55,000 bbl or 8,700 m^3) so that there might be a 1:1 comparison of effects. However, this approach does not take into account that the environment and the public would not likely be exposed to the same volumes in the event of a worst-case discharge. Even in the event of a smaller discharge (e.g., 25% of the vessel's fuel), there would still be a difference in the volumes between the fuel types.

For this study, the use of fuel-specific discharge volumes was selected as the preferred approach in that it would take into account the differences in potential exposure to the environment and public. However, even as such, the differences in the volumes of discharge for the different fuels did not differ in orders of magnitude. Additionally, small variations in the volumes would not likely have substantially changed the patterns of the results or any conclusions reached.

3.0 MODELING APPROACH

3.1 In-Water Modeling

In-water trajectory modeling was carried out in RPS's CHEMMAP and SIMAP modeling systems. Simulations of biodiesel were conducted in SIMAP, and simulations of methanol and anhydrous ammonia were conducted in CHEMMAP.

For the in-water modeling in both CHEMMAP and SIMAP, the general approach is to use stochastic (probabilistic) modeling to determine the range of distances and directions fuel discharges are likely to travel from the release sites under varying environmental conditions. The stochastic modeling approach uses multiple model runs (i.e., hundreds per scenario) to characterize the probable consequences of a discharge scenario under typical yet varying environmental conditions. For each discharge scenario evaluated, the model is run many times, with each individual discharge having a randomly selected historical start date and time. Individual trajectories are computed for each of these start dates/times, thereby sampling the variability of meteorological and oceanographic conditions in the study area (and the resulting variability in the transport of spilled fuels). Stochastic model results include predicted spatial distributions of discharges and probabilities that water surface, water column, and shoreline areas would be affected, as well as the extent of exposure and impacts.

3.1.1 <u>CHEMMAP</u>

RPS's three-dimensional CHEMMAP model (French McCay, 2001) is a chemical discharge modeling and response system that predicts the transport, fate, and impacts of chemical substances in the marine environment. CHEMMAP simulates a number of processes including: (1) slick spreading, transport, and entrainment of floating materials, (2) transport of dissolved and particulate materials in three dimensions, (3) evaporation and volatilization, (4) dissolution and adsorption, (5) sedimentation and resuspension, (6) and degradation. The chemical fates model estimates the distribution of chemical (as mass and concentrations) on the water surface, on shorelines, in the water column and in the sediments.

CHEMMAP was developed by RPS over the past 30 years and originated from the "type A" model (French et al., 1996) included in the U.S. Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) for performing Natural Resource Damage Assessments (NRDAs), under which it underwent extensive reviews. CHEMMAP estimates the distribution of chemical (as mass and concentrations) on the water surface, on shorelines, in the water column and in the sediments. The model is three-dimensional, separately tracking chemical mass that is floating on the surface, dissolved in the water column, entrained as droplets (when in liquid state) or as suspended particles (when in solid state) of pure chemical, adsorbed to suspended particulates, and in liquid solvents as droplets. Simulated fate processes include spreading (floating liquids), advection (transport by currents), dispersion (small scale mixing), evaporation from floating slicks, volatilization from surface water, entrainment (liquids), dissolution, partitioning (between dissolved phase and absorbed to suspended particulates), sedimentation, and degradation.

The model initializes the spilled mass at the location and depth of the discharge, in a state dependent upon the physical-chemical properties of the material. If the chemical is highly soluble in water and is either a pure chemical or dissolved in water (before it is spilled), the chemical mass is initialized in the water column in the dissolved state and in a defined initial volume. If the discharge is at the water surface and if the chemical is an insoluble or semi-soluble liquid that has a density less than or equal to that of water, the model initializes the material as floating on the water surface. For insoluble or semi-soluble solids, liquids, and gases discharged underwater, the spilled mass is initialized in the water column at the discharge depth in a defined plume volume, as particles, droplets, or bubbles, respectively.

The physical-chemical properties required by the model to simulate the transport and fate of the spilled material are compiled from published literature sources. The spilled chemical is modeled using the Lagrangian approach, where multiple sublots, called spillets, of the entire mass (or volume) spilled are tracked as they move in three-dimensional space over time (by addition of the transport vectors due to wind, currents, and buoyancy). Concentrations are then calculated using a three-dimensional Gaussian distribution. The technical documentation for CHEMMAP is described in a series of published reports and papers (French et al., 1996; French McCay, 2001; French McCay and Isaji, 2004; French McCay et al., 2006, 2008). CHEMMAP may be run in stochastic mode (varying inputs according to defined probability density functions) or as individual scenarios to examine representative events.

3.1.2 SIMAP

RPS's SIMAP oil spill modeling system is a computer modeling software application that estimates the physical fates and biological effects of discharges of oil in aquatic environments. In SIMAP, both the physical fates and biological effects models are three-dimensional. There is also a three-dimensional stochastic model for risk assessment and contingency planning applications. The models are coupled to a geographic information system (GIS) containing environmental and biological data, and also to databases of physical-chemical properties and biological abundance, providing the necessary inputs for the models.

Similar to CHEMMAP described above, SIMAP was also derived from the physical fates and biological effects sub-models in the NRDAM/CME and NRDAM/GLE. The physical fates model has been validated with more than 20 case histories, including the Exxon Valdez and other large spills (French McCay, 2003, 2004; French McCay and Rowe, 2004), as well as test spills designed to verify the model's transport algorithms (French et al., 1997). The technical documentation for SIMAP is in French McCay (2003; 2004; 2009).

SIMAP specifically simulates the following oil fate processes:

- Oil spreading (gravitational and shearing);
- Transport and vertical and horizontal dispersion;
- Emulsification
- Entrainment (natural and facilitated by dispersant);
- Dissolution;
- Evaporation and volatilization (to atmosphere);
- Transport and dispersion of entrained oil and dissolved aromatics in the water column;
- Adsorption of entrained oil and dissolved aromatics to suspended sediments;
- Sedimentation and re-suspension;
- Natural degradation;
- Tarball formation; and
- Shoreline entrainment.

3.1.3 Model Assumptions

For this study, the stochastic analysis for the in-water scenarios consisted of 300 individual model runs (distributed uniformly over the five discharge sites), varying the start date and time to sample the potential environmental conditions that could be present at the time of a discharge.

The discharge durations for methanol and ammonia were set to 10 minutes. For biodiesel, the discharge duration was set to 2 hours, as this fuel product would take longer to flow out of a hull or tank breach. Discharges were initialized at 3 meters below the water surface, which is a conservative assumption for assessing potential in-water impacts. Model simulations were tracked for 30 days following the discharge.

3.2 In-Air Modeling

In-air modeling was carried out using the DNV PHAST Modeling Suite (www.dnv.com/phast), which is an integrated group of models that compute mixture physical properties, discharge from containment, flashing, dispersion, thermal radiation from liquid pools, jet fires and flash fires, and explosion overpressure.

For liquid discharges, pool fire, flash fire, and vapor cloud explosion hazards are possible depending on the timing of the ignition. Human safety impacts are determined by the location potentially impacted by toxic vapor, thermal radiation, and the extent of impact of a combustible vapor cloud explosion surrounding the discharge area.

For the in-air modeling, source terms can be strongly influenced by the rate of discharge of fuel from the vessel fuel system breach into the water. This is due to the effects of loss of momentum of the discharge stream, heat transfer to air and water, pool spreading rate, turbulent mixing of the surface pool and evaporation rate from the dynamic pool surface. As fuel systems for future fuels are not yet defined, the specifics of a breach cannot be determined for this project. In order to generate an equivalent comparison without specifics of fuel systems design, the in-air modeling treated the hypothetical fuel discharge volumes as instantaneously formed pools on water.

3.2.1 Pool Calculations

The first step in determining the hazards associated with a given liquid fuel discharge scenario is to determine the associated pool size. The pool size is determined by performing a mass balance between material entering the pool from the leaking inventory and that leaving the pool from either burning or vaporization. For these two different mechanisms of material loss, two different pool sizes can be developed due to the differing mass flux values for burning fuel pools and vaporizing fuel pools. In addition to the material loss mechanism, the substrate onto which the discharge occurs is important in determining the rate of pool fire burning and the rate of vaporization. Therefore, there will be different burn and evaporation rates if a discharge occurs on land versus if it occurs onto water. The primary reference describing pool calculations in PHAST is Dodge et al. (1983).

3.2.2 Vapor Dispersion/Toxic Hazards

Vapor dispersion was performed using a validated Gaussian plume model, the Uniform Dispersion Model, the basics of which are described in Witlox and Holt (1999).

Vaporization and burn rates define the removal of material from the spreading pool. The material entering the pool was determined by using orifice flow driven by both pressure and gravity. The fuel storage conditions were used as inputs along with the hole sizes for each liquid discharge scenario to determine flow rate out of containment and into the pool. Mass flux becomes a primary input into both the determination of thermal radiation and flash fire hazards.

All simulations were conducted on a flat surface without objects (i.e., building, tanks, and other structures) to produce maximum dispersion distances. This is a conservative approach, since nearby objects have the potential to increase mixing, thereby reducing the distance to which the vapor clouds would travel.

The sizes of the vapor clouds were defined based on the volume of fuel mixed with air within its flammable limits. The full set of discharges and resulting flammable mass in the vapor cloud were calculated. The boundaries of flammable mass were defined using the LFL contour, and the density of the cloud was determined assuming the cloud to be homogenous with a concentration of the midpoint between upper flammability limit (UFL) and LFL.

Toxic impacts were relevant for ammonia and methanol. Methane is flammable, and in certain circumstances, an explosion hazard. The toxic endpoint selected was the Median Lethal Dose, also referred to as Lethal Concentration 50% (LC50). The LC50 is defined by the American Institute of Chemical Engineers (AIChE) as the concentration of a material in air which, on the basis of laboratory tests, is expected to kill 50 percent of a group of test animals when administered as a single exposure (usually 1 or 4 hours). LC50 is a measure of the toxicity of a substance.

3.2.3 Pool Fire Hazards

Pool fires were modeled using a solid flame model with no obstructions with ignition occurring at the time of maximum pool spread to achieve the greatest fire hazard distance. The solid flame model calculates radiative intensities at distances away from the center of a fire and allows for a change in hazard distance due to tilting of the flame by wind. To determine the hazard distance, an average emissive power, a burn rate, and an atmospheric transmissivity was calculated during the analysis. The primary reference describing pool fire modeling in PHAST is Dodge et al. (1983).

3.2.4 Explosion Hazards

The acute damage potential of vapor cloud explosions has been proven by many real-world accidents including the significant potential for loss of life, property, and business interruption. Much of the motivation behind the development of predictive models is a result of such catastrophic accidents.

The physical and chemical properties of flammable vapor clouds and the layout of the surrounding area influences the dynamics of blast propagation during an explosion. Additionally, it is well understood that combustible vapor requires both confinement and congestion in order to produce damaging blast waves. No damaging blast waves can occur for discharges in the open.

The concern with explosions is the destructive force, in the form of an overpressure wave, which can be produced. In the case of vapor cloud explosions, the severity of the event is a function of the fuel involved (categorized by reactivity) and the nature of the location in which the cloud forms. Specifically, if the cloud lies within or engulfs a volume that has high congestion and confinement then the severity of the explosion will be greater. The analysis approach used is the TNO Multienergy method, which is described in TNO (1997), Eggen (1995) and Mercx et al. (1998).

To estimate the potential explosion associated with each discharge, the scenario in which the cloud or some portion thereof engulfs a congested volume needed to be assessed. Given a portion of the cloud does lay in a congested volume, the explosion source will be the volume of cloud that intersects the congestion volume. The explosion overpressure results were calculated using the reactivity of the fuel in the cloud, the mass of fuel within the source volume, and the congestion/confinement level representative of the explosion source. The area surrounding the discharge point was divided into areas with various congestion and confinement levels representing potential explosion sources.

The reactivity of the fuel for each hazard is a function of the material composition for each selected fuel type and is based on the laminar flame speed of the fuel. The general rule is that those mixtures with a burning velocity of less than 41 cm/s are considered low reactivity fuel and those greater than 60 cm/s are high. All others are considered medium reactivity.

In-air hazard distances and areas are described in Figure 2. The center of the discharge is the center of the concentric circles. The fire hazard distance is depicted by the yellow shaded circle (centered at the discharge point) with diameter D_f. Vapor dispersion, which can occur in any direction, is shown by the blue shaded ellipse with dispersion distance D_d. The blue circle formed by rotating the dispersion plume (ellipse) is the entire area of possible flammable vapor cloud exposure at flammable concentration. The red shaded circle is centered at the leading point of the dispersion plume, which is the ignition point for a vapor cloud explosion. The diameter of the shaded red circle is the area impacted by a vapor cloud explosion at greater than specified explosion overpressure threshold. Because the vapor dispersion can occur in any direction, the red circle of diameter D_x depicts the area formed by rotating the vapor cloud explosion forming the explosion hazard area.

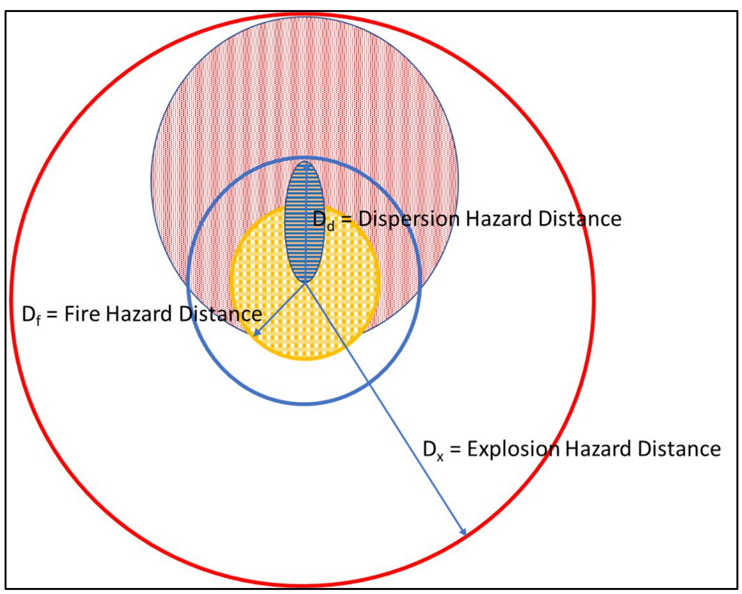

Figure 2. Relationship among in-air hazard distances and areas.

3.2.5 Model Assumptions

Each fuel type was modeled using a deterministic gaussian plume-based model and was simulated 20 times (4 times from each of the 5 discharge locations), varying the weather conditions to bound the potential environmental conditions that could be present at the time of a discharge.

All discharge durations for methanol, methane, and ammonia were set to 10 minutes, and were discharged 1 meter above the water surface from a flat horizontal disc representing vaporization of a liquid pool on the water surface. Discharging near the water surface is the most conservative approach for assessing potential in-air impacts. Model simulations were tracked for 10 minutes following the discharge, which is typically sufficient to achieve the maxima of the concentration at a distance.

Fuel storage conditions are not known at this time, as alternative fuel tank designs are not currently available. Therefore, fuel storage conditions were assumed based on other industry uses of these chemicals. These conditions are shown in Table 5.

Table 5. Assumed fuel storage conditions.

Fuel Type	Pressure (bar)	Temperature (°C)
Ammonia	10	25
Methane	1.06	-160
Methanol	0.07	23

Breach sizes were computed by constraining the duration of discharge volumes to 10 minutes and resulted in the following:

- Ammonia: 835 mm;
- Methane: 980 mm; and
- Methanol: 1,440 mm.

The Multienergy Model Uniform Confinement parameters assumed were an explosion strength of 10% and an explosion efficiency of 12.5%. Ignition locations were assumed to be located at the outer diameter of the largest pool dimension for pool fires, and at the leading edge of the vapor cloud at ½ Lower Flammability Limit (LFL) concentration for vapor cloud explosions.

4.0 DATA INPUTS

The environmental and physical data inputs used in the modeling are described in the following sections.

4.1 Currents, Winds, and Weather

Currents and winds have significant influence on the trajectory and fate of spilled pollutants in water, and they are critical data inputs to the SIMAP and CHEMMAP modeling systems. Winds are also a key factor for the in-air modeling. In order to reproduce the natural variability of currents and wind, the models require spatially- and temporally-varying input data. The favored approach is to use actual historically-observed winds and currents and perform the model simulations over a time period coincident with the observations. Since site-specific long-term historical observations are often not available, the alternative is to use long-term records of data from the outputs of atmospheric and ocean circulation models, or to develop a model of the currents. Modeled data can capture spatial variation of the parameter, in contrast with observation data which is usually available at only one location in the domain. Modeled data are generally more practical when running stochastic simulations over a multi-year time period.

For the Port of Vancouver scenarios, an existing current dataset was utilized that captures seasonal hydrodynamic circulation around the Port. This dataset was developed by using RPS's HYDROMAP hydrodynamic model to simulate local circulation from tides. HYDROMAP was used to obtain seasonally-averaged, depth-averaged tidal currents. HYDROMAP is a globally re-locatable three-dimensional hydrodynamic model capable of simulating complex circulation patterns driven by tidal forcing, wind stress, and freshwater flows. HYDROMAP employs a novel step-wise-continuous-variable rectangular gridding strategy with up to six levels of resolution. The term "step-wise continuous" implies that the boundaries between successively smaller and larger grids are managed in a consistent integer step. The numerical solution methodology follows that of Owen (1980). HYDROMAP incorporates a spatially-variable global tidal database characterization of tidal constituents for use in specifying water surface elevation (tidal) boundary conditions. Alternatively, boundary specific water level records can be used to generate water surface elevation boundary conditions. HYDROMAP creates harmonic models that are not time-stamped.

The study area was represented by HYDROMAP's 2-step nested grid system with the coarser, outer grid (offshore) having a resolution of approximately 4 km x 4 km, and the finest grid system having a resolution of 625 m x 625 m (Figure 3). The geographical coordinates of the HYDROMAP grid are approximately 47.7°N to 51.5°N, and 125.2°W to 122.3°W. The hydrodynamic model simulations were forced with tides, based on the global Oregon State University (OSU) TOPEX/Poseidon Global Inverse Solution TPXO (Egbert and Erofeeva, 2002), which is a global model used for predicting harmonic constituent of ocean tides. The tidal boundary conditions were applied along the open boundaries of the grid and were characterized based on 8 harmonic constituents (M2, S2, N2, K2, K1, O1, P1 and Q1) which comprise the majority of the tidal energy in the area. Mean river flows for each of the four seasons (fall, winter, spring, and summer) were also included in the HYDROMAP file. Seasonal components (climatic winter and summer) of the offshore currents for the present study were assembled from results of the three-dimensional hydrodynamic simulations from a high-resolution global ocean circulation model, Parallel Ocean Program (POP). The time-averaged daily outputs of the results from POP, for the global ocean at a horizontal resolution of 1/6 degree, forced by observed temperature and wind stress during 1985-1995 (Maltrud et al., 1998) were used to obtain the seasonally-averaged currents used in the present study. The seasonal currents thus assembled from POP compared well with a schematic of the large-scale boundary currents off the U.S. West Coast given in Hickey (1998).

Tidal constituent phase and amplitude from OSU TPXO model grid cells were interpolated to the HYDROMAP boundary cells. Both phase and amplitude vary continuously along the boundaries. The phase is the timing at which the maximum elevation from that constituent occurs relative to a base case equilibrium tide and amplitude refers to the height that the water level may be either above or below mean sea level.

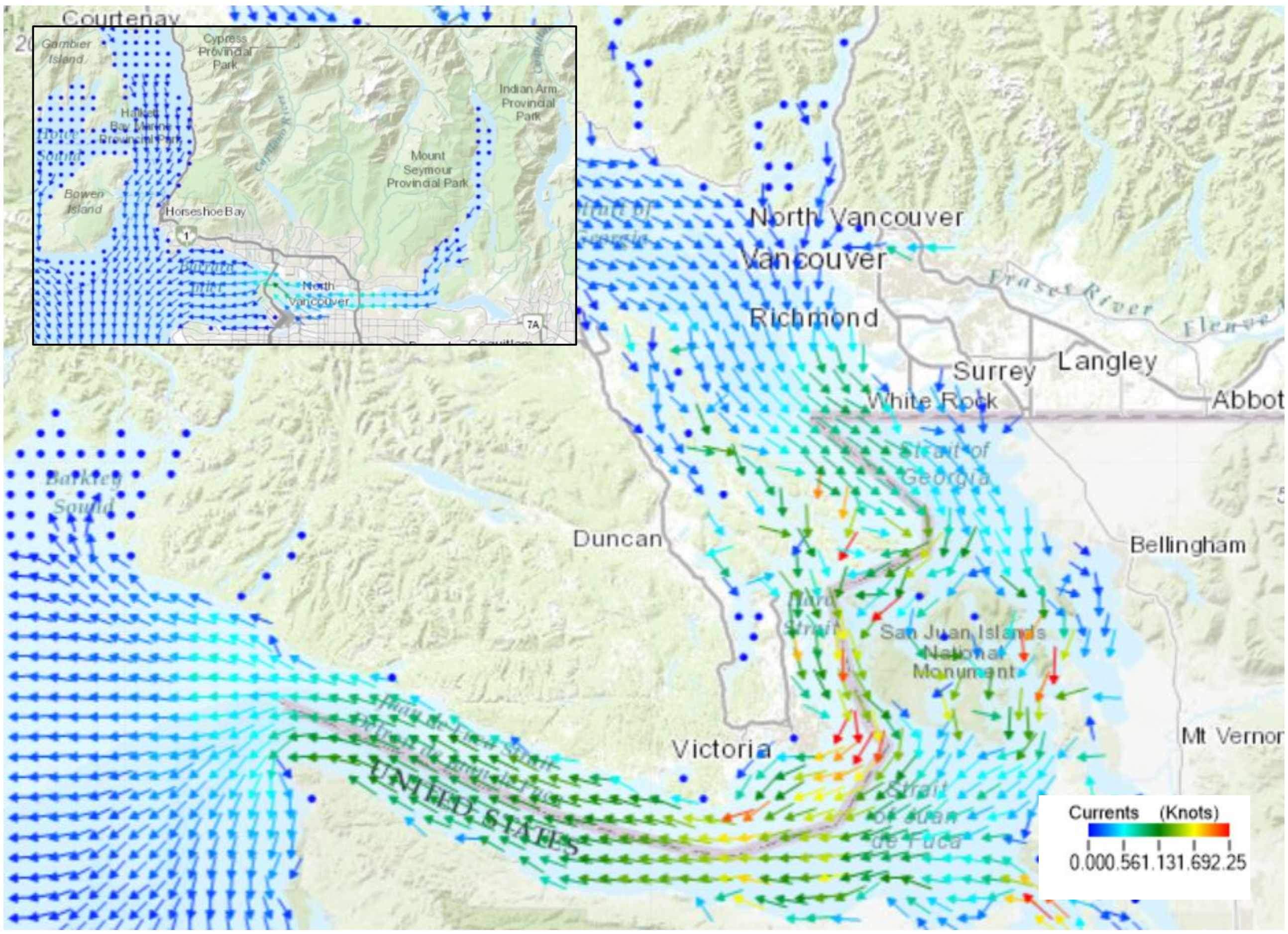

Figure 3. HYDROMAP grid for Southern British Colombia and the Port of Vancouver (shown in inset).

Although the favored approach for wind data is to use actual historically observed winds, site-specific long-term historical observations of winds are often not available for large geographic study areas. Thus, the alternative is to use long-term records from the outputs of an atmospheric model. For the in-water portion of the modeling study, a long-term (2017-2021) Weather Research and Forecasting (WRF) dataset was utilized. The WRF dataset was developed by the University of Washington (Salathé et al., 2014), and captures the spatial and temporal variation of wind over the complex geography surrounding the Port of Vancouver. The WRF model has a spatial resolution of ~0.11° (12 km) in the Pacific Northwest and a six-hour temporal resolution.

For the in-air modeling, the environmental factors required to perform the dispersion analysis are wind speed, stability class, air temperature, and humidity. These factors can influence various hazard conditions; therefore, the probable conditions at the selected discharge sites were investigated.

For the in-water modeling, the WRF dataset was used for all discharge locations. For the in-air modeling, the WRF dataset was used for discharge locations 1 and 2, but a slightly different approach was used for discharge locations 3, 4, and 5, as they are near shore. For these locations, the publicly-sourced Weather Underground (https://www.wunderground.com/) system was used. The data used for each discharge location are listed below:

- Location 1, Vancouver Anchorage in English Bay: WRF Model dataset at grid point 49.3151°N, -123.222°W.
- Location 2, Middle of Burrard Inlet: The WRF Model dataset at grid point 49.3181°N, 123.0509°W.
- Location 3, Port of Vancouver Bulk Loading Dock: WUNDERGROUND Fibreco Waterfront Station - Pulsar WS600, "INORTHVA9."
- Location 4, GCT Vanterm Container Terminal: WUNDERGROUND Wall Street Station, "IVANCO79."
- Location 5, Parkland Burnaby Refinery Dock: WUNDERGROUND Van Heights Station, "IVANCO74."

The 5th and 95th percentile wind speed values at each site were selected to predict vapor dispersion hazards. The 5^{th} percentile is the wind speed that 95% of the wind speeds are greater than, and conversely, the 95^{th} percentile wind speed is the wind speed at which the wind will exceed only 5% of the time.

In addition to wind speeds, a measure of the effect of turbulence on dispersion was also required for analysis in the in-air modeling. Turbulence increases the entrainment and mixing of air into the vapor cloud plume and thereby acts to reduce the concentration of vapor the plume (i.e., enhances the plume dispersion). It was therefore important to categorize the amount of atmospheric turbulence present at any given time. According to the Pasquil Stability scale, there are six stability classes: A, B, C, D, E and F, with class A being the most unstable or most turbulent, and class F being the most stable or least turbulent. Stability classes F and D were chosen for analysis at each site to ensure representative and conservative results.[5]

Humid air absorbs/attenuates more thermal radiation than dry air, thereby decreasing the transmissivity of the air and reducing the thermal hazard distance. Air temperature and humidity were also selected to give realistic but conservative estimates. Average air temperature and humidity were

[5] Stability class F is specified for calculation of the dispersion of natural gas accidental releases in the permit approval process governed by the U.S. Federal Energy Regulatory Commission (FERC) for liquefied natural gas facilities.

taken from the three weather station datasets. Weather conditions used in the in-air modeling are summarized in Table 6.

Table 6. Weather conditions at discharge locations.

Discharge Location	Wind Speed 5th Percentile (m/sec)	Wind Speed 95th Percentile (m/sec)	Stability Category	Relative Humidity (%)	Temperature (°C)
1: Vancouver Anchorage in English Bay	1	12	D, F	0.7	23.3
2: Middle of Burrard Inlet	1	8	D, F	0.7	23.3
3: Port of Vancouver Bulk Loading Dock	0.1	25.7	D, F	0.7	23.3
4: GCT Vanterm Container Terminal	0	13.9	D, F	0.7	23.3
5: Parkland Burnaby Refinery Dock	0	15	D, F	0.7	23.3

4.2 Shoreline Geometry and Type

RPS's oil spill models (e.g., SIMAP) include an oil-shoreline interaction algorithm that is used to estimate the amount of oil that will be retained onshore when oil reaches the coast based on the definition of shoreline type. Shoreline type is an important parameter in understanding the potential oiling in an area. For example, flat sandy beaches typically retain much more oil than steep rocky coast. Oil that cannot be retained on the shore is susceptible to further transport, thereby potentially affecting additional areas. For CHEMMAP, surface slicks interact with shorelines, depositing and releasing material according to whether the material is sticky and the shoreline type. The algorithms used are those developed for oil spills and described in French et al. (1999).

RPS constructed a detailed characterization of shoreline type in the area of interest, which allows for a more detailed analysis of the potential impacts on different shoreline habitat types in the in-water modeling. This detailed habitat grid was developed based on GIS data of shoreline location and shore/habitat type from the BC Marine Conservation Analysis and the Environment and Climate Change Canada (ECCC) Shoreline Type database. ECCC classifies the coastline in the Southern Portion of British Columbia Pilot Area into 11 different types (e.g., sand beach, mud tidal flat, vertical bedrock cliff) based on their physical properties, environmental sensitivity, and their sensitivity to oiling. Each shoreline segment is classified so that the oil spill model can calculate the interaction of the oil brought ashore. Sand beaches and vegetated shorelines typically retain more oil than rocky cliffs, and oil that cannot be retained on the shore may be transported offshore or along the coast, potentially affecting other regions. For the modelling performed as part of this Pilot Area the shoreline was defined using ECCC Shoreline Type database and the National Topographic Database (extensive flats and wetlands). Habitat and shore types included in the Port of Vancouver habitat grid include rocky shore, gravel shore, sand beach, artificial shoreline, wetlands, mud flats, and seagrass beds. The resulting habitat grid is show in Figure 4.

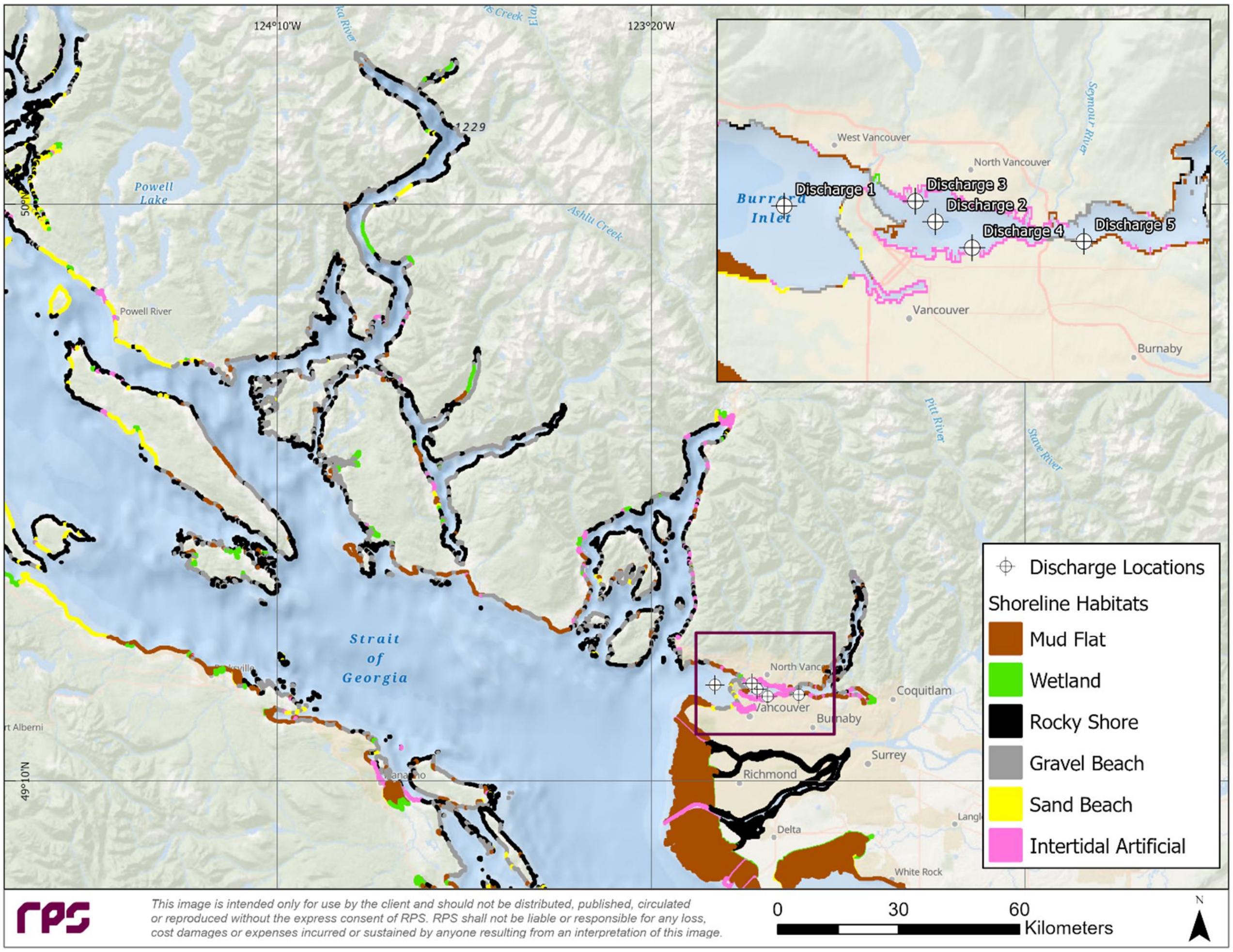

Figure 4. Habitat grid developed for in-water model simulations.

4.3 Bathymetry

The gridded bathymetry data needed for in-water modeling was obtained from the General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas (GEBCO, 2022). The gridding methods and the data sources are described in user guides and technical documents available on the GEBCO web site (www.gebco.net). The GEBCO Digital Atlas consists of depths on a global one 15 arc-second grid for the Vancouver region used for this study. The bathymetry grid used for modeling is shown in Figure 5.

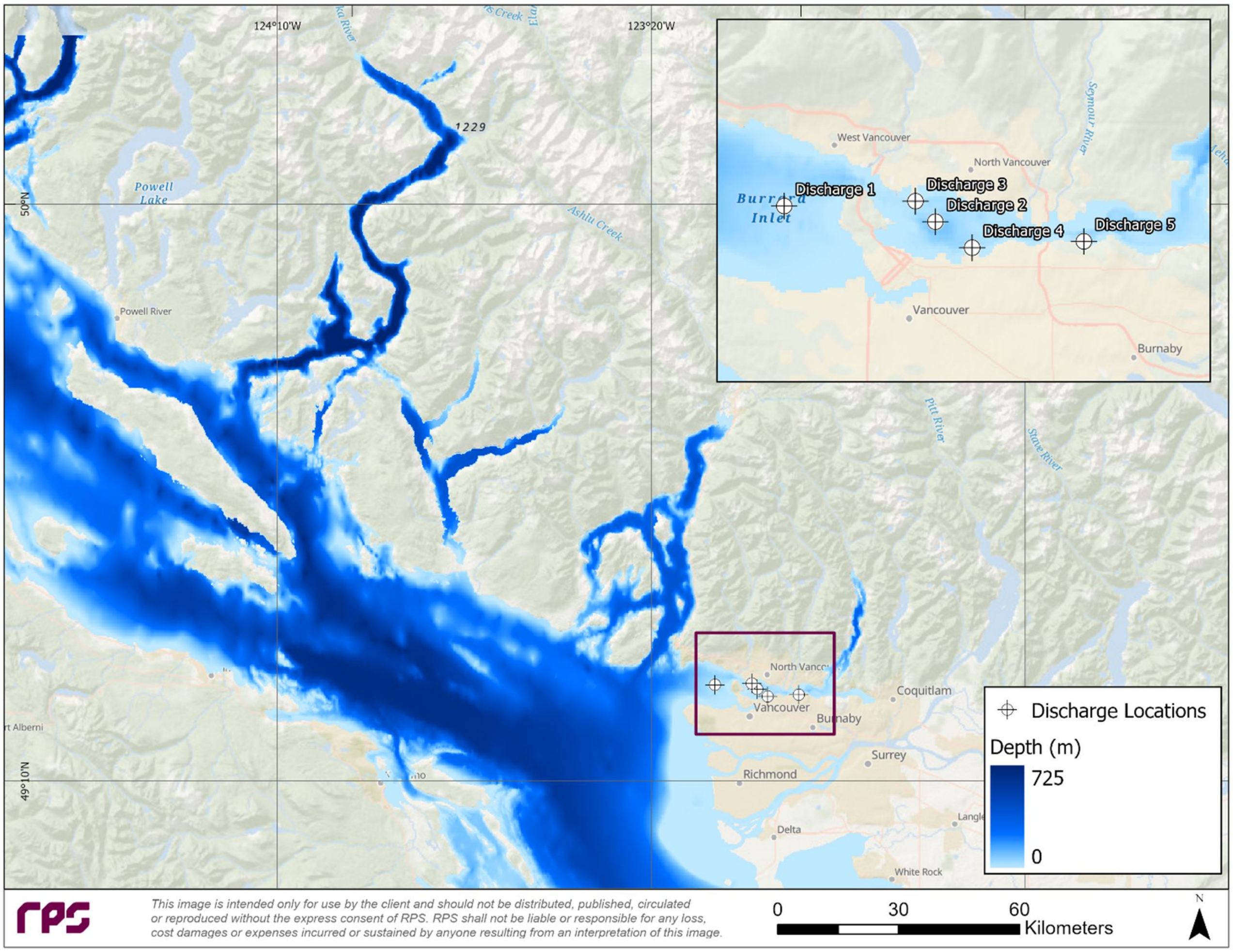

Figure 5. Bathymetry grid developed for in-water model simulations.

4.4 Water Temperature, Density, and Salinity

A definition of the physical properties of the water column in the area of interest is an important input for in-water discharge modeling. Water temperature dictates many physical attributes and weathering processes including the viscosity and evaporation rate of the discharged fuels. Water temperature and salinity also dictate the density of the surrounding water body, which influences the speed at which entrained fuels can re-surface.

For this in-water portion of this study, monthly vertical profiles of temperature, salinity, and density were obtained from the publicly available World Ocean Atlas (Boyer et al., 2018). The dataset is compiled and maintained by the U.S. National Oceanographic Data Center. The dataset consists of decades of observations from various global data management projects. The World Ocean Atlas originated from the Climatological Atlas of the World Ocean (Levitus, 1982) and has been updated with new records several times. Records were obtained using a variety of oceanographic instruments from millions of collection stations. After a comprehensive quality control process, the remaining data were averaged yearly, seasonally, and monthly and interpolated to fit a grid with ¼ degree horizontal resolution and up to 33 depth bins.

4.5 Ground Topography and Surface Type

Ground topography and surface type inputs for the in-air modeling were obtained from expert inspection of ground topography and aerial maps and categorizing surface roughness using standard methods and metrics.

4.6 Fuel Properties

Accurate characterization of fuel properties (e.g., density, viscosity, interfacial tension, evaporation curve) is critical for accurate trajectory and fate modeling, as these properties strongly influence the behavior and movement of discharged materials. Since the exact properties of the fuels that could be discharged in the region are unknown, representative proxies were assumed to define the properties necessary to run the models. For in-water modeling, RPS developed the fuel properties based on in-house datasets. For in-air modeling, Risknology used fuel properties based on thermochemical properties data curated by AIChE in the DIPPR Database (https://www.aiche.org/dippr). Key properties of the fuel products simulated in the in-water modeling are listed in Table 7. Key properties of the fuel products simulated in the in-air modeling are listed in Table 8.

It should be noted that anhydrous ammonia was modeled in a pre-dissolved state in CHEMMAP, LNG was modeled as 100% methane, and biodiesel was modeled as B100 (100% biodiesel in its unblended form). B100 is a vegetable (soybean) oil, which would behave differently in the environment than a petroleum diesel. The biodiesel does not dissolve or evaporate appreciably and would also only mix (entrain) into water under stormy conditions. A petroleum diesel would evaporate readily from the water surface and due to its low viscosity would entrain in the water column. The soluble components of a petroleum diesel dissolve readily when the oil entrains, typically causing toxicity in the area of the spill.

Table 7. Key properties of the fuels used in in-water model simulations.

Fuel Type	Density (g/cm^3 at 25°C)	API Gravity	Viscosity (cP at 25°C)	Surface Tension (dyne/cm)	Pour Point (°C)	Emulsion Maximum Water Content (%)
Anhydrous Ammonia	0.6800	N/A	0.3	N/A	N/A	N/A
Biodiesel (B100)	0.9228	21.8	73.0	9.2	-10.0	0.0
Methanol	0.7910	N/A	0.614	N/A	N/A	N/A

Table 8. Key properties of the fuels used in in-air model simulations.

Fuel Type	Vapor Pressure (bar)	Heat of Combustion (kJ/g)
Ammonia	~1×10^{-5}	16.7
Methane	250	50.0
Methanol	0.12	21.3

4.7 Consequence Thresholds

4.7.1 In-Water Modeling

The in-water stochastic analysis evaluates probabilities, as well as areas and concentrations affected, over a minimum threshold value. These thresholds are based on response requirements or environmental effects endpoints. The tabular exposure results were analyzed and presented with respect to surface oil, shoreline oil, and water column oil exposure thresholds of concern.

RPS developed thresholds of concern based on work completed in French-McCay (2016) and French-McCay et al. (2018), based in part on work described in French-McCay (2002, 2003, 2004). The thresholds of concern are in accordance with current practice in risk assessments.

SIMAP (Biodiesel)

The biodiesel modeled in this study (i.e., B100 or soybean oil) does not have the same toxicity as petroleum oil. Toxicity information for vegetable oils comprising biodiesel is not readily available. Volumes of water exceeding 1,000 mg/m^3 (~1,000 ppb) of biodiesel are considered to summarize model results. It should be noted that B100 does not have the same implications for water column exposure as petroleum oil would (see Section 4.6). However, vegetable oils are known to smother organisms and kill birds (Fingas, 2012). It is assumed that the whole oil thresholds for floating oil and shoreline oiling that have been developed for petroleum oils would apply to biodiesel as well. Surface and shoreline oil exposure thresholds are provided below.

The surface oil thickness thresholds of concern considered for this project are the following: ≥0.1 g/m^2, ≥1 g/m^2, ≥10 g/m^2, and ≥100 g/m^2, as a spatial average over the grid cell dimensions. Oil sheens are generally 0.1–1 g/m^2 (NOAA, 2016; Bonn, 2009, 2011) as a spatial average over the grid cell dimensions used to represent the concentrations of floating oil. Potential effects on socioeconomic resources may occur (e.g., fishing may be prohibited) if oil is visible on the water surface, i.e., ≥0.1 g/m^2. A threshold that is typically used for response activities is ≥10 g/m^2. The minimum thickness at which response equipment can skim/remove oil from the surface, surface dispersants are effectively applied, or oil can be boomed/collected for in situ burning has been estimated at approximately this amount of oil (NOAA, 2016; French-McCay et al., 2018). Potential for effects on wildlife (birds, mammals, reptiles) may occur if oil on the water surface is ≥10 g/m^2. For assessing potential impacts on the water surface, the threshold of ≥0.1 g/m^2 was used for this study, as this is the most conservative threshold.

The shoreline oil thickness thresholds of concern considered for this project are the following: ≥1 g/m^2, ≥10 g/m^2, ≥100 g/m^2, and ≥1000 g/m^2. Effects on socioeconomic resource uses may occur (e.g., recreation, tourism) above a threshold of 1 g/m^2. This amount of oil may trigger the need for shoreline clean-up on amenity beaches. A need for shoreline clean-up and response activities could occur above a threshold of ≥100 g/m^2 (0.1 mm). Potential for effects on shoreline biological resources could occur above a threshold of 100 g/m^2 (0.1 mm). For assessing potential impacts on the shoreline, the threshold of ≥1 g/m^2 was used for this study, as this is the most conservative threshold.

CHEMMAP (Methanol and Anhydrous Ammonia)

Bioassay studies provide data for estimating effects levels for aquatic toxicity. French-McCay et al. (2006) reviewed ecotoxicological data compiled by U.S. Environmental Protection Agency.

They estimated a Predicted No Effects Concentration (PNEC), based on the minimum EC50 for any species test. For ammonia, this was 72 mg/m^3 (~ppb) for the purple sea urchin (*Strongylocentrotus purpuratus*) in an acute toxicity test. For methanol, acute effects were estimated to occur above a threshold of 3,700 mg/m^3, based on data for the mussel *Anodonta imbecillis*. Chronic effects would be expected at approximately one order of magnitude lower concentrations than for acute effects. Thus, the thresholds of concern for ammonia and methanol used for this study were conservatively assumed to be 10 mg/m^3 and 100 mg/m^3, respectively.

4.7.2 In-Air Modeling

Pool fire hazard areas are calculated to define a hazard zone according to specified flux levels. The impacts expected from different levels of thermal radiation (measured in kilowatts per square meter, kW/m^2) are shown in Table 9. A watt is a measure of power, or energy deposition per unit of time. As a reference, the amount of power felt when the sun is at its zenith (directly overhead at sea level) is 1.2 kW/m^2. The table shows that vegetation ignites at a flux of 10 kW/m^2, wood between 12.5 and 25 kW/m^2 and damage to industrial process equipment (i.e., leakage from gasketed flange connections, bearing failure in rotating machinery, seizing of valve internal components) occurs at 37.5 kW/m^2. For this study, the thermal flux threshold of concern was assumed to be 12.5 kW/m^2.

Table 9. Impacts of exposure to thermal radiation on receptors.

Thermal Radiation	Impact on Receptors
10-12 kW/m^2	Vegetation ignites
12.5 kW/m^2	Piloted ignition of wood
25 kW/m^2	Non-piloted ignition of wood
37.5 kW/m^2	Damage to petrochemical process equipment

Data compiled by the U.S. Department of Defense summarize the effects of increasing blast pressure (overpressure) on various types of structures, as shown in Table 10. These data originate from weapons tests and blast studies. For this study, the explosion overpressure threshold of concern was assumed to be 2 psi (0.14 bar).

Table 10. Impacts of overpressure on receptors.

Overpressure	Impact on Receptors
1 psi (0.07 bar)	Window glass shatters
2 psi (0.14 bar)	Moderate damage to houses
3 psi (0.21 bar)	Residential structures collapse
5 psi (0.34 bar)	Most buildings collapse
10 psi (0.69 bar)	Reinforced concrete buildings are severely damaged or demolished
20 psi (1.4 bar)	Heavily-built concrete buildings are severely damaged or demolished

The toxic thresholds of concern were based on the published LC50 concentrations for the fuel types (see Section 3.2.2). The LC50 is 300 ppm for ammonia and 106,000 ppm for methanol. Methane is not toxic and has no LC50 concentration.

5.0 RELATIVE IMPACT METHODOLOGY

To aid in the comparison of the relative potential impact of different types of fuel discharges on different components of the environment, coloring is assigned to the results based the criteria listed in Table 11. For each environmental impact metric, criteria are defined that correspond to a relative impact level of “none” (green), “low” (yellow), “moderate” (orange) and “high” (red). These criteria were defined based on professional opinion and past modeling experience and are intended only to provide a clear basis by which to assign the color coding and make a screening level comparison of the different types of fuels. It is not our intention to quantitatively define what constitutes a “low” vs. “high” impact, as even a “low” relative impact could be devastating to a particular species or group of people, depending on the context. Future users of this study could apply their own color scales to reanalyze the results. Note that the criteria in Table 11 correspond to the consequence thresholds used for this modeling study (described in Section 4.7). If different consequence thresholds are modeled in the future, the criteria may need revision.

Table 11. Relative impact criteria for assigning color coding to the modeling results.

Impact Metric	Relative Impact Level			
	None	**Low**	**Moderate**	**High**
Water Surface Exposure				
Surface area swept (km^2) above 0.1 g/m^2	0	<10,000	10,000 to 100,000	>100,000
Shoreline Exposure				
Time to reach shore (hours)	Does not reach shore	>48	12 to 48	<12
Shoreline length contaminated (km) above 1 g/m^2	0	<10	10 to 100	>100
Water Column Exposure				
Volume of water contaminated (km^3) above threshold of concern	0	<0.1	0.1 to 1	>1
Atmospheric Exposure				
Distance to ½ lower flammable limit of vapor concentration in air (m)	0	<300	300 to 3,000	>3,000
Distance to thermal flux threshold of concern (m)	0	<300	300 to 3,000	>3,000
Distance to explosion overpressure threshold of concern (m)	0	<300	300 to 3,000	>3,000
Distance to toxic threshold of concern (m)	No toxic effects	<300	300 to 3,000	>3,000
Area affected by in-air hazard distances (km^2)	0	<0.1	0.1 to 1	>1

6.0 RESULTS

For each fuel type, the worst-case and average results for exposure of the water surface, shoreline, water column, and atmosphere are reported in Table 12 and discussed in the following sections.

Table 12. Summary of modeling results for “worst-case” discharges of alternative fuels.

Impact Metric	Biodiesel (B100)	Methanol	Ammonia	Methane
Water Surface Exposure				
Worst-case water surface area swept (km^2)	217,187	0	0	NA[a]
Average water surface area swept (km^2)	129,715	0	0	NA[a]
Shoreline Exposure				
Minimum time to reach shore (hours)	0.25	Does not reach shore	Does not reach shore	NA[a]
Average time to reach shore (hours)	4	Does not reach shore	Does not reach shore	NA[a]
Worst-case shoreline length contaminated (km)	724.4	0	0	NA[a]
Average shoreline length contaminated (km)	228.5	0	0	NA[a]
Water Column Exposure				
Worst-case volume of water contaminated (km^3)[b]	<0.01	1.75	2.42	NA[a]
Average volume of water contaminated (km^3)[b]	<0.01	0.51	0.77	NA[a]
Atmospheric Exposure				
Worst-case distance to ½ lower flammable limit of vapor concentration in air (m)	NA[c]	137	1,160	4,740
Average distance to ½ lower flammable limit of vapor concentration in air (m)	NA[c]	96.4	937	2,870
Worst-case distance to thermal flux threshold of concern (m)	NA[c]	710	753	480
Average distance to thermal flux threshold of concern (m)	NA[c]	535	646	414
Worst-case distance to explosion overpressure threshold of concern (m)	NA[c]	140	1,300	5,010
Average distance to explosion overpressure threshold of concern (m)	NA[c]	107	1,060	3,300

Impact Metric	Biodiesel (B100)	Methanol	Ammonia	Methane
Worst-case distance to toxic threshold of concern (m)	NA[c]	30.3	43,800	No toxic effects
Average distance to toxic threshold of concern (m)	NA[c]	25.5	25,000	No toxic effects
Worst-case area affected by in-air hazard distances (km^2)	NA[c]	0.004	0.108	3.02
Average area affected by in-air hazard distances (km^2)	NA[c]	0.001	0.091	0.901

[a] Methane is a gas at ambient temperatures; therefore, in-water trajectory modeling was not conducted for this fuel type.

[b] Different thresholds of concern are considered for the three modeled alternative fuels modeled in water. Results were compiled using 1,000 mg/m^3 for biodiesel, 10 mg/m^3 for ammonia, and 100 mg/m^3 for methanol based on the toxicity of the product.

[c] The hazardous characteristics of biodiesel (e.g., Fatty Acid Methyl Esters) are not well known and open literature reports are inconsistent; thus, there was insufficient information to conduct in-air modeling for biodiesel.

6.1 Water Surface Exposure

The CHEMMAP modeling did not predict floating surface water effects for methanol or ammonia. Anhydrous ammonia discharged under the water surface is predicted to completely dissolve in the water. Due to the properties of methanol, it does not float as a slick on the water surface. The biodiesel modeled using SIMAP was predicted to rise to the water surface, create a slick, and result in large surface areas swept. The maximum (worst-case) predicted surface area swept from the 300 individual biodiesel scenarios was 217,187 km^2, while the average predicted surface area swept was 129,715 km^2. Due to the properties of the biodiesel modeled in this study (B100), very little was predicted to evaporate into the atmosphere. It should also be noted that if a blended biodiesel such as B20 (20% biodiesel blended with petroleum diesel) had been modeled, it would be expected that the results would show a smaller persistent fraction of oil left floating on the water surface and a larger fraction evaporated to the atmosphere.

As methane is a gas at ambient temperatures, in-water trajectory modeling was not conducted for this fuel type, and there are no results for water surface exposure for this fuel type.

6.2 Shoreline Exposure

In the SIMAP model simulations, biodiesel was predicted to reach the shoreline very quickly, in a minimum of 15 minutes, and an average of 4 hours. This is due to the proximity of the modeled discharge sites to the coastline and would make for a challenging response effort. Because of the constrained geography of the Port of Vancouver, the simulations of biodiesel also result in a substantial amount of shoreline oiling above the 1 g/m^2 threshold (which is the threshold for cleanup on amenity beaches). The predicted maximum shoreline length oiled (out of all 300 individual modeled runs) for biodiesel was 724.4 km, and the average was 228.5 km. Of the 724.4 km oiled, 75 percent consisted of rocky and gravel shore types, followed by mudflat (11 percent), sand beach (9 percent), artificial shoreline (5 percent), and wetland (<1 percent).

Methanol and ammonia were not predicted to reach shore in the model simulations.

As methane is a gas at ambient temperatures, in-water trajectory modeling was not conducted for this fuel type, and there are no results for shoreline exposure for this fuel type.

6.3 Water Column Exposure

Biodiesel tends to float on the water surface, and does not readily entrain into the water column, resulting in relatively small areas of water column contamination above the 1,000 mg/m^3 threshold of concern. By contrast, anhydrous ammonia and methanol dissolve readily in water when discharged under the water surface. The modeled ammonia and methanol were predicted to dissolve in water, be transported by winds and currents, and evaporate into the atmosphere. The predicted worst-case volume of water contaminated by methanol in concentrations greater than 100 mg/m^3 was 1.75 km^3, while the predicted worst-case volume of water contaminated by ammonia greater than 10 mg/m^3 was 2.42 km^3. Note that different thresholds of concern are used for methanol and ammonia due to the differences in toxicity. Also, if the discharge had occurred above the water surface (rather than subsurface), the volume of water contaminated would likely be substantially less due to the tendency of these products to rapidly evaporate.

As methane is a gas at ambient temperatures, in-water trajectory modeling was not conducted for this fuel type, and there are no results for water surface exposure for this fuel type.

6.4 Atmospheric Exposure

The hazardous characteristics of biodiesel (e.g., Fatty Acid Methyl Esters) are not well known and open literature reports are inconsistent; thus, there was insufficient information to conduct in-air modeling for biodiesel. What is known about this fuel is that it has an extremely small vapor pressure, which would result in insignificant air dispersion to generate a hazard at a distance from the immediate discharge location.

There are three distinct hazards associated with in-air discharges of the fuels analyzed: fire, explosion, and toxic exposure. The underlying phenomenon giving rise to these hazards is the dispersion of fuel vapor in air.

Dispersion distances are greatest for methane due to the cryogenic condition of the fuel. The vapor evolving from a spilled liquid methane pool is sufficiently cold to behave as a denser-than-air gas, allowing for significant dispersion distances until the vapor warms to ambient air temperature. Of the cases analyzed, the distance to the lower flammability limit for methane was 4.7 km, followed by ammonia (1.2 km) and methanol (0.13 km). The trend in these dispersion distances corresponds with the vapor pressure of these chemicals, with greatest vapor pressure leading to the greatest dispersion distance and lowest to the least.

For fires resulting from ignition of a spreading fuel pool (pool fires), the greatest distance to the threshold of concern was similar for ammonia and methanol, at 753 m and 710 m respectively. The distance for the methane pool fire was approximately 60% of these values, at 480 m. The diffusion burning process of a pool fire depends on complex coupling of chemistry, fluid dynamics, and heat and mass transfer. For the scenarios analyzed, the conditions resulted in substantially larger pool diameters for the ammonia and methanol, which was the fundamental factor in greater thermal flux levels.

Vapor cloud explosion hazard distances behaved similarly to dispersion results, trending with the vapor pressure of the fuel. The greatest explosion overpressure distance to the threshold of concern was for methane, and was slightly greater than 5 km.

Although the underlying phenomenon for toxic exposure is dispersion of fuel vapor in air, the distinguishing factor for toxic hazard distances is the threshold concentration of interest. The LC50 values differ by a factor of more than 350 between ammonia (300 ppm) and methanol (106,000 ppm). The worst-case toxic hazard distance was very high for ammonia, at 43.8 km. By comparison, the toxic hazard distance for methanol was minimal, at only 30.3 meters for the worst-case scenario.

6.5 Overall Results

To summarize the final results into a single overall color for each environmental component (i.e., water surface, shoreline, etc.), the highest relative impact level received in the modeling results for that component was assigned. For example, since the worst-case volume of water contaminated by ammonia received a relative impact level of “high” (red), water column exposure is colored red for ammonia in the summary table, even though the average volume of water contaminated was “moderate” (orange) for that fuel. Thus, the most conservative coloring is assigned to each fuel. The overall results are summarized in Table 13.

Table 13. Overall relative impact of “worst-case” alternative fuel discharges on different environmental components.

Overall Relative Impact	Biodiesel (B100)	Methanol	Ammonia	Methane
Water Surface Exposure				NA[a]
Shoreline Exposure				NA[a]
Water Column Exposure				NA[a]
Atmospheric Exposure – Flammability/Explosivity	NA[b]			
Atmospheric Exposure – Toxicity	NA[b]			
Atmospheric Exposure – In-air Hazards	NA[b]			

[a] Methane is a gas at ambient temperatures; therefore, in-water trajectory modeling was not conducted for this fuel type.

[b] The hazardous characteristics of biodiesel (e.g., Fatty Acid Methyl Esters) are not well known and open literature reports are inconsistent; thus, there was insufficient information to conduct in-air modeling for biodiesel.

7.0 CONCLUSIONS

The Project team's approach for this study was to utilize advanced in-water and in-air transport modeling systems to evaluate the potential impacts of alternative fuel discharges on the water column, shoreline, and water surface, as well as potential atmospheric impacts on the environment from fire, and explosion, and toxicity. WWF requested the analysis of four types of alternative fuel identified as high priority: biodiesel, methanol, anhydrous ammonia, and LNG (which was modeled as methane). This study did not consider the future availability or commercial feasibility of these fuels, nor their baseline impacts (e.g., carbon emissions).

To develop the discharge scenarios for modeling, the largest credible discharge of each of the four alternative fuels of interest was calculated based on expected vessel traffic, existing and potential future designs of deep-draft vessels powered by the fuels of interest, the fuel volumes expected to be carried, and locations where discharges are more likely to occur within the Port of Vancouver.

This study specifically focused on worst-case discharges without any consideration of the lower probability of these magnitudes of events compared to smaller discharges. However, the standard technical definition of risk includes both the likelihood (i.e., probability) of spill/discharge incidents and the consequences (i.e., impacts) of those incidents. In other words:

Risk = probability of discharge x impacts of discharge

The fuels that were evaluated in this study are still in development and are not yet in widespread commercial use. There is limited information and only anecdotal examples of what deep-draft vessels powered by alternative fuels may look like in the future. As a result, there is considerable uncertainty in the factors that influence the likelihood of a discharge, including mitigation measures like the design and protection of fuel tanks. The probability that a spill or discharge of alternative fuel might occur in the Port of Vancouver, or the most likely volume in the unlikely event of a discharge, were beyond the scope of this study.

The model simulations evaluated the potential consequences of a worst-case discharge of each fuel type. The in-water discharge scenarios were simulated and analyzed using RPS's SIMAP and CHEMMAP spill modeling systems and in-air modeling was conducted using the DNV PHAST Modeling Suite.

The in-water modeling predicted that biodiesel would have the greatest impact on the water surface and shorelines. Biodiesel rises readily to the water surface and is transported by wind and currents as a surface floating slick. This results in a large area of water surface oiling. Due to the constrained geography of the Port of the Vancouver, this surface slick also reaches the shoreline very quickly, and results in a substantial amount of shoreline oiling. Biodiesel (B100) does not have the same toxicity as petroleum oil; however, it is known to smother organisms, kill birds, coat shorelines, and persist for several weeks. Anhydrous ammonia and methanol were predicted to have no impact on the water surface or shoreline. Anhydrous ammonia discharged under the water surface was predicted to completely dissolve in the water. Similarly, due to the properties of methanol, it does not float as a slick on the water surface. However, because of the solubility of anhydrous ammonia and methanol, these products can create large areas of water column contamination if discharged under the water surface. In the model simulations, ammonia resulted in the largest volume of water column contamination, followed by methanol. Biodiesel does not readily entrain into the water column, resulting in relatively small areas of water column contamination above the threshold of concern.

The in-air modeling assessed three distinct hazards associated with the alternative fuels analyzed: fire, explosion, and toxic exposure. Dispersion distances were predicted to be the greatest for methane. The distance to the lower flammability limit for methane was nearly 5 km, and more than four times the next largest distance, which was for ammonia. The distance to the lower flammability limit for methanol was an order of magnitude lower than for ammonia. For fires resulting from ignition of a spreading fuel pool (pool fires), the greatest distance to the threshold of concern was similar for ammonia and methanol, with methane having the smallest distance. The distance to the toxic threshold of concern for ammonia was extremely high, extending 43.8 kilometers from the discharge location. By comparison, the toxic hazard distance for methanol was minimal. The hazardous characteristics of biodiesel are not well known and open literature reports are inconsistent; thus, there was insufficient information to conduct in-air modeling for biodiesel. What is known about this fuel is that it has an extremely small vapor pressure, which would result in insignificant air dispersion to generate a hazard at a distance from the immediate discharge location.

The results of this study shed light on the potential impacts associated with worst-case discharges of various alternative vessel fuels in Western Canada. As the modeling results indicate, there is no “perfect” fuel that overall has a lower potential impact relative to other fuels. Rather, there are trade-offs between the potential impacts on different environmental components. For example, the potential impacts of methanol and anhydrous ammonia on shorelines and the water surface are very low, but these fuels are toxic and have substantial potential impacts on the water column and atmosphere. Overall, biodiesel was predicted to have the greatest impacts on the water surface and shoreline, ammonia and methanol were predicted to have the greatest impacts on the water column, and methane and ammonia were predicted to have the greatest atmospheric exposure impacts. Though the discharge volumes simulated were large, worst-case scenarios, this same pattern of impacts would be expected for smaller discharge volumes because the results are driven by the properties of the fuels and their behavior once discharged.

As more information about the designs and mitigation measures of deep-draft vessels powered by alternative fuels becomes available, future research should be conducted to refine the hypothetical worst case discharge volumes and assess the likelihood of discharges of the various types of alternative fuels. The probability of a discharge is a key component of understanding the true relative risk of each fuel, and the fuels could differ substantially from one another in this respect. Additionally, other issues, such as the feasibility of clean up and response for each fuel type, are important factors that should be considered in conjunction with the results of this study.

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APPENDIX A

Modeling Alternative Fuel Discharges in the Port of Vancouver

Scenario Development

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Modeling Alternative Fuel Discharges in the Port of Vancouver: Scenario Development

Disclaimer

This report was prepared by Environmental Research Consulting (ERC) under subcontract to Shoal's Edge Consulting for World Wildlife Fund Canada (WWF).

This report contains information intended for use by Wildlife Fund Canada (WWF) and is not intended for third-party use without prior written consent from WWF. The analyses and modeling conducted for this project were intended to be at a screening level and are based on currently available information. Modeling is predictive in nature and, while this report is based on information from sources that Shoal's Edge Consulting and ERC consider reliable, the accuracy and completeness of said information cannot be guaranteed. Therefore, Shoal's Edge Consulting and its directors, agents, assigns, and employees, and ERC accept no liability for the result of any action taken or not taken on the basis of the information given in this report, nor for any negligent misstatements, errors, and omissions. The statements in this report are the opinions of the authors and may not reflect the views of WWF.

Chapter 1: Introduction

Environmental Research Consulting (ERC) was subcontracted by Shoal's Edge Consulting as part of a project to provide technical support to World Wildlife Fund Canada (WWF) for a screening-level modeling study of potential worst-case discharges of alternative fuels associated with vessel activities in the Port of Vancouver, British Columbia, Canada. The results of this study would be used by WWF to better understand the potential ecological/socioeconomic impacts and trade-offs associated with the use of various alternative vessel fuels in Western Canada.

As part of this modeling study, ERC was tasked with developing realistic and credible scenarios for alternative fuel discharges[1] based on currently available data and within the scope and parameters of this screening-level project. This report provides documentation on the technical approach and reasoning behind the scenario development.

Technical Approach

This study specifically focuses on *worst-case discharges* without any consideration of the lower probability of these magnitudes of events compared to smaller discharges and discharges. To meet this goal, the largest credible discharge of each of the four alternative fuels of interest–biodiesel, methanol, ammonia, and liquefied natural gas (LNG)[2]–as well as their locations were calculated. *The probability that a discharge of any kind might occur in the Port of Vancouver and the most likely volume in the unlikely event of a discharge are not considered in this analysis.*

The two components of the scenarios for each of the four alternative fuels are:

- Volume of the credible worst-case discharge; and
- Location(s) of potential discharges.

In order to develop scenarios for each of the four alternative fuels, the following factors needed to be considered and analyzed:

- The types of deep-draft vessel traffic that might be expected in the Port of Vancouver in the next few decades based on current port visits;
- Existing or potential future designs of deep-draft vessels powered by these four alternative fuels;
- The largest volume of each of the four alternative fuel types that might conceivably be carried by any of these deep-draft vessels in the Port of Vancouver based on vessel design for fuel capacity and/or an estimation of potential capacity based on volumetric energy density of the alternative fuels;
- The locations where discharges of fuel might conceivably occur within the Port of Vancouver based on existing vessel traffic lanes, typical transit paths (based on current traffic), and the locations of docks/piers where loading or unloading of cargos might occur; and

[1] The term "release" is used to indicate that part or all of the discharge of the fuel might be to water, which would generally be called a "spill," and part or all of the discharge may be to the air, which would generally be called a "release." In this report, for consistency, both of these are called a "discharge."

[2] LNG is typically 85–95% methane along with a few percent ethane, even less propane and butane, and trace amounts of nitrogen. The exact composition varies by the source and processing of the natural gas. In this study, LNG was modeled as 100% methane. However, in actual practice, vessels are/would be fueled by LNG and the volumetric energy density analysis was conducted using LNG.

- The locations where a hypothetical discharge of fuel might have the greatest effect or cause the greatest damage to environmental and socioeconomic resources in the Port of Vancouver and surrounding area.

Ocean-going deep-draft vessels would generally include tankers, bulk carriers, container ships, cargo vessels, and cruise ships, as opposed to smaller tugs, ferries, fishing boats, and recreational vessels. These larger ocean-going deep-draft vessels were considered because they would be expected to carry the largest amounts of fuel even though there are more smaller vessels in the port than larger ones. For tankers, the vessel's bunker or fuel capacity would be of concern rather than its cargo. At this point, it is not known whether there would be any large-scale storage of alternative fuels at which tankers would load or unload alternative fuel cargos.

Key Assumptions

Volumetric energy density refers to the amount of energy that can be contained within a given volume. If an alternative fuel has 1.5 times the volumetric energy density (in gigajoules per cubic meter) than a conventional fuel, it will require 1.5 times the space for fuel storage. To achieve the same vessel transport capacity (transporting the ship from Point A to Point B), the alternative fuel would be required to be 1.5 times the volume of the conventional fuel. Therefore, a similar vessel with alternative fuel could be expected to discharge 1.5 times the volume that a conventionally-fueled vessel would discharge. Conversely, if a fuel has greater volumetric energy density than a conventional fuel, it will require less volume to provide the same energy to the ship to travel from Point A to Point B.

Note that if a vessel powered by alternative fuel requires *more* fuel space to account for the difference in volumetric energy density, this may, depending on the vessel's architecture, reduce the amount of cargo space available. This may potentially necessitate *more* trips to the port. Since increasing the number of port visits increases the likelihood of an accident or other situation that results in the discharge of fuel, the use of alternative fuels may actually *increase* the probability of a discharge, all other things being equal.

"All other things being equal" in this case includes the assumption that the outflow of the alternative fuel would be just as likely in the event of a collision, allision, or grounding as it is for existing vessels. However, the architecture and design of future vessels powered by alternative fuels may include different discharge mitigation measures, including the design and protection of fuel tanks to reduce the likelihood of discharge with impacts. *Note: it was beyond the scope and parameters of this screening-level study to engage naval architects or structural engineers that might speculate on the likely design of future deep-draft vessels utilizing these alternative fuels, or the types of safety and discharge mitigation measures that might be incorporated into the vessel designs.*

Since the probability of a discharge of alternative fuel in general is not within the scope of this current analysis, neither the likelihood of a discharge in the event of an impact accident (collision, allision, or grounding) or for other reasons nor the potential probability distribution of discharge volumes is included in this analysis.

Important assumptions in this analysis include:

- Ocean-going deep-draft vessel traffic or the types of vessels that would be expected to enter the Port of Vancouver to load or unload cargo would generally be the same in future decades (i.e., there would still be container ships, tankers, and bulk carriers) and that beyond any currently-known port upgrades or development, there will not be any new categories of large vessels entering the port.

- The overall geography and layout of the Port of Vancouver would not change substantially in future decades so that the chosen locations for hypothetical discharges would still be credible in the future.[3]
- Volumetric energy density can be used to estimate the potential fuel capacity of a future deep-draft vessel design if there are no specific examples of current or future vessel designs upon which to rely for an estimate of fuel capacity.
- The total volume of fuel capacity of a vessel minus an assumed 15% would be the maximum amount of fuel with which the vessel would typically be loaded at the start of its journey. For the hypothetical discharge scenarios, it was assumed that the vessel would still have about 50% of its maximum likely fuel capacity at the time of entry into the Port of Vancouver given that it would have fueled elsewhere and would not be fueling inside the port. This also assumes that the outflow of this fuel would be complete.[4]

Assumption of Future Use of Alternative Fuels in Ocean-Going Vessels

Another key assumption in this study is that the four alternative fuels evaluated in this study would actually be in widespread use based on:

- Reasonable availability and price for the maritime industry in global markets;
- Sufficient infrastructure and storage for vessels going to and from Port of Vancouver; and
- Maturity of the technology for use as fuel for ocean-going vessels of the type that would conceivably call at Port of Vancouver.

A number of shipping industry analysts have expressed concern about the availability of some of the alternative fuels evaluated in this study, as well as other practical considerations, as summarized in Table 1. Marine gas oil (MGO) and very-low sulfur fuel oil (VLSFO), which are currently in use by many large ocean-going vessels, are shown for comparison.

Table 1: Considerations for Ship Fuel Options as Seen in 2022 and Possible for 2035[5]

Fuel	Availability		Infrastructure & Storage		Maturity of Technology		Energy Density		Price	
	2022	2035	2022	2035	2022	2035	2022	2035	2022	2035
VLSFO/MGO	green	green	green	green	green	green	green	green	green	green
LNG	green	green	yellow	yellow	green	green	yellow	yellow	yellow	yellow
Methanol	yellow	yellow	yellow	yellow	green	green	yellow	yellow	yellow	yellow
Biofuels	red	yellow	green	green	yellow	green	green	green	red	red
Ammonia	red	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow

[3] This is also an important assumption in the scenario modeling with respect to water and air effects.
[4] No known outflow analyses on alternative fuel tank designs are currently available. For discharges of conventional fuels, there are data on expected outflow volumes based on the naval architecture of the vessel, fuel type, and accident type and conditions (e.g., a T-bone strike from another vessel or a hard grounding).
[5] Based on DNV presentation in April 2022 (DNV 2022), DNV 2023, and DNV-GL 2020 report. Green indicates a positive picture, yellow indicates a moderate or cautious picture, red indicates a negative picture.

Chapter 2: Port of Vancouver Geographic Layout and Vessel Traffic

The Port of Vancouver (Port of Metro Vancouver) is Canada's largest port, handling 146 million tonnes of cargo from around the world in 2021. The port is the size of the next five largest Canadian ports combined. It handles the most diversified cargo of any port in North America, including exports of coal, canola, grains, petroleum, sulfur, and fertilizers, and imports of machinery, household goods, vehicles, and refined petroleum products.[6]

Geographic Layout

Port of Vancouver includes several separate areas (Figure 1):

- English Bay (including the Vancouver Anchorage);
- Burrard Inlet (including cruise ship terminal, oil terminals, container terminals, and dry bulk terminals);
- Port Moody (including dry bulk and oil terminals);
- Roberts Bank (including container and dry bulk terminals); and
- Fraser River (including auto, dry bulk, and container terminals).

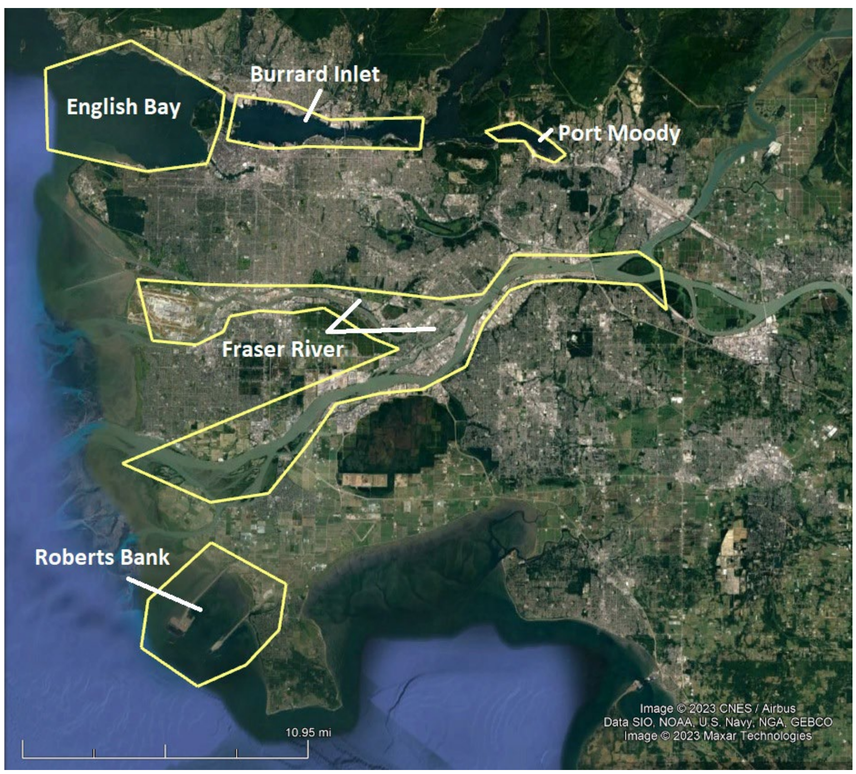

Figure 1: Port of Vancouver Geographic Layout

Deep-Draft Vessel Traffic Patterns

Tanker traffic into the Port of Vancouver generally comes through the Strait of Juan de Fuca and then travels north through the Rosario Strait (east of the San Juan Islands) up to the English Bay and into Burrard Inlet. On the outbound route, the tankers transit west of the San Juan Islands through Haro Strait and back

[6] Port of Vancouver 2022.

out the Strait of Juan de Fuca (Figure 2). Cargo vessels (e.g., bulk carriers and container ships) follow similar patterns, although some vessels transit the Strait of Georgia to the north and some enter the Fraser River (Figure 3).

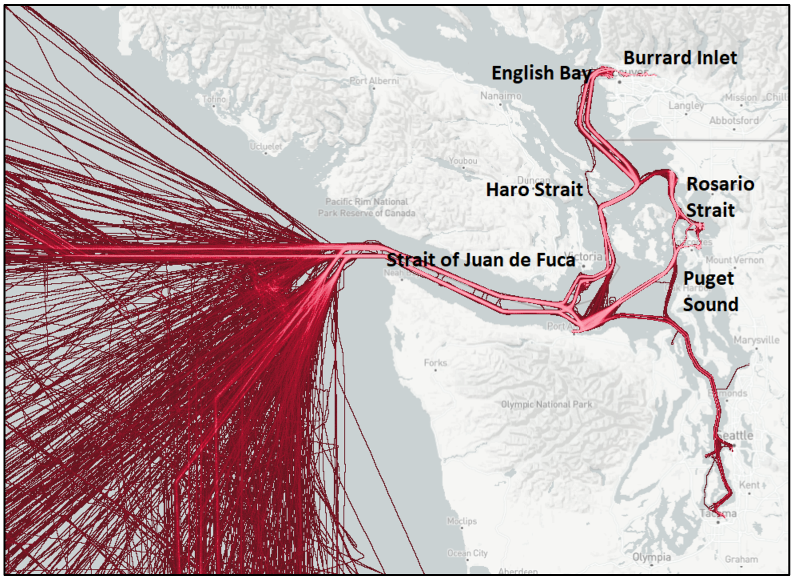

Figure 2: Tanker Traffic into Port of Vancouver (2021)[7]

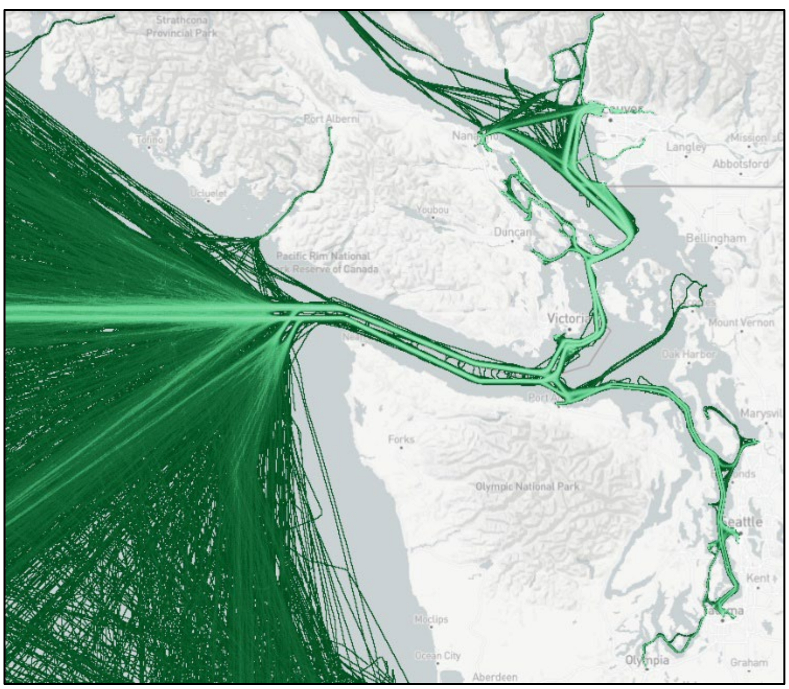

Figure 3: Cargo Vessel Traffic into Port of Vancouver (2021)[8]

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[7] www.marinetraffic.com

[8] www.marinetraffic.com

Current Deep-Draft Vessel Traffic

About 3,000 foreign vessels, including container ships, tankers, cruise ships, breakbulk and dry bulk carriers, and vehicle carriers call at the port each year (Table 2). Note that the traffic decreased significantly in 2020 and 2021 due to the global Covid-19 pandemic (including the complete absence of cruise ships). Data for 2022 are not yet available, however, it is expected that the traffic will eventually return to pre-2020 levels.

Table 2: Foreign Vessel Traffic in Port of Vancouver[9]

Vessel Type		2017	2018	2019	2020	2021
Bulk Carrier	**Vessel Arrivals**	1,523	1,448	1,414	1,477	2,477
	GRT[10]	61,000,568	58,653,692	56,926,705	58,096,383	59,034,161
Container	**Vessel Arrivals**	809	758	734	726	663
	GRT	56,244,688	56,486,453	54,632,558	54,318,520	48,366,300
Ro-Ro[11]	**Vessel Arrivals**	243	263	259	195	204
	GRT	13,381,604	14,453,818	13,594,287	10,670,458	10,727,326
Tanker	**Vessel Arrivals**	260	254	197	197	182
	GRT	5,766,256	6,815,070	4,710,684	5,120,863	4,781,810
Passenger (Cruise)	**Vessel Arrivals**	240	243	288	0	0
	GRT	18,247,479	19,166,533	23,519,557	0	0
Miscellaneous	**Vessel Arrivals**	144	179	210	135	157
	GRT	567,754	130,550	519,974	168,024	213,099
Grand Total	**Vessel Arrivals**	**3,219**	**3,145**	**3,102**	**2,730**	**2,683**
	GRT	**155,208,349**	**155,706,116**	**153,903,765**	**128,374,248**	**123,122,696**

The greatest proportion of deep-draft vessels are in the bulk carrier category. However, these vessels do not necessarily have the largest volume of fuel on board. Container ships would generally have several times the fuel capacity of bulk carriers (see Table 5 in Chapter 3).

Expected Future Port Development

The only known port development for Port of Vancouver is the increase in the size of one of the container terminals, which has largely been completed.[12] This project allows the Centerm terminal to handle 60% more containers by increasing the terminal footprint by 15%. This will likely result in an increase in container ship traffic and potentially the arrival of somewhat larger container ships.

Potential Future Deep-Draft Vessel Traffic

Predicting future vessel traffic in the Port of Vancouver would largely be based on speculation. Since the probability of an accident, such as a collision made more likely by congestion, is not within the scope of this project, the absolute number of vessels is immaterial. The more important factor would be if there might be larger vessels with large fuel capacities that might enter the port, thereby increasing the potential

[9] Based on: Port of Vancouver 2020, 2022.
[10] GRT = gross registered tonnage (metric tonnes) or the total internal volume of the vessels.
[11] Roll-on/roll-off ships designed to carry wheeled cargo, principally automobiles and trucks.
[12] https://www.dredgingtoday.com/2023/02/23/vancouver-port-announces-completion-of-centerm-expansion-project/

volume of discharge. The most likely candidates for this increase would be container ships, which are currently increasing in size. This is considered in Chapter 3 for potential fuel volume.

Locations for Hypothetical Modeling Scenarios

There are two approaches to selecting the locations of the hypothetical discharge scenarios for modeling:

1. The most likely sites for accidents that would result in the largest discharge (e.g., in busy vessel traffic lanes or where vessels are more likely to have cross-traffic); or
2. The locations at which the effects and impacts of the discharge would be greater.

Since the objective of the project is to compare the potential environmental effects of the different discharges, the second alternative is generally more appropriate. However, in considering the locations of the hypothetical discharges one needs to consider that there may be different effects based on alternative fuel type.

The location at which the greatest effects may occur for one fuel may not be the same for another. Biodiesel will largely have in-water effects, methanol and ammonia will have in-water and in-air effects. Ammonia will form a toxic cloud and have human health effects. LNG will have in-air effects, including the risk of explosion, as would methanol and ammonia.

Given that human health and safety effects will be of the greatest concern for three of the alternative fuels, a location that is dockside at one of the terminals is a credible location (e.g., accident during unloading) that might also cause the greatest effects as it would be close to port infrastructure and the local population.

Given that the vessel traffic with the largest fuel capacities and the greatest traffic congestion is in English Bay going into Burrard Inlet, the selection of hypothetical discharge locations was focused in this area.

Suggested locations for discharges are shown in Table 3 and Figure 4.

Table 3: Suggested Locations for Hypothetical Discharges of Alternative Fuels for Modeling

Discharge Number[13]	Location Description	Latitude	Longitude
Discharge 1	Vancouver Anchorage in English Bay	49.306333	-123.191450
Discharge 2	Middle of Burrard Inlet (potential collision location)	49.300000	-123.097033
Discharge 3	Port of Vancouver Bulk Loading Dock	49.308367	-123.109467
Discharge 4	GCT Vanterm Container Terminal	49.289400	-123.074050
Discharge 5	Parkland Burnaby Refinery Dock	49.291983	-123.004317

[13] Refers to map in Figure 4.

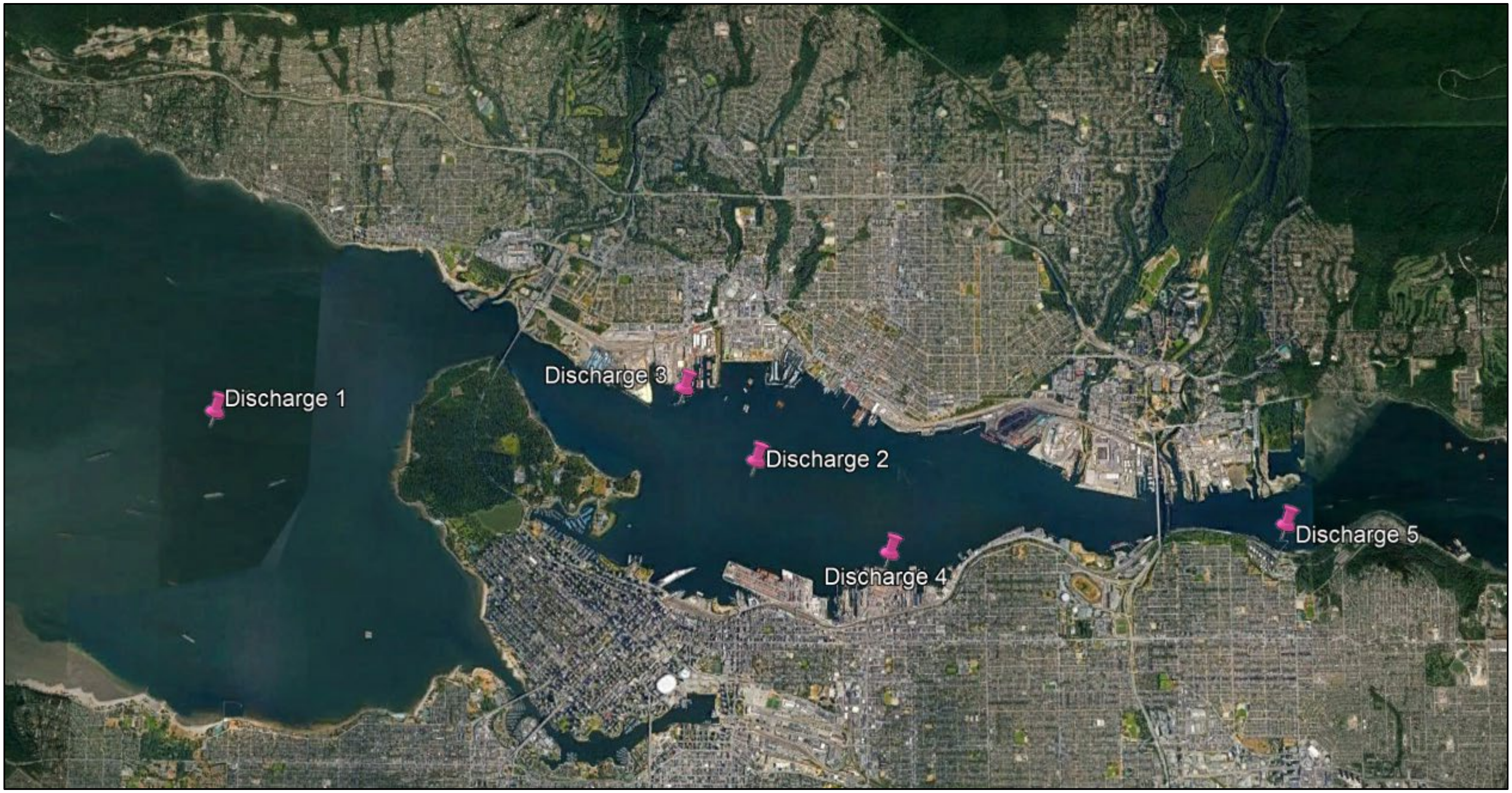

Figure 4: Suggested Hypothetical Discharge Locations for Modeling Scenarios

Chapter 3: Potential Discharge Volumes for Alternative Fuels

There are two basic approaches for estimating the fuel capacity of the vessels:

- Determining the amount of fuel that would be used on a particular type of vessel based on its volumetric energy density relative to conventional fuel (e.g., VLFSO or MGO); or
- Obtaining data on actual or proposed vessel designs specific for the alternative fuels and their actual fuel capacities.

Volumetric Energy Density of Alternative Fuels

The volumetric energy densities of the various alternative fuels and VLSFO or MGO and the volume of each alternative fuel that would be required to meet the same needs for transport relative to the conventional fuels are shown in Table 4. As the energy density decreases, as is the case for the alternative fuels, the amount of fuel required increases (Figure 5).

Table 4: Comparative Volumetric Energy Density of Fuels

Fuel	Volumetric Energy Density[14] (GJ/m^3)	Volume Required for Same Transport Capacity (Relative to VLSFO/MGO)
VLSFO/MGO	36.6	1.0
LNG	23.4	1.6
Methanol	15.8	2.3
Biodiesel	32.0	1.1
Ammonia	12.7	2.9

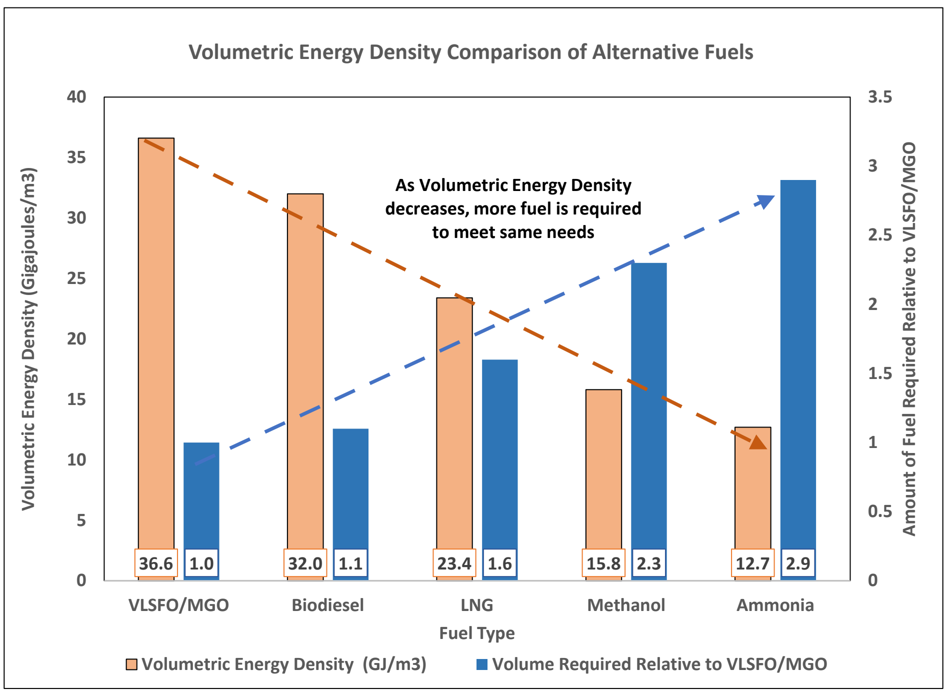

Figure 5: Volumetric Energy Density Comparison of Alternative Fuels

[14] Data based on DNV-GL 2020.

Note that LNG is typically 85–95% methane along with a few percent ethane, even less propane and butane, and trace amounts of nitrogen. The exact composition varies by the source and processing of the natural gas. In this study, LNG was modeled as 100% methane. However, in actual practice, vessels are/would be fueled by LNG. The volumetric energy density analysis described below was conducted using LNG.

Conventional Fuel Capacities of Current Deep-Draft Vessel Traffic

A sampling of 125 deep-draft vessels that called at the Port of Vancouver[15] in the month of March 2023 and for which conventional fuel capacity was known was analyzed for sizes and fuel capacities, as summarized in Table 5. While the most frequent port calls were from bulk carriers, the largest fuel capacity was in container ships.[16]

Table 5: Conventional Fuel Capacities of Current Vancouver Deep-Draft Vessel Traffic[17]

Vessel Type	DWT		GT		TEU		Fuel Capacity (bbl)	
	Max	Average	Max	Average	Max	Average	Max	Average
Bulk Carrier (N = 81)	207,906	71,629	180,966	41,475	n/a	n/a	35,739	16,467
Container (N = 22)	117,366	92,151	107,711	80,169	10,000	7,567	91,844	63,398
General Cargo (N = 5)	44,837	28,896	32,844	19,805	n/a	n/a	15,096	10,020
Tanker (N = 15)	115,668	50,419	61,237	28,967	n/a	n/a	18,467	11,316
Vehicles Carrier (N = 2)	20,703	18,099	75,206	69,161	n/a	n/a	19,134	17,818
All Vessels	**207,906**	**70,130**	**180,966**	**46,360**	**10,000**	**7,567**	**91,844**	**23,872**

Based on this dataset, the percentile volumes for capacity for conventional fuels is shown in Table 6 and Figure 6.

[15] Data on port visits derived from data on www.marinetraffic.com, which relies on AIS data and port calls for GCT Vanterm (https://webservices.globalterminals.com/sites/default/files/VTVesselSchedule.pdf) and Vancouver Centerm Terminal (https://www.dpworldcanada.com/client-centre/vancouver/vessel-berth-schedule/)

[16] The largest reported container ship to call at the Port of Vancouver was the MSC Virgo (15,000 TEU) on 6 March 2022. There is no information on the fuel capacity of this ship. However, other container ships of this size have smaller fuel capacities than the maximum capacity noted in the data for Port of Vancouver container ship visits.

[17] A fair number of large cruise ships also call at the Port of Vancouver (https://www.portvancouver.com/wp-content/uploads/2023/02/2023-Cruise-Ship-Schedule-as-of-February-28.pdf). No specific data on fuel capacity was available for the ships calling at the Port of Vancouver Cruise Terminal. The largest cruise ships (about 305 meters long) generally carry no more than 47,600 bbl of fuel oil. This fuel capacity is below the average for container ships calling in the port.

Table 6: Percentile Conventional Fuel Capacities for Deep-Draft Vessels in Port of Vancouver		
Percentile	Volume (bbl)	Volume (m^3)
50th Percentile (Median)	16,133	2,565
Average (Mean)	23,872	3,795
90th Percentile	60,848	9,674
95th Percentile	66,345	10,548
Maximum	91,844	14,602

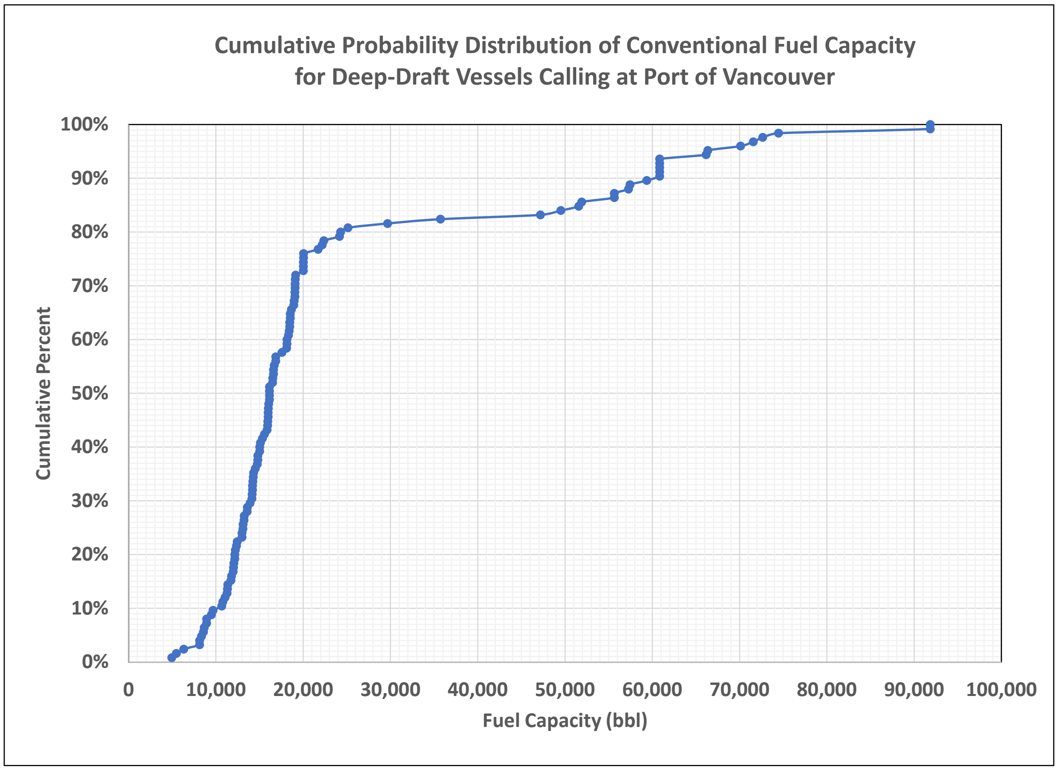

Figure 6: Cumulative Probability Distribution of Conventional Fuel Capacity

Conversions of Conventional Fuel to Alternative Fuel Capacities

The fuel capacities shown in Table 5 and Table 6 refer to the capacities for conventional fuels, such as very low sulfur fuel oil (VLSFO) and/or marine gas oil (MGO). Table 7 shows the corresponding volumes of alternative fuels based on a conversion by relative Volumetric Energy Density (Table 4 and Figure 5). These conversions assume that a similar type of vessel traveling the same distance and carrying analogous cargo would require more of the alternative fuel than if it were carrying conventional fuel. For example, the vessel with an average conventional fuel volume would require 23,872 bbl of VLSFO or MGO. If powered by methanol, it would require 38,195 bbl to have the same hypothetical transport capacity. If powered by ammonia, it would require 69,229 bbl of ammonia to have the same hypothetical transport capacity. The largest vessels would generally require considerably more fuel than smaller ones.

Table 7: Hypothetical Alternative Fuel Capacities for Deep-Draft Vessels in Port of Vancouver					
Fuel	**VLSFO or MGO**	**LNG**	**Methanol**	**Biodiesel**	**Ammonia**
Volumetric Energy Density (GJ/m^3)	**36.6**	**23.4**	**15.8**	**32**	**12.7**
Volume Required for Same Transport Capacity	**1.0**	**1.6**	**2.3**	**1.1**	**2.9**
Volume	**Volume (bbl)**				
50^{th} Percentile (Median)	16,133	25,813	37,106	17,746	46,786
Average (Mean)	23,872	38,195	54,906	26,259	69,229
90^{th} Percentile	60,848	97,357	139,950	66,933	176,459
95^{th} Percentile	66,345	106,152	152,594	72,980	192,401
Maximum	91,844	146,950	211,241	101,028	266,348

In evaluating the hypothetical alternative fuel volumes in Table 7, there are four important factors to consider:

1. The maximum volume is 38% greater than the 95^{th} percentile volume. This means that the top 5% of fuel capacities for the largest vessels are at least 38% larger than for 95% of the vessels entering the port. The largest fuel volumes represent the "outlier" cases and may not be reasonable representatives for hypothetical discharge scenarios.
2. For safety reasons, conventional bunker/fuel tanks are usually not filled beyond 85–90% capacity.
3. Depending on where the vessel last bunkered or if bunkering is to occur in the Port of Vancouver, the vessel may or may not actually have even 85–90% of the fuel tank capacity filled at the time when it is in the Port of Vancouver. At this time, it is not known where the bunkering/fueling facilities would be for the alternative fuels. However, one might assume that if the bunkering occurs outside of the Port of Vancouver, fuel tanks may be filled to about 50% at the time of port entry.
4. If the hypothetical fuel volume needs to be increased by 1.1 times (for biodiesel), 1.6 times (for LNG), 2.3 times (for methanol), and 2.9 times (for ammonia), the ship cargo area might need to be reduced in size if the vessel is retrofitted. It may also not be practical or safe to increase the fuel area in a retrofit. The entire vessel would likely need to be redesigned to better accommodate the cargo and fuel tank areas. This may mean that less cargo can be loaded onto each vessel, which may necessitate an increased number of trips to transport the same cargo. This, in turn, assumes that in the future this same cargo would be traded in the same quantities.

The first three factors have been applied in Table 8 to derive adjusted hypothetical discharge volumes for the modeling scenarios. While reduced in volume from the maximized volumes in Table 7, these would still be formidable volumes for a discharge of oil. To put the discharge of 28,197 bbl of conventional fuel (VLSFO or MGO) into perspective, this discharge volume is compared to several other well-known bunker discharges in Table 9.

The fourth factor requires a brief review of existing plans for designs for future, as well as considerable speculation. Bunker or fuel tanks that are used for conventional fuels have been retrofitted or redesigned to offer greater protection for these tanks to prevent discharges due to impact accidents (collisions, allisions, and groundings). It can be reasonably assumed that there would be similar degrees of protection for alternative fuel tanks. However, the designs for these protections would likely depend on the specific fuel involved and its properties.

Table 8: Adjusted Hypothetical Alternative Fuel Discharge Volumes in Port of Vancouver					
Adjusted Hypothetical Discharge Volume[18]	**Fuel**				
	VLSFO/MGO	**LNG**	**Methanol**	**Biodiesel**	**Ammonia**
Volume in bbl	28,197	45,115	64,853	31,017	81,771
Volume in m^3	4,483	7,173	10,311	4,931	13,001

Table 9: Comparison of Hypothetical VLSFO/MGO Discharge Volume to Historical Incidents				
Vessel	**Year**	**Location**	**Volume (bbl)**	**% of Volume of Hypothetical VLSFO/MGO Discharge**
Apollo Sea	1994	South Africa	18,167	64.4%
New Carissa	1999	USA (Oregon)	8,571	30.4%
Selendang Ayu	2004	USA (Alaska)	8,476	30.1%
Bahai Paraiso	1996	Antarctica	5,950	21.1%
Tenyo Maru	1991	USA (Washington)/Canada (BC)	4,119	14.6%
Cosco Busan	2007	USA California)	1,275	4.5%
Skrim	1992	Canada	905	3.2%

Vessel Designs for Alternative Fuels

Currently, as indicated in Table 10, there are currently some obstacles for the alternative fuels, particularly for biofuels and ammonia.

Table 10: Ship Fuel Options as Seen in 2022 and Possible for 2035[19]						
Fuel	**Availability**		**Infrastructure & Storage**		**Maturity of Technology**	
	2022	**2035**	**2022**	**2035**	**2022**	**2035**
LNG						
Methanol						
Biofuels						
Ammonia						

Some of these issues may be somewhat reduced over the next decade or more. However, there is limited information and only anecdotal examples of what deep-draft vessels powered by alternative fuels may look like in the future. Much of this information (ship designs, etc.) is proprietary and/or not available to the public or only with memberships that are prohibitively expensive.[20] There are some guidelines on safety for retrofitting of vessels and designing vessels that might be retrofitted in the future.[21] Many of the designs currently in progress or under consideration are for smaller vessels, such as tugboats or offshore supply

[18] 95th percentile volume in Table 7 (66,345 bbl) for VLSFO/MGO multiplied by 85% (to adjust for bunkering maximum) and by 50% (to adjust for likely fuel tank content at time of port entry) = 28,197 bbl.
[19] Based on DNV presentation April 2022 and DNV-GL 2020 report. Green indicates a positive picture, yellow indicates a moderate or cautious picture, red indicates a negative picture.
[20] For example, to access the database on the Society for Gas as a Marine Fuel (SGMF) is at least £4,500 (about US$5,500 or C$7,600). (https://www.sgmf.info/members/register)
[21] ABS 2022.

vessels,[22] or even small vehicles[23] rather than larger cargo vessels or tankers. This presents a significant challenge for determining an appropriate and credible discharge volume for modeling scenarios for this current project.

Examples of vessel designs with alternative fuels include:

- **Ammonia:** Japanese shipping company Mitsui OSK Lines (MOL) partnered with Mitsui & Co. and Mitsui Shipbuilding in designing a 210,000-DWT bulk carrier fueled by ammonia. There would be two ammonia tanks on deck, but specifications on tank size have not been publicly released.[24]
- **Ammonia/LNG:** The Greek shipowner Avin International took delivery of the first ammonia-ready tanker, Kriti Future (149,987 DWT), in January 2022. It has a conventional fuel capacity of 3,222 m^3 (20,266 bbl). However, it would need to be converted to run on ammonia or LNG in the future.[25]
- **LNG:** The container ship CMA CGM Jacques Saade[26] (23,000-TEU capacity) is powered by LNG and has a stated tank capacity of 18,600 m^3 (116,990 bbl).[27] This vessel is about twice the size of any container ship that currently calls at the Port of Vancouver.
- **LNG:** The first LNG-powered cruise ship (180,000-GT Carnival Mardi Gras) launched in November 2021. Its LNG fuel tank has a capacity of 3,600 m^3 (22,643 bbl) but was reported to have filled to 75% capacity (2,700 m^3 or 17,000 bbl) on its first voyage.[28]

Note that engaging naval architects and structural engineers to speculate on future deep-draft vessel design utilizing these alternative fuels or the safety and discharge mitigation measures might be incorporated into the vessel designs was outside the scope and parameters of the current screening-level project.

There are not enough data from current or planned future vessel designs to derive estimates of discharge volumes for the hypothetical discharge scenarios for Port of Vancouver. For this reason, the volumetric energy density approach was taken for this analysis.

Considerations for Future Vessel Fuel Discharge Scenarios

Future deep-draft vessel designs with alternative fuels will most likely incorporate discharge prevention, risk, reduction, and safety measures that would affect the likelihood of discharge in the event of an impact accident (collision, allision, or grounding), structural or mechanical failure, or human operational error. These measures would also likely affect the volume of discharge if the fuel tanks are breached. These considerations are not incorporated into the current analysis due to the lack of available information. Future studies should include these factors as more complete information on vessel design becomes available.

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[22] e.g., https://maritimecleantech.no/project/shipfc-green-ammonia-energy-system/; https://eidesvik.no/; https://www.wartsila.com/insights/article/methanol-fuel-for-thought-in-our-deep-dive-q-a#operational-considerations;
[23] https://www.canarymedia.com/articles/sea-transport/startup-amogy-raises-46m-to-fuel-cargo-ships-with-green-ammonia
[24] *Maritime Executive* (27 January 2023).
[25] https://www.offshore-energy.biz/worlds-first-ammonia-ready-vessel-delivered/
[26] https://www.cma-cgm.com/static/PL/attachments/CMA%20CGM%20Jacques%20Saade.pdf
[27] According the www.marinetraffic.com, this ship has a fuel oil capacity of 3,893 m^3 (24,486 bbl). It is unclear if this fuel oil in addition to or instead of LNG.
[28] https://maritime-executive.com/article/north-america-s-first-lng-cruise-ship-fuels-preparing-for-mv

Use of Fuel-Specific Volumes as Opposed to Equal Volumes for Modeling

The volumes calculated for the hypothetical discharge scenarios, as shown in Table 8, vary from 31,017 bbl (4,931 m^3) for biodiesel to 81,771 bbl (13,001 m^3) for ammonia, a volume 2.6 times larger. The calculated volumes represent credible worst-case discharge scenarios for the different alternative fuels. Based on the analytical approach described above, these would be the volumes that the environment, including the ecological resources, and the port and surrounding city infrastructure and population would be exposed to in the unlikely event of a worst-case discharge from a deep-draft vessel in the port. The modeling of the respective hypothetical scenarios simulates the potential behavior of the discharged fuels and the effects that might occur.

In comparing the fuels with regard to harmful effects, the question may arise as to whether the volumes of the discharge should be held constant (e.g., all discharges at an average volume of 55,000 bbl or 8,700 m^3) so that there might be a 1:1 comparison of effects. Using the equal-volume approach, one might be able to conclude, for example, that Fuel A is 10 times as harmful to the environment and the public as Fuel B.[29] However, this does not take into account that the environment and the public would not likely be exposed to the same volumes in the event of a worst-case discharge. Even in the event of a smaller discharge (e.g., 25% of the vessel's fuel), there would still be a difference in the volumes between the fuel types.

For this study, the use of fuel-specific discharge volumes was selected as the preferred approach in that it would take into account the differences in potential exposure to the environment and public. However, even as such, the differences in the volumes of discharge for the different fuels did not differ in orders of magnitude. Additionally, small variations in the volumes would not likely have substantially changed the patterns of the results or any conclusions reached.

[29] In the modeling, the exposure of fuels to the water surface, shoreline, water column, and atmosphere differ so that there is no clear way in which to quantify that one fuel is X times more or less harmful, making this a gross simplification.

Chapter 4: Summary

The recommended scenario discharge volumes for the four alternative fuels are as shown in Table 11.

Table 11: Recommended Hypothetical Alternative Fuel Discharge Volumes for Modeling

Units	Recommended Discharge Volume by Alternative Fuel			
	LNG	Methanol	Biodiesel	Ammonia
Volume in bbl	45,115	64,853	31,017	81,771
Volume in m^3	7,173	10,311	4,931	13,001

The recommended locations for the discharges are shown in Table 12 and Figure 7.

Table 12: Suggested Locations for Hypothetical Discharges of Alternative Fuels for Modeling

Discharge Number[30]	Location Description	Latitude	Longitude
Discharge 1	Vancouver Anchorage in English Bay	49.306333	-123.191450
Discharge 2	Middle of Burrard Inlet (potential collision location)	49.300000	-123.097033
Discharge 3	Port of Vancouver Bulk Loading Dock	49.308367	-123.109467
Discharge 4	GCT Vanterm Container Terminal	49.289400	-123.074050
Discharge 5	Parkland Burnaby Refinery Dock	49.291983	-123.004317

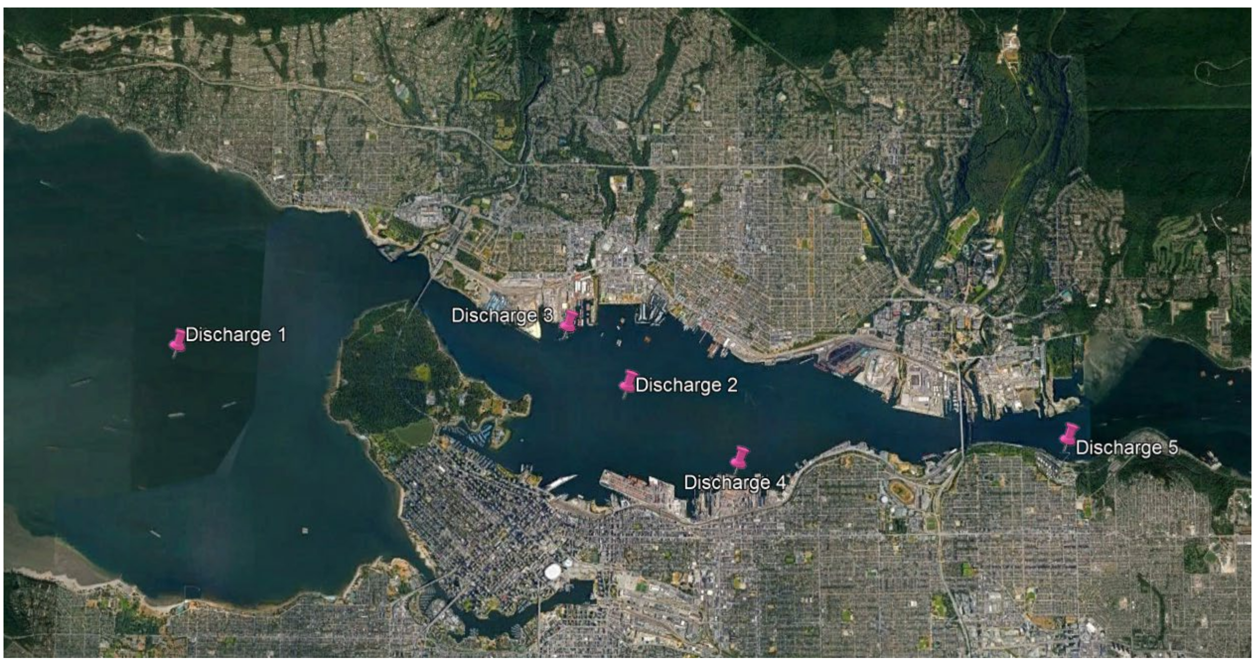

Figure 7: Suggested Hypothetical Discharge Locations for Modeling Scenarios

[30] Refers to map in Figure 7.

Glossary of Terms

Barrel (bbl): a measurement of oil that is the equivalent of 42 US gallons or 0.159 m^3

Bulk Carrier: merchant ship designed to transport unpackaged bulk cargo (e.g., grain, coal, ore).

Deadweight Tonnage (DWT): carrying capacity of a ship in metric tonnes (the amount of weight a ship can carry, including cargo, stores, and fuel)

Gross Registered Tonnage (GRT): same as Gross Tonnage

Gross Tonnage (GT): internal volume of a ship

LNG: liquefied natural gas[31]

MGO: marine gas oil

Ro-Ro Vessel: roll-on/roll-off ships designed to carry wheeled cargo, principally automobiles and trucks.

TEU: Twenty-foot Equivalent Unit

Transport Capacity: movement of a given volume of cargo over a given distance.

Twenty-foot Equivalent Unit (TEU): Approximate size of 20-foot-long (6.1 m) intermodal container, used to measure approximate number of intermodal containers on a container ship

VLSFO: very low sulfur fuel oil

Volumetric Energy Density: amount of energy stored in given amount of fuel per unit volume.

[31] LNG is typically 85–95% methane along with a few percent ethane, even less propane and butane, and trace amounts of nitrogen. The exact composition varies by the source and processing of the natural gas. In this study, LNG was modeled as 100% methane. However, in actual practice, vessels are/would be fueled by LNG and the volumetric energy density analysis was conducted using LNG.

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