Non-linear source term and scenario for an operational oil spill model

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Abstract

This study presents time-varying oil spill discharge functions and scenarios for operational oil spill models. This study prescribes non-linear models based on experimental measurements (Tavakoli et al. in Ocean Eng 38(17–18):1894–1907, 2011) and then upscaled to the spill duration and discharge quantity for actual oil spill incidents. Scenarios consist in *collision* and *grounding* incidents for the instantaneous spill mode; *light*, *medium*, and *severe* incidents for the continuous spill mode; *spilt*, *containment*, and *retention* practices for the spill management mode. A performance analysis of deterministic simulations indicates that the non-linear source terms and scenarios present realistic and reasonable results, showing the detailed spill patterns on the surface ocean, tail-off oil sheens along the areas swept by the dispersion and significantly different results when oil spill management and mitigation practices are activated. For oil spill modelling in support of field operations, responders and decision makers should be made aware of the variability of oil sheen spatial patterns induced by the oil spill source term to better interpret simulation results and assess the impact of source uncertainty on the clean-up, mitigation, ecological and socio-economic risk.

Keywords Oil spill · Non-linear · Discharge rate · Scenario · Operational · Assessment

1 Introduction

Oil spill incidents are considered major disasters in the marine environment. The severity of the impact depends on a diverse set of factors, including but not limited to: quantity, release rate, the type of incident, and the approach to oil spill mitigation and response. Studies [3, 7, 48] have presented evidence that increased oil quantity and release rate have a non-linear impact of the initial environmental damage and on the time to be spent in oil spill cleanup and recovery operations. A slow, steady rate of oil exposure tends to have less severe immediate effects on the aquatic environment. The characteristics of quantity and release rate are also related to the type of incident [1, 29, 41, 56, 58], such as the discharge from vessel collision, grounding, oil pipelines, and oil platforms, causing varying amounts of damage to the marine environment and the coastal areas. Effective management practices are

normally used to control oil transport and fate in the ocean [42]. Therefore, realistic oil discharge dynamics to drive oil spill simulations play an important role to yield more reliable model results for prevention and mitigation of the impacts of oil spills on the environment and economy.

Numerous oil spill models, such as GNOME [63], MEDSLICK-II [15], OILMAP [50], OILTRANS [5], OpenDrift [12], have been developed to simulate the evolution of oil slicks, weathering processes and forecast the fate of oil spilled for contingency planners and pollution response teams. These Lagrangian element-tracking models exhibit various levels of complexity and applicability in operational use during an emergency. In general, all Lagrangian elements are considered to spread from a single location at any given time. They can be released entirely at the same time (i.e., instantaneous discharge), or evenly over a given period of time (i.e., continuous discharge of specified duration) [62]. Instantaneous discharge refers to

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the release of oil into the environment over one computational timestep. For continuous discharge, all Lagrangian elements are evenly distributed in a finite amount of time-step. As discussed in Reed et al. [44] and Spaulding [49], these simplified assumptions are commonly applied in oil spill models. However, these descriptions of oil discharge dynamics almost always oversimplify the circumstances of an oil spill incident.

In reality, spills from vessels are discrete events by which the entire volume of a cargo vessel may be discharged over the course of a specified duration (a few hours or days), while spills from offshore facilities may result in the continuous discharge of oil at a constant flow rate over the course of days, or even months depending upon the success of response efforts [1, 60]. Oil discharge is a dynamic flow influenced by the source location, dimension, damage severity and environmental conditions, etc. There are studies [13, 22–24, 31, 32, 52] that were dedicated to estimate the changes in rate of oil spill discharge for multiple incidents under various circumstances. Oil outflow modelling is one method of choice for estimating the dynamics of oil spill discharge. For example, Goerlandt and Montewka [23] proposed a Bayesian network model to estimate accidental oil outflow from tankers in order to assess the uncertainty of the spilled quantity. Giel and René [22] developed an oil outflow model for *collision* and *grounding* accidents of tankers, suggesting that complex oil outflow models and physical damage simulation applications could be utilized as a final analysis layer in a causal chain analysis. However, these models often require detailed information, such as ship velocity, collision angle, collision location, obstruction depth, obstruction apex angle, obstruction tip radius, rock eccentricity, inert tank pressure, minimum outflow, etc. This information is generally not available during a response to an oil spill incident.

Based on historical oil spill incidents, studies have suggested that the dynamics of oil spill discharge are correlated with the cause and status of oil spill incidents [11, 20, 29, 41, 45, 51, 56, 58]. Vessel *collision* and *grounding* represent significant potential incidents where the instantaneous oil discharge may result in unfavorable consequences to both human and the environment due to a significant amount oil released [43]. A continuous discharge occurs either in accidents or in deliberate operational discharges, when oil is released into the aquatic environment from shipping, offshore extraction of oil, or pipelines [9, 10]. Usually, the accidental and operational discharges are considered as a continuous oil release over a specified duration, particularly when vessels collide slightly or come in distress at sea (i.e., engine breakdown, fire, explosion) and other situations, such as break open, run aground close to the shore, a blowout of an offshore oil well, and a pipeline breaks [26]. The dynamics of oil discharge over the course

of a specified duration influence the impact severity of an oil spill incident. This led us to the idea of developing an interface to activate an appropriate source term model and scenario on the basis of typical incidents [29, 36, 51], such as *collision*, *grounding* and operational discharge, while taking common spill management practices into account.

Goerlandt and Montewka [23] indicated that a ship-ship *collision* is a complex, highly non-linear phenomenon which can be understood by a dynamic process of redistribution of kinetic energy and by the deformation of the steel structures. The following studies of Tavakoli et al. [53] and Kollo et al. [31], Tabria et al. [52] highlighted that oil spill from a grounded tanker can take a long period of time, as a large fraction of the oil can remain inside the damaged vessel. Although oil spill is a dynamic process dependent on the damage location and the redistribution of kinetic energy, it is unrealistic either to discharge the entire oil load from the damaged vessel in one mode time-step (e.g., 30 seconds) or to discharge at a constant rate during the entire incident period (see Fig. 1). It is important to have an accurate estimate of the quantity and release rate of hydrocarbons, and yet no proven techniques existed for estimating the flow dynamics over incident duration [60]. Those complex oil outflow models were mainly designed for risk assessments and analyses; the

Fig. 1 The concept model of non-linear models (highlighted in grey) proposed as advanced options for the operational oil spill model. In general, the default source term for instantaneous oil spill (highlighted in red) was one single discharge at one time-step. The discharge rate in the default continuous oil spill (highlighted in blue) was treated as a constant rate throughout the specified duration

detailed model parameterization that they require is incompatible with the constraints of an environmental emergency response.

In the context of emergency response operations, oil spill model parameterization, such as the type of incident, discharge quantity, and spill duration, are required to be listed on an operational modelling request form [27, 28, 40]. If available, the anticipated oil spill mitigation and response methods are also specified in the requests. These elements of information can then be used to support model parameterization and simulations; model results are provided to contingency planners and pollution response teams. That said, the possibilities for improvement of the oil spill source term modelling depend on considerations of data availability and feasibility in an operational response situation.

In the Environmental Emergency Response Section (EERS) of the Canadian Centre for Meteorological and Environmental Prediction (CCMEP), Environment Climate Change Canada, the Canadian Oil Spill Modelling Suite (COSMoS) is a software framework that enables oil spill modelling in support to operations during oil spill response. Similar to other operational oil spill models, COSMoS features two modes by default for oil spill discharge: instantaneous discharge (i.e., all Lagrangian elements released at one time-step) and continuous discharge (i.e., constant release rate over a finite number of time), as illustrated in Fig. 1. The model does not yet feature an interface to adjust the dynamics of oil spill discharge when the management practices need to be evaluated.

The objectives of this study are (i) to develop and fit non-linear regression models and scenarios based on the experimental dataset of Tavakoli et al. [53] conducted at the SINTEF Sealab in Trondheim, Norway, (ii) to evaluate the performance of non-linear discharge models versus default oil discharge models from simulations to highlight their differences and the importance of more realistic oil discharge dynamics, and (iii) to implement an easy-to-use interface of non-linear oil spill discharge models and scenarios to activate simulations for continuous, instantaneous incidents, and oil spill management and prevention practices.

This paper is organized as follows. In Sect. 2, we describe the experimental dataset of Tavakoli et al. [53], scenario development, and strategies for the user interface design, model implementation in COSMoS, and model evaluation. In Sect. 3, we present results from the experimental data fitting performance for various scenarios, the implementation of user interface, model simulations, and statistical evaluation. A discussion about why we need to consider the time-dependent oil discharge, how to practically implement source term in an operational oil spill model, and the features, major impacts and effects of new oil spill

scenarios are provided in Sect. 4, followed by concluding comments in Sect. 5.

2 Methodologies

2.1 Experimental dataset and scenario development

Experimental datasets for the development of non-linear source term of oil spill discharge are scarce and limited. Nevertheless, it was found that the experimental tests carried out at SINTEF Sealab in Trondheim, Norway [53] contain suitable and complete time series of discharge quantity under various experimental designs. Therefore, this dataset is ideal for non-linear regression analysis and for the design of scenarios for various types of incidents.

In the experimental test of Tavakoli et al. [53], a model tank was built at 1/30 scale (a horizontal section of 100 × 50 cm² and a height of 100 cm) of an existing floating production storage and offloading (FPSO), which was used to measure the oil flows from damaged ships with different tank designs during *collision* and *grounding* incidents. The basin tank was approximately 12 m long, 5 m wide and 3 m deep. Various punctures were drilled into the model tank to represent different severity of damage due to *collision* and *grounding* scenarios.

The experimental investigation presented 15 tests to study oil release from tanks with various tank designs (single hull, double bottom, double side, and double hull), and damage above and below the waterline. The various complex configurations possible with the experimental system allow to characterize oil discharge dynamics under various circumstances. From the experiments of Tavakoli et al. [53], suitable experimental datasets were selected and applied to the proposed incident scenarios, as shown in Fig. 2. The discharge dynamics of *collision* and *grounding* from the experimental tests were used to develop scenarios of instantaneous spill incidents (Fig. 2a, b). The different diameters of punctures were used to model the severity level of continuous spill incidents that is associated with leakage rates (Fig. 2c–e). The experimental tests with different tank designs for the spilled oil and retained oil cases were considered as the effect of management practices that are associated with containment and mitigation of an oil spill incident (Fig. 2f–h).

2.2 Best-fit non-linear models development

Non-linear regressions were used to fit selected models to the experimental datasets of oil flow and leakage. Thus, non-linear dynamics of oil spill were developed by fitting

Fig. 2 Best-fit non-linear models for two instantaneous oil spill scenarios: **a** collision and **b** grounding. Three severity levels for continuous oil spill scenarios: **c** light, **d** medium, and **e** severe. Three models for management practices: **f** spilt, **g** containment, and **h** retention. For the up-scaled process, the experimental datasets of Tavakoli

et al. [53] are normalized to a scale of 0 – 1 in discharge time (x-axis) and accumulated quantity (y-axis). The results of goodness of fit are listed in SS and RMSE, presenting the Sum of Squares and Root Mean Square Error, respectively. The non-linear regression models are based on the experimental datasets of Tavakoli et al. [53]

the oil spilled volume over time for the cases in Tavakoli et al. [53]: a puncture in the bottom (i.e., *grounding* scenario), a puncture in the side (i.e., *collision* scenario), different sizes of punctures in the size (i.e., severity scenarios), and a puncture in various tank designs (i.e., management scenario).

Based on the shape of the graph, a series of exponential models were used for non-linear regression analysis. Specifically, the pseudo-first order association kinetics of the fluid outflow with parameterizable plateau of discharge dynamics was used for the general cases of continuous oil discharge. The two-phase association model was applied

for cases where the overall oil discharge is the result of combining a fast and slow exponential decay.

The experimental study of instantaneous oil discharge indicated that an abrupt break point can be found after the spill started. Therefore, a non-linear model with a hinge function was applied to the dataset, while ensuring that the two curved lines gently intersect at a time. For cases with a plateau followed by an exponential curve, the standard one-phase association model was applied for the management scenarios. This equation was particularly useful for cases where a finite amount of oil is retained for a period of time, then discharged into the environment at

some time. If oil retention was incomplete or a proportion of oil is gradually being released, the allosteric sigmoidal model was applied for oil discharge dynamics with a sigmoidal curve followed by an exponential curve.

The underlying numerical data points from the experimental investigation [53] were extracted using a semi-automated tool, WebPlotDigitizer, Version 4.2 [46]. The best-fit non-linear regression analysis was conducted using a statistics software, GraphPad Prism, version 8.0. [25]. The results of goodness of fit test (i.e., *SS* and *RMSE*) were used to evaluate how well a non-linear model fits the experimental datasets. *SS* calculates the sum of squared differences from the mean and is used to determine the

variance of two variables (i.e., $\sum (X - \bar{X})^2$). *RMSE* is the standard deviation of the residuals to quantify how accurately the model predicts the oil discharge. The non-linear models and their associated coefficients are listed in Table 1.

2.3 Oil spill scenarios and user interface design

An effective use of the appropriate non-linear oil discharge models for the oil spill model requires adequate scenarios that can be toggled from a simple user interface. This user interface is based on an inventory of historical oil spill

Table 1 The functions and their associated coefficients used for the best-fit non-linear models in this study. The oil discharge dynamics from the experimental datasets of Tavakoli et al. [53] were illustrated in Fig. 2

Mode	Scenario	Function	Coefficient
Instantaneous	<i>Collision</i>	$Y = \text{Intercept} + \text{Slope}_1 \times (X - X_0) + (\text{Slope}_2 - \text{Slope}_1) \times \text{Delta} \times \ln(1 + \exp((X - X_0) / \text{Delta}))$	Intercept = 0.7416 Slope ₁ = 52.42 X ₀ = 0.01491 Slope ₂ = 0.2533 Delta = 0.002275
	<i>Grounding</i>	$\text{Span}_{\text{fast}} = (\text{Plateau} - Y_0) \times \text{Percent}_{\text{fast}} \times 0.01$ $\text{Span}_{\text{slow}} = (\text{Plateau} - Y_0) \times (100 - \text{Percent}_{\text{fast}}) \times 0.01$ $Y = Y_0 + \text{Span}_{\text{fast}} (1 - \exp(-K_{\text{fast}} \times X)) + \text{Span}_{\text{slow}} (1 - \exp(-K_{\text{slow}} \times X))$	Plateau = 1 Y ₀ = 0 Percent _{fast} = 22.3 K _{fast} = 100.9 K _{slow} = 101.0
Continuous	<i>Light</i>	$Y = Y_0 + (\text{Plateau} - Y_0) (1 - \exp(-K \times X))$	Y ₀ = 0 Plateau = 1.18 K = 1.9
	<i>Medium</i>	$\text{Span}_{\text{fast}} = (\text{Plateau} - Y_0) \times \text{Percent}_{\text{fast}} \times 0.01$ $\text{Span}_{\text{slow}} = (\text{Plateau} - Y_0) \times (100 - \text{Percent}_{\text{fast}}) \times 0.01$ If $Y \leq 1$, $Y = Y_0 + \text{Span}_{\text{fast}} (1 - \exp(-K_{\text{fast}} \times X)) + \text{Span}_{\text{slow}} (1 - \exp(-K_{\text{slow}} \times X))$ If $Y > 1$, $Y = 1$	Plateau = 1.049 Y ₀ = 0 Percent _{fast} = 6.919 K _{fast} = 4.485 K _{slow} = 4.488
	<i>Severe</i>	$\text{Span}_{\text{fast}} = (\text{Plateau} - Y_0) \times \text{Percent}_{\text{fast}} \times 0.01$ $\text{Span}_{\text{slow}} = (\text{Plateau} - Y_0) \times (100 - \text{Percent}_{\text{fast}}) \times 0.01$ If $Y \leq 1$, $Y = Y_0 + \text{Span}_{\text{fast}} (1 - \exp(-K_{\text{fast}} \times X)) + \text{Span}_{\text{slow}} (1 - \exp(-K_{\text{slow}} \times X))$ If $Y > 1$, $Y = 1$	Plateau = 1.001 Y ₀ = 0 Percent _{fast} = 32.8 K _{fast} = 9.399 K _{slow} = 9.395
Management	<i>Spilt</i>	If $X \leq X_{\text{option}}$, $Y = Y_0$ If $X > X_{\text{option}}$, $Y = Y_0 + (\text{Plateau} - Y_0) (1 - \exp(-K \times (X - X_0)))$	Y ₀ = 0 Plateau = 1.18 K = 2.379
	<i>Containment</i>	If $X \leq X_{\text{option}}$, $Y = V_{\text{max}} \times X^h / (K_{\text{half}}^h + X^h)$ If $X > X_{\text{option}}$, $Y = V_{\text{max}} \times X_{\text{option}}^h / (K_{\text{half}}^h + X_{\text{option}}^h)$	V _{max} = 2.0 h = 1.0 K _{half} = 1.0
	<i>Retention</i>	$V_{\text{max}} = 2 \times X_{\text{option}}$ $Y = V_{\text{max}} \times X^h / (K_{\text{half}}^h + X^h)$	h = 1.0 K _{half} = 1.0

The coefficients were obtained from the non-linear regression; the coefficients used in the scenario *containment* and *retention* were further modified for the application in this study. *X* and *Y* present the variables about time and spill quantity, respectively, ranging from 0 to 1. *X_{option}* is the variable of fractional time, which is controlled by a slider bar in the interface (Fig. 3)

incidents and feedback from years of experience in operational responses at EERS, according to (i) whether the oil spill is instantaneous or a long-term leak, (ii) whether the oil spill is caused by *collision* or *grounding*, (iii) whether the severity level of long-term leak is determined, (iv) whether the oil spills into the water and spreads to a larger region, and (v) how effective response or cleanup is. Based on these concepts, advanced source term scenarios were developed and implemented both in COSMoS and the user interface, including three prescribed modes: instantaneous, continuous, and management practices, as shown in Fig. 3.

The instantaneous mode includes *collision* and *grounding* scenarios, because their oil discharge dynamics are usually treated as a significant release during the first few hours of an oil spill incident. For operational modelling, the *collision* and *grounding* are regarded as instantaneous oil spills. The continuous mode includes three severity levels: *light*, *medium*, and *severe*, representing how quickly the oil spill can be released into the water over the course of incident time. The management mode includes *spilt*, *containment* and *retention*, based on a concept of controlling the spill from the perspective of time and/or oil quantity. The *spilt* scenario is categorized in association with practice management that can affect the starting time of oil spill. The *containment* and *retention* are designed to be used for cases where a certain proportion of oil can be prevented to further transport in the water.

Following operational best practices at EERS, the concept of designing a user interface for operational use should be based on a single interface window with clear, simple and adequate options to select scenarios and source term models. In the proposed design, each scenario can be selected by a click on its associated button. The oil discharge dynamics is also updatable when parameterizing the scenarios in the management mode via the slider bar (Fig. 3). Time series of accumulated oil discharge is immediately updated and displayed in the user interface when a scenario is selected or adjusted with the slider bar

Fig. 3 The user interface of prescribed scenario selection in SPI. Each button activates its associated calculations of non-linear model and simultaneously displays the dynamics of oil discharge on the screen, as showed in Fig. 4. The effective time of management practices can be specified by adjusting the slider bar of Fractional Time

of fractional time. The real-time display of the dynamic oil discharge is particularly important when a source term is needed for the interpretation of model results, as shown in Fig. 4.

This user interface is embedded into an operational environmental emergency response tool, SPI (Spherical Projection Interface), developed and supported operationally 24/7 by EERS [18]. SPI is a workflow software, offering processing, analysis and visualization capabilities to enable operational response and the execution of dispersion models in a user-friendly environment. The best-fit non-linear models are programmed in the Tcl/Tk programming language and results of oil discharge dynamics are displayed within SPI.

2.4 Oil spill modelling suite

The dynamics of oil discharge displayed in SPI creates an initial file (i.e., dispersion model namelist) to specify which non-linear model and parameters are used within the oil spill model, the Canadian Oil Spill Modelling Suite (COSMoS). COSMoS is a software suite developed at Environment and Climate Change Canada to model oil spill trajectories and fate, based on the EERS' Modèle Lagrangien de Dispersion de Particules (MLDP) to move particles in water [14]. Following Berry et al. [5], COSMoS predicts the slick trajectory, and basic fate and behavior, such as oil spreading, evaporation, entrainment, emulsification, mass loss to shores from stranded oil, and density, viscosity, and composition change. The model is using best available meteorological and environmental (wind, currents, waves, water temperature, salinity, and ice) forecasts, interfaced with pre- and post-processing scripts.

In addition to the display of non-linear models in SPI (Fig. 4), the non-linear models are coded in the C programming language within COSMoS. Each non-linear model is developed in a relative scale (0 to 1, see Fig. 2), thus the model can be scaled with the estimated quantity of oil and model duration listed on the modelling request form. Lagrangian elements are distributed to each model timestep based on the relative amount of oil discharge during each timestep. The model was verified for mass conservation, except for cases where oil leakage is mitigated by management practices to prevent the further spill and transport.

2.5 Model performance and evaluation

2.5.1 Model inputs and key parameters

Hibernia oil field (Lat.: 46.818848, Lon.: -48.703710) located 350 km off the coast of Newfoundland, Canada was selected as the location of a hypothetical oil spill to

Fig. 4 The discharge dynamics are displayed in SPI and updated when the scenario is selected or the fractional time is adjusted for the scenarios of management practices. Due to the nature of sim-

plified oil discharge model by default (see Fig. 1), the one-time discharge and linear accumulation for the instantaneous and continuous oil spills are not displayed in the interface

test the non-linear source term models. This location was chosen to ensure that no Lagrangian elements can be transported to the coastline and beached within a 12-hour simulation. Lagrangian element stranding on shorelines was purposely avoided to allow a simpler evaluation of the differences between the default and advanced source

term scenarios. Oil spill simulations with a diesel fuel oil and 12-hour model duration also reduce the effects of other complicated fate and behaviour, such as water-in-oil emulsification, photo-oxidation, bio-degradation, and sedimentation. This study used 100,000 Lagrangian elements for each simulation in COSMoS and its density in the

spatial distribution was used to compute the oil surface concentration.

The simulation duration was set to 12 h with 5-min output timestep, starting at 2019-10-22 22:00 UTC. The model output grid resolution for oil spills (i.e., for surface concentrations) is 25 m and grid point spacing in the modelling grid (i.e., for input fields) is 1 km. A single set of meteorological inputs from the High-Resolution Deterministic Prediction System (HRDPS) at a horizontal resolution of 2.5 km [37] and oceanic inputs from the WebTide Tidal Prediction System [21] were prepared and used in each simulation.

Diesel oil (light oil; density: 831.0 kg m^{-3} ; viscosity: $0.0028 \text{ kg ms}^{-1}$) and Bunker C fuel oil (heavy oil; density: 985.1 kg m^{-3} ; viscosity: 15.1 kg ms^{-1}) from the COSMoS oil library were selected to compare model outputs. The total quantity released was 10,000 liters for scenarios without oil clean-up management practices. With identical forcing datasets, simulations showed similar trajectories and coverages of oil slicks for both diesel oil and Bunker C fuel oil. Therefore, model results for diesel oil only are presented in this study.

2.5.2 Comparisons of the default versus non-linear models

Two control simulations with the linear source term were carried out with the default method: (i) the instantaneous spill where the entire quantity was released into water in the first model timestep and (ii) the continuous spill with a constant discharge rate through the entire simulation duration. Eight test simulations with non-linear source terms (see Table 1 and Fig. 4) were conducted to compare with the control simulations. Therefore, the model evaluation is categorized into three groups: (i) instantaneous oil spill: the control simulation for instantaneous oil spill vs. three test simulations in *collision*, *grounding*, and the severity level *severe*; (ii) continuous oil spill: the control simulation for continuous oil spill vs. three test simulations with severity level *light*, *medium*, and *severe*; (iii) oil spill management practices: the control simulation for continuous oil spill vs. three test simulations in *spilt*, *containment*, and *retention* scenarios.

2.5.3 Model evaluation tool and statistics

In addition to the visual comparison of trajectories, this study uses a statistical validation tool, TheJudge, to compare model outputs between the control and test simulations. TheJudge is a validation tool that is developed by EERS, CCMEP. TheJudge can be used to either compare model results together or for statistic analysis and visualization. In this study, statistical indicators in TheJudge, namely overlapping area ($OV_{(A,B)}$), Pearson's correlation coefficient ($COR_{(A,B)}$), fractional bias ($FB_{(A,B)}$),

and Kolmogorov-Smirnov parameter ($\%, KSP_{(A,B)}$), are used to evaluate the performance of the default linear models versus non-linear oil discharge models in COSMoS. These statistical indicators are commonly used for the evaluation of Lagrangian particle dispersion models [16, 47]. In the present case, however, those indicators are not used to verify against observations, but to measure the difference between default scenarios (instantaneous release and linear source term) and the proposed scenarios, and to show that the impact on shape and transport of slick could not be simply reproduced with an increased random walk.

These statistical indicators are calculated by first rasterizing the Lagrangian particles onto a lat-lon grid of 0.000225° (roughly 17 m horizontally by 25 m vertically at the latitude of experiment location), based on residence time and particle density, averaged over the output time-step (e.g., 30 seconds). This effectively gives an estimation of the oil concentration over each grid cell. Each grid point pair where a non-null value is present in either A or B is then treated as an observation/prediction pair. In other words, for the purpose of those indicators, every grid point that has a non-null value of A (later referred to as field A) is regarded as if it was an observation ("control"), and every non-null valued grid point of B (later referred to as field B) is considered as if it was a prediction ("test").

Overlapping Area $OV_{(A,B)}$ is defined as the intersection of two oil sheens with a surface concentration greater than 15 L km^{-2} . The areas and surface concentrations are displayed in Fig. 5. Intersection of two given fields A and B is a set which consists of all the elements which are common to both A and B (i.e., both fields are not null), as expressed in Eq. 1 [14]. TheJudge calculates $OV_{(A,B)}$ as the sum of overlapping grid cell areas. Thus, $OV_{(A,B)}$ is the sum of the overlapping area in m^2 , ranging from 0 to the area of the largest slick. $OV_{(A,B)}$ could be 0, because it takes the explicit location of surface concentration into account at each model timestep. In this study, higher $OV_{(A,B)}$ indicates better intersection of two oil sheens with a surface concentration greater than 15 L km^{-2} ; 0 means that no explicit location of surface concentration is overlapped in two simulations [57].

$$OV_{(A,B)} = A \cap B \quad (1)$$

Pearson's Correlation Coefficient $COR_{(A,B)}$ (Eq. 2) is a measure of the linear correlation between two variables X and Y. It is presented as a value between +1 and -1, where 1 is total positive linear correlation, 0 is no linear correlation, and -1 is total negative linear correlation. As shown in Eq. 2, Pearson's correlation coefficient is the covariance of the

Fig. 5 The oil spill simulations of surface concentration for the diesel oil at T_0+12 h. **a, d** Simulations of original models for the instantaneous and continuous oil spills, respectively. The rest of sub-figures are the simulations based on different non-linear discharge dynamics. The dynamics of oil discharge refer to Fig. 4. The indices

of A to F are based on the Bonn Agreement Oil Appearance Code [6], referring to surface concentrations of A: 15–40, B: 40–300, C: 300–5,000, D: 5,000–50,000, E: 50,000–200,000, and F: > 200,000 L km^{-2} , respectively. The grey surface area represents the swept area that is visited by Lagrangian elements during the simulation

two variables divided by the product of their standard deviations [4, 17, 39].

$$COR_{(A,B)} = \frac{\sum_i (A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum_i (A_i - \bar{A})^2} \sqrt{\sum_i (B_i - \bar{B})^2}} \quad (2)$$

Fractional Bias It is also frequently desirable to have a measure of the relative or fractional difference between the model “control” (A) versus “test” (B) simulations of surface oil concentrations greater than 15 L km^{-2} [57]. $FB_{(A,B)}$ is a measure of mean bias to indicate systematic errors. As expressed in Eq. 3, $FB_{(A,B)}$ could be a negative value, depending the result of $\bar{B} - \bar{A}$. The detailed description of $FB_{(A,B)}$ can be found in Seigneur et al. [47] and Yu et al. [61].

$$FB_{(A,B)} = \frac{\bar{B} - \bar{A}}{0.5(\bar{B} + \bar{A})} \quad (3)$$

Kolmogorov-Smirnov Parameter (%) The Kolmogorov-Smirnov method (K-S method) is one kind of goodness of fit method that compares the maximum distance between the experimental cumulative distribution function and the theoretical cumulative distribution function [33, 34]. K-S method is one of the most useful and general non-parametric methods for comparing two simulations, as it is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two simulations [19, 39]. Kolmogorov-Smirnov parameter (%) is expressed as:

$$KSP_{(A,B)} = \max |F_A(x_k) - F_B(x_k)| \times 100\% \quad (4)$$

where F_A and F_B are the respective cumulative frequency of each variable giving the probability of each variable not greater than x_k in the “control” (A) and “test” (B) simulations, respectively.

3 Results

3.1 Experimental data fitting for various scenarios

Figure 2 shows that the selected non-linear models fit well with the experimental datasets as the statistical results indicate. The sum of squares, SS shows a value smaller than 0.020 for the following scenarios: *collision*, *light* severity level, and three management practices. Scenarios of *grounding* and severity level of *medium* and *severe* present a slightly higher value of SS at 0.192, 0.038, and 0.073, respectively. Similarly, these scenarios with a higher SS also show a higher $RMSE$. For example, scenarios of *grounding* and *severe* level in the continuous oil spill present a larger value in SS and $RMSE$ compared with other scenarios.

Table 1 lists all non-linear models used for eight scenarios in this study. Functions for the scenarios of *collision*, *grounding*, and *light* severity level are straightforward and no further step is needed in constraining volume spilled. Because of the nature of the two-phase association model, numerical constraints ($Y_0 = 0$ and $Y = 1$, Table 1) are used to ensure the conservation in total quantity of estimated oil spills. This study also creates the scenario *spilt*, *containment*, and *retention* for management practices, based on the available dataset of Tavakoli et al. [53]. For scenarios of management practices, the dynamics of oil discharge is solely controlled by a variable, fractional time (X_{option}), which is controlled by a slider bar in the interface (Fig. 3).

3.2 Interface and scenarios for operational use

Figure 3 presents an interface to select the non-linear oil discharge models. The fundamental objective of this interface is to resolve the common issue in oil spill models, that default discharge rates were oversimplified and generalized as illustrated in Fig. 1. Because of this oversimplified calculation for the discharge rate in the default model, its dynamics was not visualized in SPI. With a new feature in Fig. 3, once the scenario and value in the slider bar were updated, the dynamics of oil discharge over the course of simulation duration is displayed in SPI (Fig. 4). Although COSMoS relies on the discharge rate for each model timestep, it is much easier to interpret oil dynamics based on the accumulated amount, presented on the right axis of Fig. 4. Since the x-axis presents the actual simulation

duration, the non-linear models (i.e., X in Table 1) is up-scaled to the actual simulation duration.

3.3 Model simulations: oil transport and fate

Figure 5 presents the oil transport and fate at the end of simulations (i.e., $T_0 + 12$ h) for two default models (Fig. 5a, d) and eight non-linear models. Overall, each simulation presents different patterns of oil surface concentration, suggesting that the source term in oil discharge dynamics plays an important role in oil spill simulation. The detailed information from the model simulations in Fig. 5 is described in Sects. 3.3.1 to 3.3.3 for the scenario instantaneous, continuous, and management practices, respectively.

3.3.1 Instantaneous oil spills

With non-linear oil discharge dynamics, more detailed oil sheens are found at every model timestep. For example, in Fig. 5b, the instantaneous oil spill due to *collision* shows a tail shape (i.e., comet tail) of oil sheen, which is commonly seen in oil spill incidents. The detailed spatial distribution of oil concentration is found in the spill pattern, compared with results of the default model (Fig. 5a). By default, the model simulates a pattern with several contours explicitly without the tail shape of oil sheen.

The simulation with the non-linear model for the scenario *grounding* (Fig. 5c) shows an oil sheen with subtle edges and an irregular shape rather than the oval shape presented in the default model. For the oil spill due to *grounding* (Fig. 5c), a larger area with surface concentration contour is found when compared with the default model (Fig. 5a). Simulations produce significantly different surface concentration patterns with variation of the dynamics of instantaneous oil spill.

3.3.2 Continuous oil spills

Figure 5d–g present the continuous oil spill simulations based on the default model and non-linear models for three severity levels: *light*, *medium*, and *severe*, respectively. As presented in Fig. 4c–e, the *light* severity continuous spill scenario features a closer pattern to the default model; the *medium* and *severe* scenarios have a different, increased rate of oil discharge for the first few hours of simulations. With increasing oil discharge, the oil sheen is aggregated and the tail shape fades. For example, Fig. 5d, e show much similar oil surface concentration patterns when compared to Fig. 5f, g, because their rates of oil discharge are closer to each other than when they are compared to the severity levels *medium* and *severe*, as shown in Fig. 4c–e.

The default model with a constant discharge rate simulates a smaller sheen with higher surface concentrations and a tail near the source location. The non-linear model with the *light* severity level simulates a larger oil sheen with higher surface concentrations. The slick tail modelled with the default continuous source model is not simulated in the *light* severity level. This is caused by the higher discharge rate in the first few hours and smaller rate near the end of simulation in the non-linear model of *light* severity level. With an increasing discharge rate in the first few hours and a decreasing rate to the end (Fig. 4d, e), it is easily seen that the high surface concentrations aggregate and that the sheen tail fades.

3.3.3 Oil spill management practices

Results of source scenarios with oil spill management practices on oil transport and fate are introduced and presented in Fig. 5h–j for the scenario *spilt*, *containment*, and *retention*, respectively. The discharge dynamics is only controlled by a single variable (X_{option} , Table 1), which was designed to allow emergency responders to quickly modify the delayed time in discharge (i.e., *spilt*), the time when the discharge stops (i.e., *containment*), and the reduction in discharge (i.e., *retention*). Simulations show reasonable and expected results when controlling the discharge time and quantity. Because of the 2.52 h (i.e., 21% of 12 h model

duration) delay in oil discharge, the *spilt* scenario features a smaller oil sheen, a shorter transport distance, and a rounded edge of oil sheen that may not have been influenced by the strong currents from the northwest direction, as shown in Fig. 5h.

When oil discharge is stopped at T_0+06 h, the higher surface concentration area is closer to the tail of oil sheen, as shown in Fig. 3i. By comparing Fig. 5g, i, the patterns of oil sheen are similar in the *severe* level and the *containment* scenario, except for the high surface concentration area. In Fig. 5j, with a 30% reduction in oil discharge (i.e., 70% of estimated oil spill quantity is assumed to be discharged into the ocean), the *retention* model produces a pattern of oil transport similar to the pattern modelled with the *light* severity level scenario (Fig. 5e). However, the area of the highest concentration contour in the scenario *retention* is significantly smaller than in the *light* severity level scenario.

3.4 Model evaluation: statistical analysis

Figures 6, 7 and 8 show the statistical results of overlapping area ($OV_{(A,B)}$), Pearson's correlation coefficient ($COR_{(A,B)}$), fractional bias ($FB_{(A,B)}$), and Kolmogorov–Smirnov parameter (%), $KSP_{(A,B)}$ in every model timestep (i.e., 30 seconds) over a 12 h simulation duration. The statistical definitions can be found in Sect. 2.5.3. As described

Fig. 6 The 12 h time series of statistical results of **a** overlapping area, **b** Pearson's correlation coefficient, **c** fractional bias, and **d** Kolmogorov–Smirnov parameter for the model evaluation: the control

simulation for instantaneous oil spill versus three test simulations in *collision*, *grounding*, and *severe* level. The statistical definition can be found in Sect. 2.5.3

Fig. 7 Similar to Fig. 6, but this evaluation is for comparing the simulations of continuous oil spills: the control simulation for continuous oil spill versus three test simulations in the severity level of *light*, *medium*, and *severe*

Fig. 8 Similar to Fig. 6. The model evaluation is for the oil spill management practices: the control simulation for continuous oil spill versus three test simulations in *spill*, *containment*, and *retention* scenarios

in Sect. 2.5.2, three groups of model evaluations are presented in Figs. 6, 7 and 8, respectively.

3.4.1 Instantaneous oil spills

In Fig. 6a, $OV_{(A,B)}$ decreases approximately at T_0+45 minutes

and reaches no overlapping area between the control and test simulations. In general, the scenario *severe* level shows a slightly larger $OV_{(A,B)}$ compared with the scenarios of *collision* and *grounding*. Similarly, $COR_{(A,B)}$ decreases significantly after the discharge at T_0 and it reaches to 0 approximately at T_0+45 minutes, and is followed by negative $COR_{(A,B)}$, as shown in Fig. 6b. It indicates that the test simulation with non-linear models simulate higher surface concentrations compared with the control simulation with the default discharge model.

Figure 6c shows that scenario *severe* has a lower $FB_{(A,B)}$ before $T_0+1.5$ h compared with the scenario *collision* and *grounding*. The scenario *collision* and *grounding* have a very close $FB_{(A,B)}$ within T_0+15 minutes. In particular, the scenario *grounding* generally has a higher $FB_{(A,B)}$ compared with *collision*. The comparisons of $KSP_{(A,B)}$ indicate that the selected models show unique simulations due to the characteristic difference in oil discharge dynamics (see Fig. 4).

A significant quantity of oil discharge within T_0+45 minutes in the scenario *grounding* introduces a higher $KSP_{(A,B)}$ (Fig. 6d), because the scenario *grounding* creates the closest discharge dynamics to the default model compared with the scenario *collision* and *severe* level. The tail shape of oil sheen in the scenario *collision* could lower $KSP_{(A,B)}$, because the tail shape of oil sheen only appears in the scenario *collision* in this comparison.

3.4.2 Continuous oil spills

The varying contributions of the three severity levels of oil discharge are clear on the resulting oil spill transport and fate from Fig. 7a–d. They show a slightly higher $OV_{(A,B)}$ in the scenario *severe*, however $OV_{(A,B)}$ decreases over time compared in the scenario *light* and *medium*. As Figs. 4 and 5 showed, the scenario *light* presents a similar discharge dynamics to the default continuous spill, therefore the location and surface concentration of oil sheen is approximately close to the default model, resulting in a higher $OV_{(A,B)}$, as shown in Fig. 7a.

Figure 7b also indicates that a higher $COR_{(A,B)}$ can be found in the scenario *light*, followed by the scenario *medium* and *severe*. With the influence of ocean currents and surface winds on oil transport and fate, $COR_{(A,B)}$ normally decreases over time, particularly when the oil spill is non-linearly discharged into the ocean.

Similarly, Fig. 7c shows clearly decreasing trends of $FB_{(A,B)}$ in three severity levels. The scenario *severe* shows a significantly high $FB_{(A,B)}$, especially before T_0+3 h; fractional bias increases for scenarios *light* and *medium* within T_0+1 h, resulting in a larger difference in discharge dynamics during the first hour of oil spill (Fig. 4c, d). $KSP_{(A,B)}$ in Fig. 7d presents an opposite trend compared with $OV_{(A,B)}$ in Fig. 7a. Approaching to T_0+12 h, the

scenario *light* features a lower $KSP_{(A,B)}$, followed by the scenario *medium* and *severe*.

3.4.3 Oil spill management practices

The scenario *spilt* initializes the discharge at $T_0+2.52$ h (i.e., 21% of 12 h simulation duration), therefore the trends of statistical analysis start when the oil is released (Fig. 8, red curve). Although the scenario *spilt* features a delayed discharge, it still presents a higher $OV_{(A,B)}$ after T_0+6 h, following a similar trend with the scenario *retention* (Fig. 8a). The oil *containment* practice contains oil spill at T_0+6 h (i.e., 50% of 12 h simulation duration) further induces a significant decrease in $OV_{(A,B)}$.

The scenario *spilt* features the $T_0+2.52$ h delay in the discharge time and the quantity of discharge non-linearly accumulates to 100% of estimated quantity of oil spill. The scenario *retention* initiates discharge at T_0 and the quantity of discharge non-linearly accumulates to 70% of spill quantity. Generally speaking, the scenario *spilt* presents a higher $OV_{(A,B)}$ compared with the scenario *retention* after T_0+6 h, but follows a similar trend with the scenario *retention*. It suggests that a more precise quantity of oil spill in the model could yield a better result in oil transport and fate compared to a case with a well-captured discharge time of a smaller spilled volume.

Figure 8b indicates that the scenario *containment* and *retention* show similar trends in $COR_{(A,B)}$ over a 12 h simulation except for the time from T_0+6 h to T_0+9 h. This discrepancy in $COR_{(A,B)}$ from T_0+6 h to T_0+9 h between the scenario *containment* and *retention* could be caused by the shifting direction of ocean currents and the location of oil hot spots (i.e., areas with higher surface oil concentration, Fig. 5h, j). On average, the scenario *spilt* features a higher $COR_{(A,B)}$ compared with the scenario *containment* and *retention*.

Figure 8c presents the scenario *retention*, yielding a lower $FB_{(A,B)}$; the scenario *containment* yields a decreasing trend in $FB_{(A,B)}$, resulting in its discharge oil stopped at T_0+6 h. Regarding the scenario *spilt*, $FB_{(A,B)}$ accumulates starting from $T_0+2.52$ h to T_0+7 h, followed by a decreasing trend of $FB_{(A,B)}$. The scenario *spilt* shows a $FB_{(A,B)}$ closer to 0 when compared with the scenario *containment* and *retention*, indicating a lower bias for the scenario *spilt* in the comparison with the default model.

Figure 8d presents a consistently decreasing trend of $KSP_{(A,B)}$ for the scenario *spilt*. Both scenario *containment* and *retention* show a similar trend, however the scenario *retention* yields a relatively higher $KSP_{(A,B)}$ before $T_0+\sim 8$ h and a lower value afterwards, compared against the scenario *containment*.

4 Discussion

This study found that there are significant differences among these 12 h oil spill simulations based on non-linear oil discharge dynamics with respect to the default source scenarios in COSMoS. By viewing their overall similarity in dynamics and given the same discharged volume, it was not initially expected that oil movement, fate, and behavior would show such significant differences from the default emission scenarios. Hence, it raised two questions for discussion: (i) what is the nature of the differences between the default source terms and time-dependent oil discharges? (ii) what is the most practical way to implement a choice of different source terms in an operational context? These questions are discussed in the following Sects. 4.1 and 4.2.

4.1 Time-dependent oil discharge dynamics for oil spill model

The default source term models in COSMoS for the instantaneous and continuous oil spills are based on the hydrostatic equilibrium, assuming that the flow velocity of the fluid is constant over time. Oversimplified assumptions are commonly used for oil spill incidents, such as spilling the total vessel capacity in a one-time release (i.e., instantaneous spill) or leaking oil from the vessel within a finite time and constant rate (i.e., continuous spill). However, this study demonstrates that oil spills are significantly affected by the dynamic oil discharge under various accident types, scenarios, vessel designs, and management practices. These influencing factors are better captured with a dynamic spilling rate and duration. Simulations in this study implies that the hydrostatic equilibrium is insufficient to describe oil discharge and unable to comprehensively and accurately model an accidental oil spill.

Prior to the experimental datasets of Tavakoli et al. [53] used in this study, studies [2, 30, 59] shared similar experimental observations, suggesting that fluid flow from a leaking container is hydrodynamic and features of the outflow are associated with different stages. The actual hydrodynamics could be influenced by the mixture of water and oil, the damage characteristics (e.g., orifice/rupture location, size and shape), and the structure design of a vessel. The flow characteristics could be more complex due to the effect of turbulence, viscosity, air bubbles, and droplet size distribution. On the other hand, studies [31, 35, 54] also developed models to estimate the oil flow through the rupture as the orifice flow governed by the modified Bernoulli's equation.

Although their models provide an approach to estimate time-varying variable discharge, these analytical models still require many assumptions to simplify the complex spilling process, especially when dealing with the flow motion inside the oil containers. Furthermore, the required information for these analytical models is difficult to obtain during an emergency situation. For example, the “key parameter” in the hydraulic modeling approach, the difference between the water level outside and the oil level inside the tank is essentially never reported in the initial modelling request. With the limited information provided during the emergency response, this study suggests that estimating time-varying oil discharge dynamics based on experimental datasets offers a practical approach to construct a realistic source dynamics for operational oil spill simulations.

The statistical time series analysis (Figs. 6, 7, 8 demonstrates that the non-linear oil discharges result in completely unique spatial and temporal patterns compared with the default source terms in COSMoS. As Table 2 summarized, each non-linear discharge scenario features its unique time-dependent oil discharge that causes different impacts and effects on the oil movement, fate, and behavior. For instantaneous and severe spill incidents, a significant volume of oil discharged within a short period of time (i.e., ~70 to 75% released within 1–2 h) causes an immediate impact on the first few hours of the simulation results (i.e., $T_0 - T_0 + 3$ h to +6 h), leading to a significantly different oil trajectory and fate in the remainder of the simulation.

In the time series of statistical indicators (Figs. 6, 7, 8), the significant changes observed in those indicators during the first few hours (i.e., when a significant volume of oil is discharged within a short period of time) leads to completely different oil sheens patterns (i.e. $OV_{(A,B)} = 0$) during the subsequent time evolution of the slick. Because an intense release is featured in the *collision*, *grounding*, and *severe* modes, their oil spreading and transport are significantly different from the results of default continuous models. Tove and Frode [55] indicated that oil spreading could be the most critical factor in the processes and that oil spreading is strongly associated with the initial spill volume, especially for the instantaneous and severe oil spills. Oil spilled within the first 1–2 h could also be largely affected by spreading, resulting in a great reduction in $OV_{(A,B)}$ (Table 2). With the effects of shear currents and vortices on the stretching of the surface slick, oil spreading and transport play critical roles in resulting surface oil sheen pattern and coverage. Furthermore, spreading intensifies oil weathering processes (e.g., evaporation) sensible to total slick area.

Interestingly, the *spilt* modes show a higher $OV_{(A,B)}$ compared with the *light* severity mode after 12 h of oil

Table 2 The feature, major impact, and time-varying effect for non-linear oil spill scenarios

Mode	Scenario	Feature	Major impact time period	Time-varying Effect		
				$OV_{T_0+0.6h}$	OV_{T_0+6h}	OV_{T_0+12h}
				Normalized (%)		
Instantaneous	<i>Collision</i>	~75% released non-linearly in first 1 hr ~25% released linearly for the rest hours	T_0 to T_0+3 h	100	0	0
	<i>Grounding</i>	100% released non-linearly in first 2 h	T_0 to T_0+3 h	87	0	0
Continuous	<i>Light</i>	~70% released in first 6 h Similar to the default continuous mode	T_0 to T_0+12 h	33	72	79
	<i>Medium</i>	~70% released in first 3 h	T_0 to T_0+9 h	34	70	0
	<i>Severe</i>	~70% released in first 1.5 h	T_0 to T_0+6 h	46	56	0
Management	<i>Spilt</i>	Spill delayed at a specific time	T_0 to T_0+12 h	0	69	100
	<i>Containment</i>	Spill stopped at a specific time	T_0 to T_0+12 h	33	62	0
	<i>Retention</i>	Partial released at a specific volume	T_0 to T_0+12 h	30	59	83

The feature of each scenario is summarized based on Figs. 2 and 4. The major impact describes the time period with significant changes and transitions based on Figs. 6, 7 and 8. $OV_{(A,B)}$ (Eq. 1) in $T_0+0.6$ h, T_0+6 h, and T_0+12 h are normalized based on the maximum values in their associated time series, representing the time-varying effects of non-linear scenarios on the overlapping area of two oil sheens over at beginning, intermediate, and final stage of a 12 h oil spill simulation, respectively

spill simulations (100% vs. 79%), as listed in Table 2. It may be caused by the major changes in oil sheen pattern and coverage during T_0+6 h to $+12$ h due to the transitions in ocean currents and winds. Weather and ocean currents can change how oil spill spreads, and oil spill in seawater spreads differently in changing environment [38]. That said, the oil transport, fate, and behavior in the ocean are inevitably influenced by the variability of atmospheric and oceanic environment along with the time-dependent oil discharge dynamics. Notwithstanding the dynamic and multiple potential behaviors of oil leaking from a damaged vessel in an oil spill incident, the external dynamic ocean conditions, such as currents, wave, tide, water turbulence, wind energy, in any combinations, also play an important role in the spilling process.

In this study, significant differences between oil slick patterns formed by a time-varying discharge model with respect to default discharge models are confirmed by the time series of statistical metrics. The analysis demonstrates that time-varying discharge is a critical source term parameter for oil spill simulations, resulting in the different temporal and spatial patterns in oil transport, fate, and behavior.

4.2 Practical source term modelling for operational implementation

During the process of non-linear regression analysis, this study found that the usability of best-fit models for operational implementation depended on: (i) the integrity in the experimental dataset that was able to describe its dynamics during the entire process of oil spill, (ii) the accuracy of

data points that was sampled at a high frequency without outliers, (iii) the comprehensive experiments that were conducted based on a well-constructed method to provide essential information to design various potential models, and (iv) the simplicity of experimental data points that were fitted to present a straightforward and uncomplicated dynamics over the course of discharge. This study is able to effectively configure the non-linear regression models and scenarios based on the experimental data of Tavakoli et al. [53].

With the non-linear regression models that are normalized at the scale of 0 to 1, the time-varying oil discharge dynamics for COSMoS is up-scaled to the actual spill volume at each modelling time-step. This interpretation of time-dependent oil discharge dynamics in an oil spill incident considers two main assumptions: (i) the actual oil spill presented a time-associated flow and its dynamic trend could follow a simple general cumulative distribution curve, and (ii) a simplified computing procedure in order to yield a time-varying discharge for the operational implementation when considering all kinds of potential incident causalities and little firsthand knowledge of the incident complexity and further managements. At EERS, emergency responders seek practical solutions not only to improve the source term modelling, but also for efficiency in service delivery. This study demonstrate a method that quickly estimates more realistic oil discharge dynamics which can be implemented in operational oil spill models.

This study proposes a three-layer structure to design the one-window user interface to activate the source term modelling: (i) instantaneous scenarios: *collision* and *grounding*, (ii) continuous scenarios: three different

strengths of outflow dynamics, and (iii) prevention and management practices: three common methods for mitigation of oil spills in time or quantity, that can be controlled by one slider bar in the third layer of the user interface. This study found that a simple and clear design of the user interface allows emergency responders to select the simulation scenario quickly, so the time saved can be used for other pressing preparations, diagnostics, and decision making, such as communications with partners, and quality and risk impact assessments on weather and oceanic forecasts. The statistical analysis of historical inventory and user's experience could also greatly improve and simplify the design of the user interface and the source model selection.

Although oil spill scenarios can be simply summarized from the historical inventory for operational implementation, it is undeniable that each oil spill is unique, particularly for the implementation of scenarios related to oil spill mitigation and management practices. Oil spill mitigation and management variables directly influence the severity of an oil spill [8]. This study found that the goal of countermeasures (i.e., booming, skimming, and sorbents) for oil spill management is generally to limit the volume discharged in the environment and prevent extensive spreading. Therefore, a variable was implemented to regulate the discharge dynamics for the scenario *spilt* (i.e., delaying the discharge time), *containment* (i.e., spill stops in prior to the estimated incident duration), and *retention* (i.e., reducing the spill volume). These various means of mitigation are commonly used by oil spill response agencies, hence the need to include these as source term scenarios. With these features in operational oil spill models, the model simulations could provide useful information for further contingency planning, risk assessment, and decision making, in accordance with the response organization's mandate and requirements.

5 Conclusions

In this study, a set of non-linear discharge models is developed based on the experimental data of Tavakoli et al. [53] and a list of likely scenarios, based on historical spill incidents, is proposed. The purpose of this study is to improve the source term representation in oil spill models beyond the linear, simple source terms commonly found in oil spill simulations. According to the statistics of historical incident inventories and operational experience at the Environmental Emergency Response Section (EERS), the complex time varying functions for two instantaneous oil spill scenarios (i.e., *collision* and *grounding*), three severity levels (i.e., *light*, *medium*, and *severe*) for continuous oil spill scenarios, and three models for management practices

(i.e., *spilt*, *containment*, and *retention*) were added to the Canadian Oil Spill Modelling Suite (COSMoS) and to the operational environmental emergency response interface, Spherical Projection Interface (SPI).

The results of simulations show that the time varying discharge significantly change the temporal and spatial patterns resulting from oil transport, fate, and behavior. For environmental emergency response in oil spill incidents, responders and decision makers should, in a certain measure, be aware of the oil spill source term to better interpret simulation results and assess the impact of source uncertainty on the clean-up, mitigation, ecological and socio-economic risk assessment.

This study was not designed to replace the default source terms that were constructed based on the hydrostatic equilibrium and the one-time discharge concept for continuous and instantaneous oil spills, respectively. In fact, this study provides a solution to run ensemble simulations of oil spill models to characterize the uncertainty intrinsic to the limited knowledge of the source term in an operational context. In addition, the real-time discharge displayed on the user interface and the simplified design for a quick model activation contributed to the integration of advanced source terms for oil spill simulations in COSMoS.

Simulating the movement of an oil spill and product/service delivery are often held back by insufficient data for model parameterization, particularly in the first few hours of the oil incident or during an instantaneous oil spills. The detailed model parameterization includes release rate, actual spill volume, oil types, time of release and spill location that could be updated a few hours later. The on-duty responders must continuously update predictions with new data and explore the consequences and likelihood of other possible scenarios. This study demonstrates a simple and straightforward way to activate time-varying source terms modelling based on the controlled experiments of Tavakoli et al. [53]. This method is particularly useful for emergency responses that only have "best guess" model inputs and little firsthand knowledge of the incident complexity and further managements. The method also provides an easy way to run simulations with multiple oil spill scenarios and to analyze probability assessment with ensemble simulations. This however is beyond the scope of this particular study and would be the subject of future work. That said, the method proposed here can support further activities by responders and decision makers to understand, manage, and reduce the risk of marine oil spills, activities such as identifying likely spill affected areas, developing comprehensive and quantitative risk impacts, and using such scenarios to engage a broad spectrum of stakeholders to raise awareness and increase resilience.

In the longer term, one priority for further research would be to improve those non-linear functions for oil spill management practices. In some cases, the control of oil discharge is targeted at a certain volume and within a strict time frame. Such a scenario requires a few more variables from the data enquiry and a practical method for implementation in models. Although consistent measurements over the course of an oil spill incident are rare and limited, model validation based on observations could contribute to model improvement as well as provide insights on source term dynamics and oil movements. In this study, significant differences among scenarios have already been presented for incidents without beaching (i.e., no contacting with shoreline); a different pattern in oil movement and fate is expected when involving the Lagrangian element stranding along the shoreline. With the results presented in this study, it is shown that simulations with multiple scenarios can be used as a fundamental dataset for testing model robustness and uncertainty. These insights are important for planning aimed at reducing the likelihood of oil spills, providing effective emergency response, and facilitating oil recovery.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this article.

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