UPPSALA
UNIVERSITET

Examensarbete vid Institutionen för geovetenskaper
Degree Project at the Department of Earth Sciences
ISSN 1650-6553 Nr 650

Comparative Analysis of Hydrodynamic Models to Simulate Petroleum Spills in Lake Mälaren

Jämförande analys av hydrodynamiska modeller för att simulera oljeutsläpp i Mälaren

Mehdi Khankishpour

INSTITUTIONEN FÖR
GEOVETENSKAPER

DEPARTMENT OF EARTH SCIENCES

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ISSN 1650-6553

Published at Department of Earth Sciences, Uppsala University (www.geo.uu.se), Uppsala, 2024

Abstract

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This master's thesis presents a comprehensive comparative analysis of three hydrodynamic lake models Mälarmodellen (DHI), Seatrack Web, and the IVL model to simulate petroleum spills in Lake Mälaren.

The study aims to identify the most suitable model for Norrvatten, the primary drinking water supplier for North Stockholm, which relies on Lake Mälaren for its water supply. While this thesis was conducted in collaboration with Norrvatten, the researcher independently performed the analysis of the oil spill simulation models. Specialists from Stockholm Vatten och Avfall and Norrvatten ensured the models' suitability by selecting criteria elements and sub-elements based on their priorities, and they provided valuable background information and feedback on the context of the study. However, the researcher independently conducted the model analysis to ensure the integrity and originality of the work. By evaluating the models based on accuracy, reliability, and ease of use, the research seeks to enhance preparedness and response for potential petroleum spills. Key objectives include conducting tests where each model is applied to various hypothetical spill scenarios, such as small-scale fuel leaks from recreational boats and large-scale oil spills from commercial tankers, to evaluate their effectiveness in predicting and managing these events. The study also assesses factors such as computational efficiency and the ease of use of each model for operators and practitioners, including the simplicity of the interface and the level of expertise required to operate it. The findings contribute to safeguarding public health and the environment by improving spill response mechanisms and ensuring the protection of water resources in the Lake Mälaren region.

The results indicate significant variations in model performance, highlighting the importance of local conditions and specific requirements in model selection. Notably, the study underscores Regularly checking and updating the models to address any data gaps and uncertainties that may arise. This ongoing process helps improve the accuracy and reliability of spill predictions and response strategies.

Keywords: Petroleum spills, hydrodynamic models, Lake Mälaren, Seatrack Web, Mälarmodellen (DHI), IVL model, spill simulation, Norrvatten, Multi criteria decision analysis, computational efficiency, model comparison

Degree Project E in Water Engineering, 1HY290, 30 credits
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ISSN 1650–6553, Examensarbete vid Institutionen för geovetenskaper, No.650, 2024

The whole document is available at www.diva-portal.org.

Popular science summary

Comparative Analysis of Hydrodynamic Models to Simulate Petroleum Spills in Lake Mälaren

Mehdi Khankishpour

Lake Mälaren, Sweden's third-largest lake, is source of drinking water for over two million people. This lake not only supports human life but also sustains a rich array of ecosystems. However, it faces significant environmental threats, particularly from oil spills, which can occur due to the heavy traffic of commercial and recreational vessels. Oil spills pose a severe risk to water quality, aquatic life, and ultimately public health, making it crucial to predict and manage these incidents effectively.

This study compare three hydrodynamic models designed to simulate oil spills in Lake Mälaren. These models Seatrack, DHI (Mälarmodellen), and IVL help to understand how oil spread in the lake under various conditions. Each model has its strengths and weaknesses, and this research aims to determine the most suitable model for Norrvatten, the primary drinking water supplier for North Stockholm. Oil spills are challenging to manage because they can spread quickly and have long-lasting impacts on the environment. By using hydrodynamic models, we can predict how oil will move through water, allowing for faster and more effective responses to contain spills and minimize damage. This proactive approach is essential for protecting drinking water sources like Lake Mälaren, especially in areas close to Norrvatten (Görväln) water treatment plants.

Seatrack Model is highly efficient in real-time spill response scenarios. It provides quick simulations and visual maps showing how oil spreads on the water's surface, which is crucial for immediate actions during an emergency. DHI Model is known for its detailed and complex simulations, the DHI model can predict both surface and underwater oil movements. However, it requires more computational power and time, making it less suitable for quick decision-making but valuable for detailed planning and understanding long-term impacts. IVL Model focuses on specific pollutants, like ethers found in some fuels, and their potential to dissolve in water. It is particularly useful for assessing the risk of chemical contamination that might not be visible on the water's surface but can still pose a threat to water quality.

Combination of these models could offer the best approach to managing oil spill risks in Lake Mälaren. For immediate responses, Seatrack provides rapid predictions, while DHI offers a deeper understanding for long-term environmental management. Additionally, incorporating the IVL model's focus on chemical pollutants can ensure a more comprehensive strategy to protect water quality. By continuing to refine these models and integrate them into emergency response plans can protect Lake Mälaren from the potentially devastating effects of oil spills, ensuring safe drinking water and preserving the lake's ecological health for future generations.

Keywords: Petroleum spills, hydrodynamic models, Lake Mälaren, Seatrack Web, Mälarmodellen (DHI), IVL model, spill simulation, Norrvatten, Multi criteria decision analysis, computational efficiency, model comparison

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Introduction

The significance of water in the formation and expansion of communities cannot be overstated. Water is an essential resource necessary for the maintenance of ecosystems and life (Acreman, 2001). In the 13th century, a significant alteration occurred in Lake Mälaren, which is strongly linked to the rise of Stockholm as a major urban center. Originally a bay of the Baltic Sea, Lake Mälaren was gradually transformed into an inland lake due to post-glacial rebound, a geological process where the land rises after being compressed by ice sheets (Willen, 2001). This transformation included the closure of the natural outlet to the Baltic Sea and the creation of new waterways that directed maritime traffic through Stockholm. As a result, Stockholm became an important commercial hub.

Today, Lake Mälaren is the third-largest lake in Sweden (Ahl and Willen, 1971) and plays a crucial role in providing potable water to over 2 million people while maintaining the region's ecological balance. However, the preservation of water quality in Lake Mälaren is a significant challenge due to ongoing urbanization, agriculture, and industrialization (Mälaren's Water Conservation Association, 2014-2024). Efforts to maintain and improve water quality are essential for ensuring the continued health of both the human population and the local ecosystems.

Oil spills, particularly those involving petroleum, pose significant environmental threat to water resources, including both surface water bodies such as rivers, lakes, and seas, as well as subterranean water reservoirs (Pogharnitskaya, et al. 2016). Spills may arise from a multitude of factors, including transportation accidents, storage tank leaks, or incidents during offshore drilling operations. The introduction of petroleum products, such as oil or gasoline, into water sources may result in significant environmental and public health ramifications (Wiens, 2013). The poisoning of drinking water sources is a significant issue that is closely linked to petroleum spills (Jernelöv, 2010). In Sweden, oil spills are the most common environmental damage incidents, with around 600 addressed annually despite improvements in response techniques (Swedish Salvage Rescue, 2021). The discharge of oil into water can result in acute toxicity and non-lethal impacts, affecting both aquatic ecosystems and drinking water sources (The Swedish Agency for Marine and Water Management, 2021). Sea traffic to and from Lake Mälaren introduces the risk of oil spills, especially through the Södertälje canal and the Hammarby lock. Statistics from the passage line Södertälje indicate a rising trend in tanker traffic, primarily transporting diesel fuel and petrol to Västerås (Regional oil protection plan for Stockholm County, 2022). A new sulphur directive mandates the transition to low-sulphur bunker oil, which increases the vulnerability of bunker tanks on ships to leakage, particularly gas tankers carrying ammonia to Köping, due to the fuel's potentially higher corrosiveness on materials not designed to withstand its properties. Low-sulphur bunker oil typically contains higher levels of certain chemical compounds, such as organic acids, which can accelerate corrosion in bunker tanks not specifically designed to withstand these corrosive properties (Hänninen and Rytkönen, 2006). Additionally, the transition often involves changes in storage and handling practices, which can inadvertently contribute to increased vulnerability to leakage if not properly managed or if equipment is not updated to accommodate the new fuel specifications (Regional oil protection plan for Stockholm County, 2022). The EU Directive 2020/2184 underscores the importance of continuous monitoring and regulation to ensure safe drinking water and protect public health. Additionally, the summary notes the broader consequences of water pollution on public health and the environment, citing waterborne diseases, chronic health issues, harm to ecosystems, disruption of biodiversity, and degradation of water quality. Overall, ensuring the quality of drinking water is crucial for the well-being of both humans and the environment (Dettori, et al 2022).

Petroleum products, extensively used as fuels, are complex mixtures derived from crude oil. They contain aliphatic and aromatic hydrocarbons with low water solubility. Concerns arise from potential spills contaminating drinking water sources, distribution systems, and treatment facilities. Exposure is typically short-term due to accidental spills, resulting in elevated total petroleum hydrocarbon concentrations. The Total Petroleum Hydrocarbons Criteria Working Group categorizes these hydrocarbons based on carbon atoms and boiling points, providing a practical method for assessing health risks associated with larger-scale contamination of drinking water by petroleum products (WHO, 2017).

Petroleum products include a range of hazardous substances, such as benzene, toluene, ethylbenzene, and xylene (BTEX), which have the potential to infiltrate water sources and compromise their suitability for human consumption (Fortenberry, et al. 2018). Furthermore, these pollutants could last in the environment for extended durations, resulting in enduring harm to ecological systems and presenting health hazards to both people and animals (Wiens, 2013).

Given the risks associated with maritime operations and the potential influence on Lake Mälaren's water quality, it is necessary to prioritize the modeling of petroleum spills. Modeling is crucial for effective prediction and management of oil spills, offering advantages over monitoring alone. Models provide predictive capabilities, enable scenario testing, and integrate complex factors for comprehensive predictions. While monitoring is essential for real-time data, modeling allows for proactive risk assessment and response planning (Liu et al. 2013). These models aim to replicate the dynamics of petroleum spills in aquatic environments, considering several elements like hydrodynamics, meteorological conditions, and the characteristics of the spilled material (Zhu et al. 2018). Modeling an oil spill's behaviour allows for prediction. If authorities have accurate predictions of the spill's trajectory and result, they may be able to better plan their responses, evaluate risks, and make decisions in the event of an oil spill. This allows for better containment, cleanup, and mitigation efforts.

Regardless, when considering variables like weather, wind patterns, and spill characteristics, models for oil spills have limitations due to uncertainties and assumptions made during simulation. Differences between real spill incidents and model projections may occur when these elements vary (specifically, when there are unexpected changes in weather conditions, wind patterns, or the physical and chemical properties of the spilled material), which affects the accuracy and reliability of simulation results.

Additionally, data gaps or inaccuracies caused by weather data, spill source characteristics, and input data can limit the ability to make accurate predictions, especially in areas with limited monitoring infrastructure or data coverage, affecting the validity of model outputs. These limitations highlight the need for continuous improvement of modeling techniques, better data collection, and the inclusion of uncertainty in model outputs when making decisions about oil spill prevention and response. Moreover, they underscore the importance of combining modeling with real-time monitoring to enhance oil spill management in Lake Mälaren. This comprehensive approach is essential for effectively addressing the challenges posed by oil spills and improving predictive and management capabilities.

Hydrodynamic modeling of petroleum spills is a central aspect of this research. IVL (Swedish Environmental Research Institute), Seatrack Web, and DHI (Mälarmodellen) are three modeling tools available for simulating petroleum spills. Using these models, this study seeks to thoroughly examine three potential petroleum spill scenarios in Lake Mälaren, considering factors like spill location, volume, duration of spreading, and probability. Through analysis and simulation, the aim is to provide significant insights into the dynamics of petroleum spills. Additionally, the study has compared the performance of these models to understand which one would be most suitable for the needs of Norrvatten, a key organization responsible for treating water from Lake Mälaren for drinking purposes. However, a significant knowledge gap exists in understanding which of these models best suits the specific needs of Norrvatten, the drinking water producer for 14 municipalities in North Stockholm, responsible for safeguarding the water supplies drawn from Lake Mälaren. As Liu et al. (2013) emphasize, the selection of appropriate oil spill models is crucial for effective prediction and management of oil spills, offering advantages over monitoring alone. Yet, no systematic comparison has been conducted to assess these models based on criteria such as accuracy, reliability, ease of use, and compatibility with local conditions specifically for Norrvatten's needs.

The importance of addressing this gap is underscored by Zhu et al. (2018), who note that Models for oil spills have limitations due to uncertainty and assumptions made during simulation. Differences between real spill incidents and model projections may occur when these elements are variable, which impacts the accuracy and dependability of simulation findings. This highlights the need for a context-specific evaluation, especially considering Liungman and Mattsson's (2011) observation that the model's reliability decreases with depth due to the easier inflow and outflow representations," which may be particularly relevant for Lake Mälaren's complex hydrology.

Addressing this gap requires a comprehensive evaluation of these three modeling tools, considering their performance in simulating hydrodynamics and petroleum spill scenarios in Lake Mälaren. By conducting such comparative analyses, Norrvatten can select the most appropriate tool to enhance their preparedness and response capabilities in the event of petroleum spills, thereby safeguarding water supplies and protecting public health and the environment.

This Master thesis aims to comprehensively investigate petroleum spills in Lake Mälaren, focusing on modeling their spread in the lake and comparing different models. The evaluation of model performance includes assessing how accurately each model simulates hydrodynamics and petroleum spill scenarios, considering factors such as prediction accuracy, computational efficiency, ease of use, and the ability to handle various spill conditions. Additionally, the study examines economic considerations and operational feasibility. By doing so, the research contributes to the protection of human health and the environment in the Lake Mälaren region. The objectives of the study are as follows:

1. Analyse and compare model formulations and underline theoretical background regarding oil spill representation in Mälarmodellen (DHI), the Seatrack model (SMHI), and the IVL model.

2. Assess the models using a set of predefined hypothetical spill scenarios that vary in terms of spill size, location, and environmental conditions, such as different weather patterns and water currents. This evaluation will determine how each model predicts the spread and impact of oil in these scenarios by comparing outputs, including the extent of oil spread, concentration over time, and potential impact zones, as represented in graphical and tabular outputs.

3. Investigate computational efficiency, user-friendliness, and operational capabilities by measuring the time each model takes to complete simulations under identical conditions to determine how quickly results are generated, which is crucial for real-time spill response. Evaluate the ease with which users can interact with each model, including the simplicity of the interface, the learning curve associated with model operation, and the availability of support and documentation for users. Assess each model's flexibility and reliability in managing different spill scenarios, considering factors such as the ability to simulate various oil types and environmental conditions, the presence of any bugs or errors, and the consistency of model outputs. Additionally, examine aspects such as the availability of coast guard resources to support model operations and the overall cost of using each model, including licensing fees.

Background

It is critical to comprehend hydrocarbons in the context of oil spills and their effects on sources of drinking water. We can divide hydrocarbons into four main classes: ethers, esters, aliphatic hydrocarbons, and aromatic hydrocarbons. Because of their ring-like shape, aromatic hydrocarbons such as benzene and toluene pose serious dangers to the quality of drinking water when they leak from an oil spill (IARC, 2018). Aliphatic hydrocarbons, often found in spilled oil, can impact supplies water supplies with their straight or branched carbon chains. Fuels use ethers, which could potentially contribute to pollution in the event of a spill. Examples of these additives include (MTBE) methyl tert-butyl ether (WHO, 2005). While esters, like rapeseed methyl ester (RME), are bio-components in fuels that may be good for the environment, their release might nevertheless have an adverse effect on the quality of water. It is critical to examine these hydrocarbon classes to determine their effects on the safety of drinking water in the event of an oil spill. The table below (Table 1) shows the European fuel standards overview.

Table 1. Europian fuel standards overview.

Topic	Description
Fuel Standards	European standards ensure fuel compatibility. Updates occur every five years. Environmental concerns are secondary to safety and efficacy.
Diesel Fuel	European diesel meets EN590 standards. Swedish diesel (MK1) has stricter limits on aromatics. Cold weather performance is assessed by CFPP and Cloud Point, adapted to Swedish conditions.
Petrol	European diesel meets EN590 standards. Swedish diesel (MK1) has stricter limits on aromatics. Cold weather performance is assessed by CFPP and Cloud Point, adapted to Swedish conditions.
Ethanol Fuel E85	European E85 complies with EN15293 standards. Specific denaturing agents are mandated. Octane numbers RON> 104 and MON> 88 are achievable.
Hydraulic Oil	Essential for hydraulic systems, hydraulic oils have critical properties obtained through additives. Swedish standards require biodegradability and minimal water toxicity. RISE Sweden maintains a regularly updated list of compliant fluids.

Diesel fuel in Europe follows the EN590 standard, with Sweden's MK1 diesel having an even lower aromatic content limit (5% max) than the European norm (7% max). Freezing weather performance, as measured by factors such as Cold Filter Plugging Point (CFPP), is critical, with requirements tailored to Sweden's diverse environment (Westerholm, 2001). In Sweden, MK1 petrol is subject to specific regulations for European petrol (EN228). These regulations include lower olefin content and a maximum oxygen content of 2.7% for MTBE and ETBE (Ethyl Tertiary-Butyl Ether). MTBE discontinued in some countries because of worries about water pollution, differs from ETBE, which is favoured for its renewable supply of ethanol (Alakangas, 2011).

Authorized denaturing chemicals must be used when the alcohol percentage of European E85 ethanol (EN15293) is above 70%. RON (research octane numbers) and MON (motor octane numbers) ratings are significant in this context. Hydraulic oils are classified into three categories: mineral, synthetic, or biobased. These oils must adhere to Sweden's SS-155434 standards, which require them to be biodegradable and have minimal water toxicity (Athanassiadis, et al. 1999).

Oil quickly spreads out to form a thin layer just a few millimeters thick on the water's surface. Gravity and surface tension play a significant role in promoting the spread of spills. Despite their assorted sizes, spills tend to attain a consistent average thickness of around 0.1 mm very rapidly. The movement of currents and the influence of the wind affect both the surface oil and the dispersed droplets in the water body. The oil undergoes evaporation, emulsification, dispersion, dissolution, photooxidation, sedimentation, and biodegradation, which cause changes in its physical and chemical characteristics and might lead to its removal from the surface of the water (Péquin, et al. 2022). The processes are interdependent and collectively known as oil weathering.

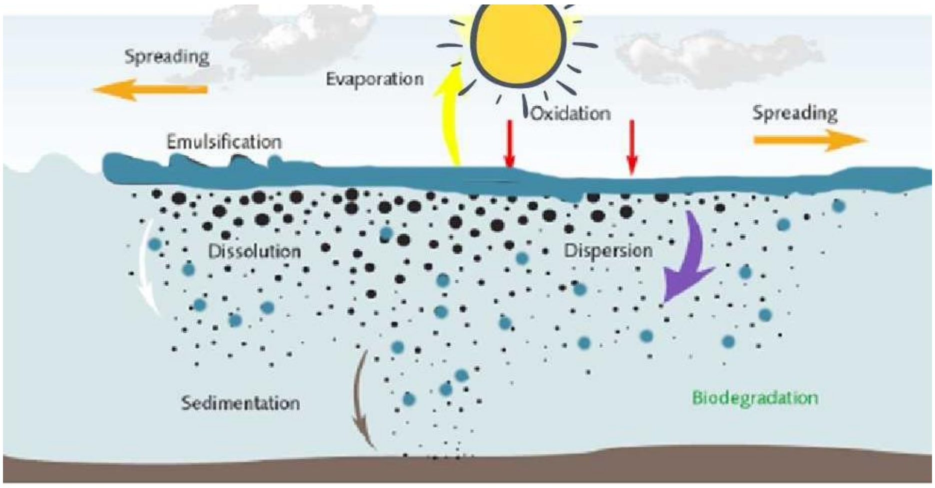


Figure 1. The weathering mechanisms that are involved with oil at sea. Modified from (Fate of marine oil spills, 2002).

Figure 2 present an acknowledge emulsification, biodegradation, and photochemical oxidation as long-term weathering processes, while it considers spreading, evaporation, dispersion, and dissolution as short-term weathering processes.

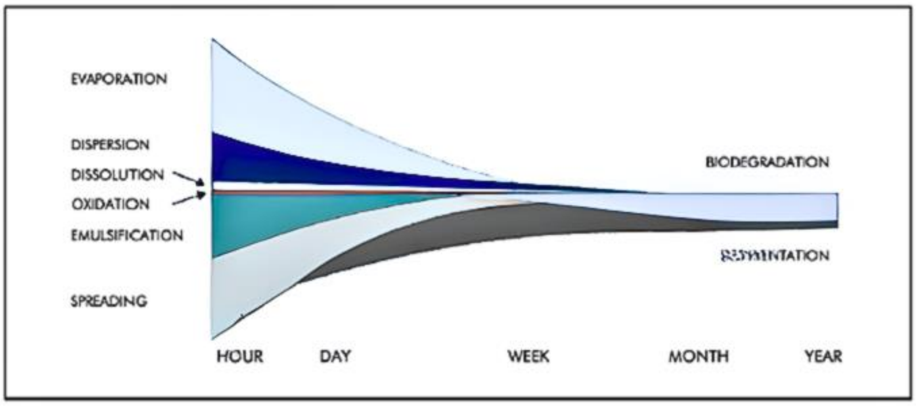


Figure 2. This diagram illustrates the progression of a crude oil spill over time, depicting the varying significance of weathering processes. The width of each band corresponds to the level of relevance for the respective phase. Modified from (Fate of marine oil spills, 2002).

Figure 3 shows the quantities of fuel supplied to service stations in Sweden by fuel providers, according to recent data (operational power Sweden, 2024) In terms of delivery, diesel has surpassed all other fuels since 2010. No publicly available sources report the percentages of 98-octane and 95-octane fuel volumes.

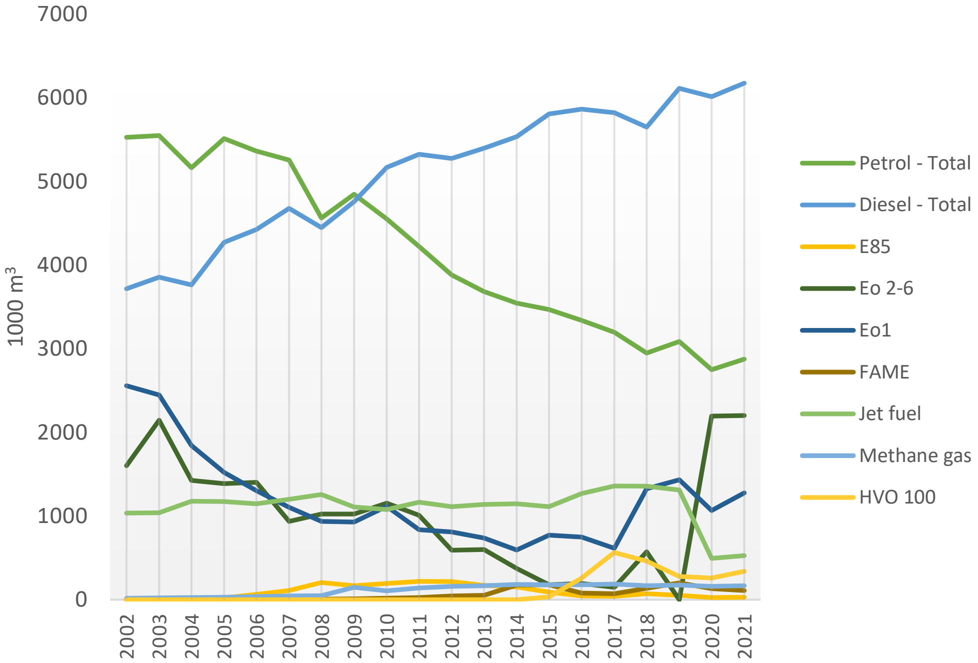


Figure 3. Volumes of various fuels that were manufactured and sold on the Swedish market (Drive Sweden, 2023: Delivered volume of oil products and renewable fuels – per year).

Seatrack model

Seatrack is an online platform designed to assist industries, water conservation groups, and local governments in evaluating risks to water bodies, managing oil spills, and training personnel. Drawing from extensive expertise in modelling fluid dynamics and dispersal patterns in lakes and coastal regions.

Seatrack uses a 3D Lagrangian particle model (PADM) to simulate oil spills. It solves fluid mechanics equations in three dimensions, incorporating advection, turbulence, Stokes drift, and buoyancy. The model tracks individual particles representing oil, considering their interactions with boundaries and various physical processes affecting oil dispersion and transport in marine environments. Seatrack offers advanced features such as early detection of potential water contaminants, prediction of pollution spread, and identification of pollution sources. It accommodates various petroleum substances, algae outbreaks, and floating objects, providing a user-friendly interface with standardized map tools and seamless integration with GIS data. Seatrack is designed for risk assessment, establishing protective measures, responding to oil emergencies, and crafting environmental assessments. It can be customized to specific regions. By entering spill characteristics such as location, type, depth, and volume, Seatrack generates visualizations of pollution movement over time, complete with animated maps and comprehensive data analysis.

Seatrack system is developed by SMHI (Sverige's Meteorologiska och Hydrologiska Institut), Seatrack consists of three main parts:

1. Oil Observation: Simulates the movement of observed oil in the water. It allows users to specify the oil location using existing oil detection, coordinates input, or hand-drawing on the map. Simulation can be run both forwards and backwards in time.
2. Continuous Oil Spill: Simulates the movement of oil from sources such as oil-leaking vessels. Users specify outlet depth and location for the simulation.
3. Floating Object: Tracks lost buoys and other objects. Initial location and wind factor of the lost object are required for simulation, which can be run both forwards and backwards in time.

The Seatrack model allows users to select oil classes based on viscosity intervals: Light, Medium, and Heavy oils. Default values are provided for each interval: Light (Light Diesel Fuel), Medium (Intermediate Oil), and Heavy (Bunker C). Alternatively, users can select specific oils from a list of 11 specified options, each with fixed densities ranging from 700 kg/m^3 to 1000 kg/m^3. Some oils emulsify, including Light-medium crude, Heavy crude, and Bunker C, while others do not. Emulsification is the process of mixing two or more liquids that are usually immiscible (do not easily mix), like oil and water, to form a stable mixture (Liungman et al., 2011).

The model validation process incorporated data on water levels, current measurements, temperature, and ice conditions from satellite observations provided by the Swedish Meteorological and Hydrological Institute (SMHI). At a number of different places throughout the Mälaren, SMHI performs automated measurements of the water levels as they are responsible for this region. In order to offer a thorough portrayal of the lake's water level, the SMHI has been calculating an average water level from six different measurement stations since January of 2016. Furthermore, current measurements were obtained from two distinct straits: one situated deep within the Mälaren region at Kvicksund, and the other situated in the tiny strait that leads towards Strängnas at Sanda islet (Liungman and Mattsson, 2011).

The Seatrack model relies on the temperature data. Two of the most important locations in the northeastern region of Mälaren are where the temperature measurement stations have been carefully placed. Among them are two stations situated in the eastern areas of Mälaren, as well as three stations that are situated along the influx from the north, which finally flows out. As an additional point of interest, during the ice season, SMHI uses satellite images on a daily basis to track the ice conditions in a number of different areas, including Mälaren. These maps are an invaluable resource for comparing the conditions of the ice that have been seen with the ice extent and thickness that have been predicted. In spite of the fact that a superficial verification of ice in the model has been carried out, special attention was put on three chosen days in 2022 in order to ensure accuracy and consistency (Liungman and Mattsson, 2011).

The PADM oil drift model, which is a Lagrangian particle dispersion model, is the basis of the Seatrack model. Particle clouds represent the synthetic material. The trajectory of each particle is defined by flow fields that change with space and time as well. Flow fields are considered to be unaffected by particles. Coastlines, the bottom, and surfaces are examples of boundaries that might affect particles. Particles stick to or glide along solid limits; they can't transcend them. They may be constant or change with time, place, and temperature in terms of attributes including position, mass, volume, size, chemical characteristics, and density. There are primarily two parts to the PADM: spreading which encompasses all particle movement mechanisms and weathering of oil.

An organized grid of six-sided cells is supposed to define the flow field at certain time intervals. Staggering the grid positions the flow velocities on the faces of each cell. The flow field within a cell is controlled by the velocities on the six faces, where the perpendicular component of the velocities is constant on all six faces. Assuming flow parameters are constant over a particular time period, the model allows for spatial differences limited by grid resolution. As a result, the particle spreading simulations do not account for variations in sea levels. In Seatrack Web, ice is not explicitly represented as a border that is constantly shifting. Ignoring the effects of ice on oil in transit or storage, the emphasis is on ice's effects on oil on the surface. Particles propagate outward from their initial location; this process is called spreading. The aggregate of these individual velocities is the overall velocity. The interaction between particles and physical limits influences the spreading.

It is particularly helpful to recognize the difference between horizontal spreading at the surface and turbulent mixing differentiation in the water column when dealing with oil, which usually forms a cohesive slick on land but breaks up into individual droplets below. In oil, horizontal spreading may be caused by both gravity and self-induced shears, which work together to counteract the effects of viscous and gravitational forces. In the current version, the gravity-induced horizontal spreading of oil relies on Fay's formula for the gravity-viscous spreading is given by: In this updated version, the formula for gravity-viscous spreading, which is used to describe the horizontal spreading of oil due to gravity, is provided by:

$$\mathrm{A_{oil}}(t) = 2.1\pi \left(\frac{V^2\, \mathrm{g'oli}}{(\sqrt{\mu}/\rho))} \right)^{1/3} \sqrt{t} \qquad (1)$$

$A_{oil}(t)$: time-varying area of the oil slick
V: spilled volume [L]
μ: viscosity of water [mPa.s]
ρ: Density of water [M/L^3]
g′oli: The buoyancy acceleration of oil [L/T^2]

Dispersion is the process of dispersing particles from the water's surface into the column. Oil needs a different methodology than dissolved chemicals, which are represented using turbulent mixing. Because oil tends to form cohesive slicks on the surface, typical turbulent mixing caused by wind shear may be ineffective at breaking them up. Instead, by hypothesizing that dispersion happens by breaking surface waves over the oil slick, which fragments it and submerges oil droplets to depths determined by wave energy. The dissipation breaking wave energy, Eb, is computed using the breaking wave height, Hb.

$$\mathrm{Eb} = 0.0034\rho g \mathrm{Hb}^2 \qquad (2)$$

The proportion of surface covered by breaking waves per unit time is approximated as:

$$\mathrm{Fb} = 3\times10^{-6} W^{3.5} \qquad (3)$$

Where W is the wind speed. A simple calculation Hb = 1.5Hs was used to get the breaking wave height from the significant wave height. The mass of oil to be spread for each size class Q is then calculated as follows:

$$Q = r_{ice}\ \Delta t c_v\ E_b^{0.57} F_b d^{-0.7} \Delta d A_{oil} \qquad (4)$$

Q: The mass of oil to be dispersed [kg]
r_{ice}: correction factor to consider the presence of ice.
$c_v = 4450v{-}0.4$: An empirical coefficient dependent on the oil viscosity in centistokes oil [L^2/T]
D: The mean diameter for the current size class [m]
Δd: The diameter interval of the size class [m]
A_{oil}: Surface area of the oil slick [m^2]

Three procedures establish the diameter of the oil droplet:

1) It is determined using the dispersion algorithm for surface-dispersed oil.
2) A normal distribution with a mean of 5 mm, standard deviation of 2 mm, and a minimum value of 0.01 mm is used to randomly sample the diameter for oil spilled at deep.
3) The diameter is equivalent to the thickness of the surface spill for oil mixed down from the surface by turbulence.

Oil Weathering: An amount of oil with common features such as mass, volume (including water-in-oil), density, mass of oil, mass of water-in-oil, and bulk viscosity is represented by each particle when oil drift is forecasted using Seatrack Web. The processes of evaporation and emulsification cause these characteristics to alter. Asphalt, kerosene, and light, volatile gasoline are just a few of the petroleum compounds that might be modelled.

Evaporation: Various exposure periods are included in the empirical data as evaporated fraction values (f_e). Following exposure, the oil's mass (M) is determined by equation 5 where M_0 is the initial mass of fresh oil.

$$\mathrm{M} = (1 - f_e/100)\, M_0 \tag{5}$$

Emulsification (water-in-oil): Mass fraction numbers (m_w) showing the proportion of water in a water-in-oil emulsion at different emulsification exposure durations are included in the empirical data. This is the formula for determining the mass of water in the emulsion, (M_w):

$$M_w = \mathrm{M}\left(\frac{m_w}{100-m_w}\right) \tag{6}$$

The densities and viscosity provided are conventional approximations for fresh oils at common temperatures found in sea water. During the beginning of a simulation, oils are categorized as either fresh or fully weathered. In order to address the presence of uncertainty in a drift simulation, the option of activating a feature known as uncertainty spreading may be used. Every individual particle on the surface is given an extra random velocity, the size of which is determined by the anticipated uncertainty in the wind prediction. This method replicates a collection of simulations with marginally varying external influences, which solely impact the particles on the surface.

The Seatrack Web model is set up as a Lagrangian particle spreading system (PADM) combined with forecasted flow and wind fields. It uses data from HIRLAM and HIROMB models for wind, ocean currents, turbulence, ice, and sea surface temperature. The document does not describe specific validation processes, which significantly impacts our ability to assess result reliability. This setup influences results through the accuracy of input data, assumptions in particle tracking algorithms, and representations of complex processes like oil weathering and ice interactions. The inclusion of an uncertainty spreading feature suggests awareness of forecast limitations, but without validation details, it is challenging to fully evaluate the model's performance and result accuracy.

DHI Model

The DHI MIKE 3 Flow Model FM is a hydrodynamic model developed by the Danish Hydraulic Institute (DHI) for simulating fluid dynamics in aquatic environments. It employs advanced computational techniques to solve fundamental fluid mechanics equations, including conservation of mass, momentum, heat, and turbulent kinetic energy. The model generates three-dimensional representations of hydrodynamic processes such as flow patterns, water levels, temperature distribution, and turbulent mixing in various water bodies including oceans, coastal areas, estuaries, rivers, and lakes. MIKE 3 FM incorporates a wide range of environmental factors, including wind forcing, water level variations, freshwater inflows, density variations, bottom friction, atmospheric heat exchange, and Coriolis effects, to provide a comprehensive simulation of aquatic systems. The DHI model automates simulation towards points of interest, predefined within the model, and located in various positions, as illustrated in the figure 4.

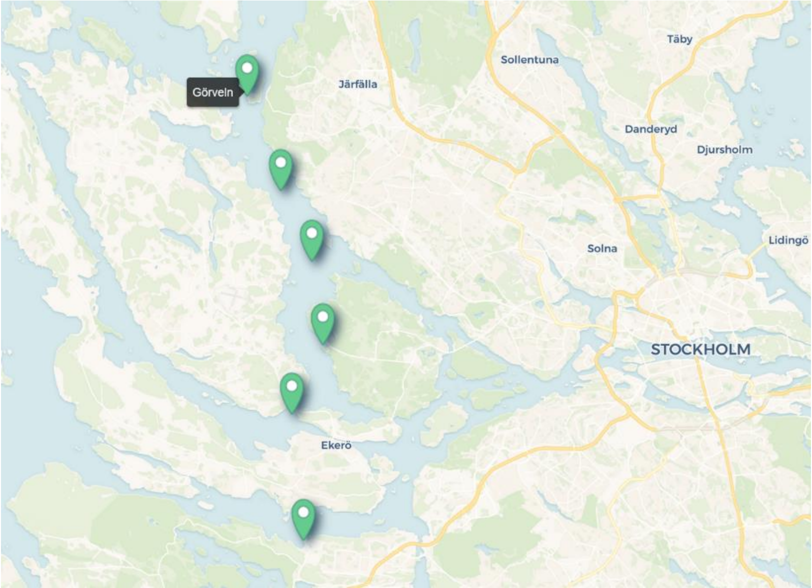


Figure 4. Location of Point of interest predefined by model.

The Oil Spill Module, an add-on to the MIKE 3 Flow Model FM, enhances the model's capabilities by simulating the weathering and movement of oil particles in aquatic environments. It employs a Lagrangian approach to track the movement of discrete oil particles and Eulerian approach for advection-dispersion calculations of dissolved oil. The model considers key environmental factors such as currents, wind, waves, and ice data as inputs for the simulation. Different types of oil are characterized based on parameters like density, viscosity, pour point, and maximum water content. Various weathering processes, including spreading, evaporation, emulsification, dispersion, dissolution, biodegradation, and photo-oxidation, are incorporated into the simulation to accurately represent oil spill dynamics.

The Hydrodynamic Model MIKE 3 FM solves the basic fluid mechanics equations that describe the movement (flows) and properties (density, temperature, etc.) of water. The equations are based on the conservation of mass, momentum, heat, and turbulent kinetic energy. The model calculates flows, water levels, temperature, and turbulence in a three-dimensional computational grid as a function of time. MIKE 3 FM considers all the major hydrodynamic processes such as wind driving on the surface, driving due to variations in water level, inflows of freshwater from land, turbulent mixing, heat transport, driving due to density variations, bottom friction, heat exchange with the atmosphere and Coriolis effect due to the Earth's rotation. more detailed description of the hydrodynamic model is available in the documentation for MIKE 3 (DHI 2009b).

It is worth noting that Norrvatten, among other organizations, currently utilizes this model for environmental assessments and management strategies. Overall, the DHI MIKE model provides a tool for assessing the environmental impacts of oil spills, evaluating response strategies, and enhancing emergency preparedness. Its ability to simulate complex hydrodynamic processes and incorporate detailed oil spill modeling makes it suitable for studying and managing environmental risks associated with oil contamination in aquatic ecosystems (DHI oil spill scientific description, 2024).

The model describes two primary components of oil: the lighter, more volatile portion and the heavier, less volatile fraction. Hydrocarbons with boiling points lower than 300°C and molecular weights lower than 160 g/mol make up the volatile fraction. The larger portion consists of hydrocarbons, such as asphaltene and wax, with molecular weights more than 160 g/mol and boiling points ranging from 250 to 300°C and higher. As a collection of smaller oil quantities, each shown by a single oil track particle, the model depicts the overall quantity of spilled oil (DHI Oil Spill Scientific Description, 2024). The particles go through stages of weathering and drifting. The eight internal state variables of each oil track particle are:

- Volatile oil mass: Mass of light and volatile hydrocarbons subject to evaporation, dissolution, biodegradation, and photooxidation.
- Heavy oil mass: Mass of heavier hydrocarbons subject to dissolution, biodegradation, and photooxidation, without evaporation.
- Amount of asphaltenes: Quantity of asphaltenes in the oil, considered conservative as they neither degrade, evaporate, nor dissolve.
- Amount of wax: Quantity of wax in the oil, also considered conservative.
- Water fraction of oil: Water content in the oil particle.
- Droplet diameter: Diameter of the oil droplet, influenced by wave action.
- Area of oil: Contact area with the sea surface, representing the equivalent area of a circular slick for the individual oil track particle.
- Immersed state (0/1): Indicates whether the particle is in the water phase (1) or stranded on the shoreline (0). Certain processes are only active for immersed particles, such as changes in area and water content, dissolution, and dispersion processes.

Weathering Processes:

- Evaporation: Initially dominant, especially for lightweight products like gasoline. Evaporation rates depend on factors such as oil type, surface area, wind, and sea conditions. Two options for the modelling of the evaporation are included 1. the evaporation process for one particle that is in contact with the water surface (within 5 cm from surface) 2. Most oils were found to follow logarithmic loss curves, but a smaller amount fitted square root loss curves with time for periods up to about 5 days (DHI Oil Spill Scientific Description, 2024).
- Dissolution: Water-soluble components dissolve into seawater, reducing the size of the slick but potentially increasing environmental toxicity.
- Emulsification: Equilibrium process between oil and water phases, affecting stability and demulsification ability (Xie et al, 2007).

- Sedimentation: Few crudes sink on their own, but the model accounts for vertical movement driven by buoyancy forces.
- Biodegradation: Gradually removes petroleum pollutants from the marine environment.
- Vertical Dispersion: Important for moving oil into the water column, facilitated by winds, currents, and turbulent seas. The entrainment of oil from the sea surface into the water column (Delvigne and Sweeney, 1988).

$$Q_d = CD^{0.57} \, SFd^{0.7} \, \Delta d \qquad (7)$$

Q_d: Vertical dispersion
C: entrainment coefficient
D: dissipation wave energy [J/m2)]
S: fraction of sea surface covered by oil (assumed to be 1 around each particle)
F: fraction of sea surface covered by breaking waves per unit time [s-1]
d: mean diameter of droplet size
Δd: droplet size interval

- Dynamics of Viscosity: Change in viscosity as a result of emulsification can be calculated using Mooney equation (Sebastião and Guedes Soares, 1995).

$$\mu = \mu_0 \cdot \exp\left[\frac{2.5 \cdot Y_w}{1 - C \cdot Y_w}\right] \qquad (8)$$

μ = Change in viscosity as a result of emulsification
μ_0= parent oil viscosity [cP].
C = viscosity constant (Mooney constant), final fraction of water content, 0.7 for crude oil and heavy fuel oil, 0.25 for home heating oil
Y_w = water fraction [kg/kg]

When simulating the movement of oil particles, the model considers the interplay between currents, wind drag, and bed drag. Something floating on the water's surface may be influenced by the wind. (DHI Oil Spill Scientific Description, 2024).

The DHI oil spill model is a Lagrangian model that uses pre-run hydrodynamic results and divides oil into light volatile and heavier fractions. It simulates various weathering processes and uses eight internal state variables for each oil track particle. The model relies on oil-specific parameters from databases or distillation data, as well as environmental data from hydrodynamic inputs. While the model's setup appears comprehensive, incorporating many important processes affecting oil spills, the documentation lacks specific information about model validation. This absence makes it challenging to assess the model's reliability and the influence of its setup on results. The simplification of oil into two fractions and the use of pre-run hydrodynamic data may affect prediction accuracy. Without validation studies or sensitivity analyses, it is difficult to gauge the model's real-world accuracy. More information would be needed to fully understand the model's reliability and how its setup impacts results (DHI Oil Spill Scientific Description, 2024).

The IVL ether water simulator

The IVL ether-water simulator developed by the Swedish Environmental Research Institute (IVL) in collaboration with leading experts in environmental chemistry and ecotoxicology, integrates a multifaceted approach to simulate real-world scenarios of fuel spills and their subsequent interaction with water bodies. Key processes considered include diverse fuel types such as ethanol blends, petrol variants, diesel, and hydrotreated vegetable oil (HVO), each with distinct chemical compositions and environmental impacts. Factors such as water temperature, depth, and velocity incorporated to mimic realistic spill conditions and their influence on fuel dispersion.

Model input includes fuel types such as Ethanol 85, petrol 95 octane, petrol 98 octane, MK 1diesel, and HVO, along with parameters like the amount of fuel (m3), water temperature (C), depth of raw water intake (m), and water velocity toward intake (cm/s). Post-calculation, the simulator generates a graph illustrating ether concentration (µg/L) versus distance from the spill, providing valuable insights into the spatial distribution of contaminants in water bodies post-spill. Even in low quantities, some compounds that are contained in fuels have the ability to alter the smell and taste of water. Although these substances may not be hazardous, they are still undesirable for drinking water generation. This is according to the rules of the Swedish National Food Agency (LIVSFS 2017:2), which emphasize the necessity for odorless and tasteless drinking water in order to minimize any potential health risks in general (Strandberg, et al. 2022). The model addresses a specific topic relevant to those who manufacture drinking water. The query is as follows: "How far must a petrol spill containing ether occur in order to prevent its taste or smell from being detectable at my raw water intake?"

The model considers a number of elements to assess the potential for fuel spills near raw water intakes, including horizontal advection, water velocity, spreading angle, and the evaporation of ether into the atmosphere. The inclusion of a critical odor threshold for ether is of utmost importance. This threshold was identified by olfactory testing to be between 1-4 µg/l. This threshold is critical for estimating when the dispersion plume of a spill will reach a raw water intake and the distance required for the ether concentration to drop below this level (Strandberg, et al. 2022). The model relies on calculations and experiments to determine the amount of ether that dissolves in water at a temperature of 20°C. It assumes a fuel spill of X cubic meters (Vol_{Fuel}) over a circular water surface with an initial radius (r_0). Users have the option to choose between three types of fuels: E85, Petrol 95 Octane, and Petrol 98 Octane. This selection provides information such as the concentration of ether in the fuel (C_{Ether}) in grams per liter, the water-accommodated fraction (WAF, WAF_{Ether}) of ether in micrograms per liter (µg/L), and the percentage of ethanol ($Vol\%_{Ethanol}$).

The model kindly assumes that all of the WAF-available ether gets dissolved into the water up to the raw water intake (Z) depth. The ether beginning concentration (c_0) in an aqueous solution is expressed in µg/L after the ether is diluted with the initial volume of water.

$$c_0 = \frac{Vol_{Fuel} \times c_{ether} \times 1000 \times Sol_{ether}}{\pi \times Z \times {r_0}^2} \tag{9}$$

c_0: The ether beginning concentration
Solether: Ether percentage in an aqueous solution (Solether = cether/ WAFether)
WAFether: water accommodated fraction

The figure 5 presents a conceptual model that demonstrates the procedure. On the left side, there is a depiction of a fuel spill that occurred inside a certain radius at a specific time, denoted as t0. It is assumed that the fuel's ether interacts with the water in the raw water intake column, namely at the depth of the water. The figure on the right depicts the plume's growth in the direction of water velocity. As the period progresses, the plume's radius expands, causing a fraction of the ether in the water to vaporize (Strandberg, et al. 2022).

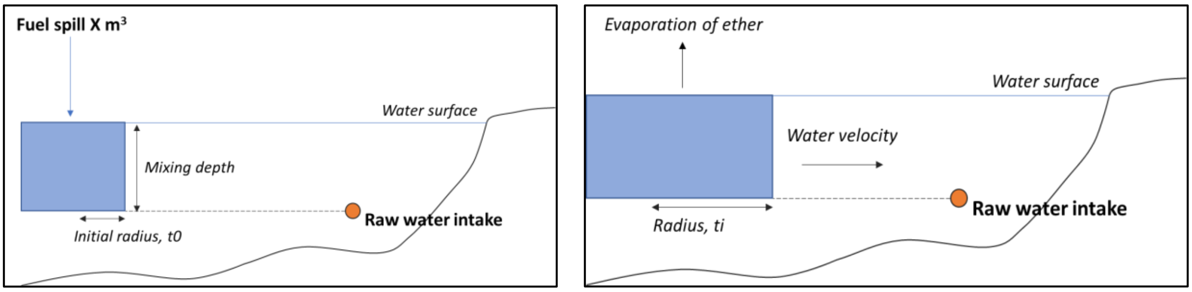


Figure 5. Conceptual model. Left: Fuel spill at t0 with ether mixing in water. Right: Plume expands rightward with radius increase and ether evaporation from (Strandberg, et al. 2022).

The approach involves analysing fuel samples through GC-MS for chemical composition, creating water-accommodated fractions (WAFs) to simulate contamination, and conducting odor threshold tests, ecotoxicological assessments, and evaporation experiments on selected samples. This setup aims to comprehensively evaluate fuel impacts on water and aquatic ecosystems. The documentation provides little explicit information on model validation, which is a significant limitation.

While standard methods are used for chemical analysis and ecotoxicological tests, there's no clear description of how the overall model was validated against real-world scenarios or independent data sets. The model relies on chemical analysis data of substances in fuels and WAFs, odor threshold data from panel tests, ecotoxicological test results on various organisms (crustaceans, algae, bacteria), and evaporation experiment data at different temperatures and ethanol concentrations. This diverse dataset aims to capture various aspects of fuel behaviour and environmental impact (Strandberg, et al. 2022).

Water temperature serves as a crucial input for the IVL model. Figure 6 presents plots of water temperature data (in degrees Celsius °C) sourced from the Swedish environmental monitoring database, Miljödata-MVM, as illustrative examples of temperature values in Swedish surface water sources (miljodata.slu.se, 2024). This data spans from February to September 2023 and originates from various monitoring stations situated within Lake Mälaren, the third largest lake in Sweden. Specifically, measurements were taken at a depth of 0.5 meters from the lake's surface. Due to the unavailability of 2024 data, the temperature data for 2023 was utilized to facilitate the execution of the IVL model for this master's thesis.

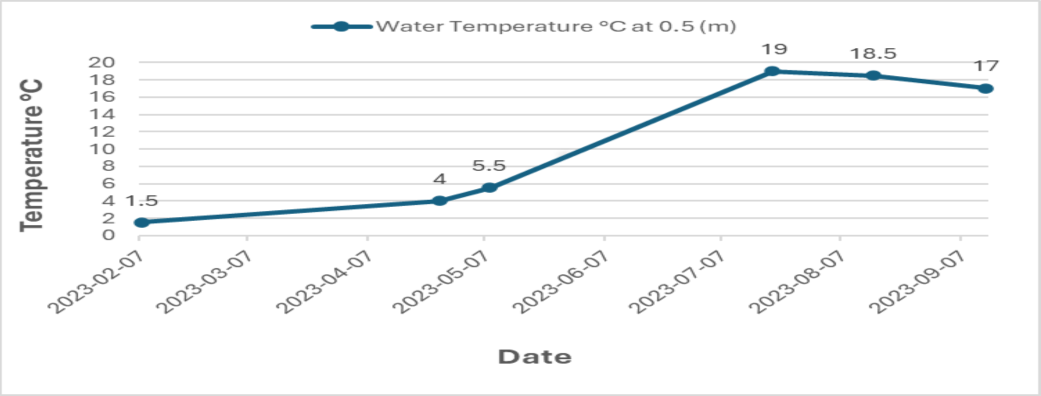


Figure 6. Lake Mälaren-Görväln water temperature (°C), Feb-Sep 2023.

Methodology

The method utilized for this master's thesis consists of four separate phases. First, the theoretical backgrounds of the three models based on scientific documentation of the models are examined to get an overview of each. Second, different scenarios are selected to ensuring the model is run effectively across various conditions. Third, after running the simulator, qualitative analyses are conducted to identify the advantages, disadvantages, and operating processes of each model. Fourth, a multicriteria decision analysis (MCDA) is carried out, which comprises evaluating the importance of multiple criteria and doing quantitative studies to evaluate the performance of each model. Furthermore, to strengthen the validity of this research, the model makers collaborated by giving thorough replies to questions regarding their models. This cooperation has resulted in a more complete knowledge and accurate evaluation of each model's skills and limits.

Model Setup

The Seatrack model was set up using input parameters such as oil type, volume, spill location coordinates, and environmental conditions (e.g., water temperature, wind speed, ice cover). Data were sourced from the Swedish Meteorological and Hydrological Institute (SMHI), including wind and temperature time-series data, and currents. Evaporation in Seatrack is modelled based on empirical evaporation rates for various oil types, considering factors like wind speed and temperature. The DHI model employed advanced hydrodynamic simulations to predict oil behaviour in water. Input data included spill volume, oil properties, water temperature, and currents, also sourced from SMHI and local monitoring stations. The model features a detailed evaporation sub-model that calculates evaporation rates based on oil type and environmental conditions (e.g., temperature, wave activity). This model divides oil into volatile and non-volatile fractions to simulate weathering processes.

The IVL ether-water simulator was designed to model the dispersion and evaporation of volatile fuel components in water. Key inputs included fuel type, spill volume, water temperature, depth of water intake, and water velocity, obtained from the Swedish environmental monitoring database (Miljödata-MVM) and IVL’s internal datasets. Unlike the other models, IVL focuses on the dissolution and evaporation of ethers and other volatile compounds. It uses empirical data to calculate ether concentrations in water and simulate their evaporation rates under different conditions.

Study Area

Lake Mälaren, with its lowland characteristics featuring over 8,000 islands, islets, and skerries, is an integral component of the region's landscape. It spans an area of 1,122 km^2, has an average depth of 12.8 meters, and reaches a maximum depth of 66 meters. The lake's outlet flows through Slussen in Stockholm to Norrström, with an average water flow of just over 160 m^3/s. As a source of drinking water for a substantial population, Lake Mälaren is essential to map for the presence of environmental toxins (Gudmundsson et al. 2022). A diverse range of land uses, including agricultural, forestry, wetland, and urban areas, make up the 22 650 km2 watershed. The area is home to three million Swedes, or about a third of the country's total population. Most of them live in urban areas, and both the overall population and the rate of urbanization are on the rise (Introduction to Sustainability Science, 2016).

The environmental toxins such as Heavy Metals, Persistent Organic Pollutants and nutrients in Lake Mälaren primarily originate from the western waterways that flow into its basins. Different basins exhibit varying turnover times, influencing the settling of substances in the water. For instance, Galten, the westernmost and smallest basin, has a rapid turnover time of a couple of weeks, while central fjords like Prästfjärden have a turnover time of almost two years. The turnover time is important because a long turnover time means that substances in the water have time to sink to the bottom and become sediment. This means that pools with a long turnover time get lower levels of environmental toxins, while pools with a low turnover time have higher levels. Understanding these dynamics is crucial as it affects the accumulation of environmental toxins and nutrient salts, shaping the lake's water composition even without human influence (Mälaren’s vattenvårdsförbund, 2014-2024).

Norrvatten is a municipal cooperative that specializes in producing and distributing high-quality drinking water to 14 municipalities in North Stockholm. It places a particular emphasis on expanding its services in the northern parts of Greater Stockholm. Norrvatten is crucial in providing clean drinking water to almost 700,000 people, as well as serving key healthcare institutions and Arlanda Airport. This plays a vital role in promoting regional development (Norrvatten.se, 2024). Figure 7 depicts the map showcasing the location of the main water treatment plant, Görvälnverket, situated in the Järfälla municipality near Lake Mälaren. Norrvatten plays a crucial role in operations, producing around 1600 Liters of drinkable water every second (norrvatten.se, 2024). Due to a bidirectional transfer capability across networks, Norrvatten can additionally receive backup from Stockholm Vatten, which is 1500 L/s (Groundwater Group, 2008).

Figure 7. Study area showing the location of the Norrvatten water treatment plant, Görvälnverket, situated near Lake Mälaren in Järfälla municipality. The marked circle indicates the site for oil spill simulation scenarios (maps.eniro.se, 2024).

Scenarios

The precise geographic locations and circumstances to be examined have been identified along the shipping route near Görväln as shown in figure 8 below, which serves as the intake of Norrvatten and is subject to possible risk. When considering the diverse array of scenarios that could lead to oil spills in Lake Mälaren, it is essential to recognize the broad spectrum of vessels traversing its waters. From commercial ships and tankers to hobby boats, each type of vessel brings its own set of challenges and considerations when it comes to spill prevention and response.

Commercial vessels, responsible for transporting oil and fuel, pose significant risks during accidents or mechanical failures on shipping route near Görväln (Norrvatten). These vessels, like freighters and tankers, carry large volumes of oil. Spills from these vessels could severely impact water quality, especially considering that Norrvatten utilizes this water source after treatment for drinking purposes. Additionally, rare but impactful events like sunken vessel spills require special attention due to their potential for environmental damage and subsequent implications for water treatment processes.

On the other hand, recreational boats, though individually carrying smaller fuel loads, potentially contribute to oil spill risks. Collisions, fuelling mishaps, and improper waste disposal are common scenarios leading to these spills. Despite their smaller scale, these incidents can still harm water quality and marine life in Lake Mälaren over time

The scenarios for potential oil spills near Görväln were developed based on the types of vessels commonly navigating the area, oil spills, and the specific geographic of Lake Mälaren. Given the variety of commercial and recreational vessels that traverse this shipping route, each scenario reflects a different risk profile based on vessel type, the volume of oil carried, and the likelihood of specific incidents occurring.

Three different coordinates, 1, 2, and 3, were selected along the shipping route (figure 8). Coordinate 1 was chosen for its proximity to Görväln on the shipping route. Coordinate 3 was selected because it is the intersection on the shipping route near Görväln. Coordinate 2 was randomly chosen, positioned between coordinates 1 and 3, and also close to Görväln. Each scenario was then assigned a specific coordinate: scenario A to coordinate 1, scenario B to coordinate 2, and scenario C to coordinate 3. Our exploration encompassed a range of scenarios involving both commercial and recreational vessels, taking into consideration factors such as spill quantities, spreading durations, and the likelihood of occurrence at each coordinate. Furthermore, the following scenarios were examined:

- **A. Collision between Hobby Boats (Location 1):** Two hobby boats collide while navigating Lake Mälaren, resulting in damage to fuel tanks and subsequent oil spillage. Each boat carries 50 cubic meters of gasoline or diesel, totalling 100 cubic meters (Light Diesel Fuel). The spreading duration is estimated to last 3 hours. This scenario is fairly common during peak boating seasons or in congested areas of the lake.
- **B. Spill from a Sunken Vessel (Location 2):** A large vessel, such as a freighter or tanker, sinks in Lake Mälaren due to an accident or mechanical failure, releasing 500 cubic meters of oil from its onboard storage tanks (Heavy: Bunker C). The spreading duration is estimated to last 3 hours. While the likelihood of this scenario is low, it carries potentially high impact.
- **C. Collision between Commercial Vessels (Location 3):** Two commercial vessels collide within Lake Mälaren, resulting in damage to their fuel tanks and subsequent oil spillage. Approximately 1000 cubic meters of diesel (Jet fuel 802 kg/m^3) is involved in this scenario, with the spreading duration estimated to last 1 hour. Although relatively unlikely, this scenario is plausible, especially in areas with heavy shipping traffic.

The location of scenarios A, B, and C on the shipping route near Görväln is illustrated in the figure 8, along with the precise coordinates for both the Seatrack and the DHI models, which are presented. For security reasons related to Norrvatten, the specific coordinates used in the study are not included in this report to protect sensitive information.

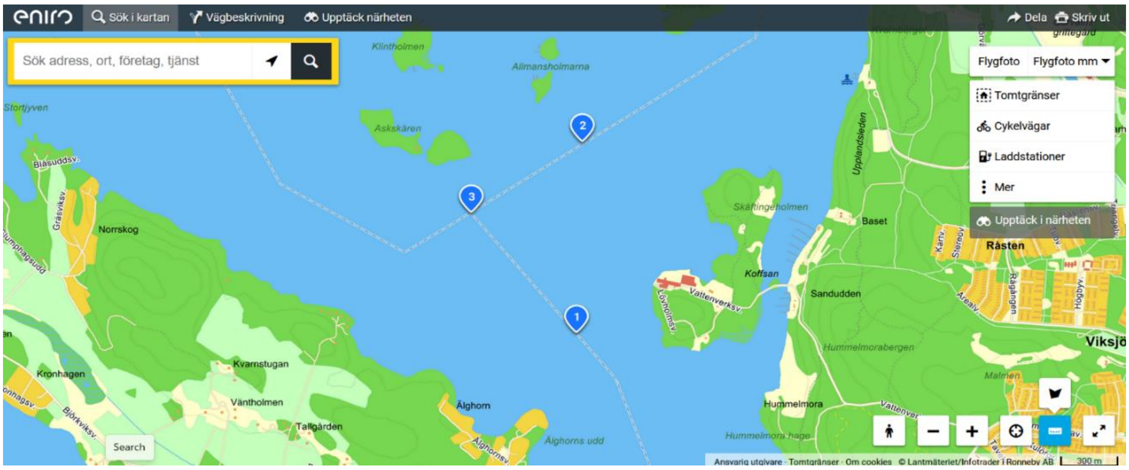


Figure 8. Shipping route locations near Görväln (Norrvatten) in Lake Mälaren. The figure illustrates three distinct locations along the shipping route near Görväln.

Qualitative analysis

Qualitative analysis were chosen to compare Seatrack, DHI, and IVL oil spill models because this approach allows for a deeper understanding of each model's unique characteristics and operational processes. Unlike quantitative analysis, which focus on numerical data and statistical comparisons, qualitative analysis enable you to explore and interpret Strengths and Weaknesses of the model. As a means of making the assessment procedure more manageable, the Sea track model and the DHI model were chosen for comparison since they are more comparable based on characteristic of the model. Following that, the IVL model was subjected to comparison. Qualitative analysis considers factors such as Model Selection, Coordinate Selection, Timeframe Customization, Simulation Options, Oil Type Selection, Parameter Customization, Output Representation, Data Output Options, Simulation Time, Flexibility in Analysis, Limitations, Errors, and spill options. For the purpose of maintaining consistency in the study, all three scenarios (A, B, and C) had the same start date and time (2024-02-18, 22:30) and end date and time (2024-02-21, 20:30). After executing the models and identifying their strengths and weaknesses, a matrix table was utilized to conduct qualitative analysis in order to investigate their performance in greater depth.

Multi-criteria decision analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is employed as an effective methodology for the comparison of complex alternatives, particularly when multiple, often conflicting criteria must be considered in decision-making processes. A structured and systematic evaluation of each option based on predefined criteria is enabled by MCDA, ensuring a comprehensive and transparent decision-making process is achieved. The integration of both quantitative and qualitative factors is facilitated by this method, through which a holistic view of each alternative's strengths and weaknesses is provided. This approach is not only utilized for the selection of the most suitable model, but it is also ensured that the decision-making process is aligned with the specific needs and preferences of water management professionals at Norrvatten and Stockholm Vatten och Avfall. Through the application of MCDA, a robust and defensible decision can be reached, which is grounded in a comprehensive analysis of all relevant factors.

With the aim of offering an overall ranking of possibilities, from the most favoured to the least liked option, MCDA is both a method and a collection of tools. Keeney and Raiffa (1976) provided the first comprehensive explanation of MCDA in 1976; their work is still relevant today (Dodgson et al; 2009). Multicriteria decision analysis (MCDA) is used to assess different alternatives. As part of MCDA, the assessment criteria are ranked and weighted. An evaluation of three oil spill models (Seatrack, DHI, and IVL), was conducted using various predefined criteria. These criteria, including user friendliness, support, possibility to evaluate different scenarios, possibility to evaluate different kind of spills, cost, accessibility, model performance, computational time, and complexity of the model, were weighted based on their relative importance. Weights were assigned to each criterion to reflect their relative importance in the decision-making process. The assigned weights (3 different methods) are shown in table 3. When assigning weights in MCDA, it is essential to consider the relative significance of each criterion to the objectives of the analysis. A weight of 0.1, for example, indicates that the criterion contributes 10% to the overall decision, while a weight of 0.2 indicates a contribution of 20%.

This process involves creating a detailed table that outlines the requirements, where points are allocated to each criterion element and sub-element based on their significance. These ratings of criterion elements and sub-elements and ranking of criterion elements are determined collaboratively with Helene Ejhed, the Norrvatten specialist, and Frida Ekman from Stockholm Vatten och Avfall. This collaborative effort intended to discover the most significant aspects related to the requirements and preferences of both water producers, while assessing the performance of these models. It also considered the priorities of water producers in general.

Each model is assessed against each criterion element using a rating score from 1 to 3, where 1 indicates the weakest performance and 3 indicates the strongest performance (see Table 2). The rating score from 1 to 3 was chosen because it effectively highlights the most important elements in a simple and clear manner, ensuring that the assessment remains focused on the top three critical aspects. Additionally, the criteria elements are ranked from 1 to 9, with 1 being the strongest and 9 being the weakest (see Table 2). For the criteria sub-elements, each model is rated on a scale from 1 to 5, where 1 represents the weakest performance and 5 represents the strongest. This detailed evaluation captures the performance of each model effectively, as shown in Table 6.

Table 2. Rating scores from 1 to 3 and ranking from 1 to 9 for each criteria element, determined in collaboration with Helene Ejhed, the Norrvatten specialist.

Criteria elements	Rating score	Ranking
User friendliness	3	2
Support	2	6
Possibility to evaluate different kind of spills	2	4
Possibility to evaluate different scenarios	2	5
Cost	2	7
Accessibility	1	9
Performance of the model	3	1
Computational time	3	3
Complexity of the model	1	8

To understand the uncertainty of the MCDA approach, the weight for each criterion was calculated using three different methods as follows, where n is the total number of elements. The decision to use three methods was based on the need for a balanced, robust analysis while avoiding unnecessary complexity.

Method 1:

$$Weight = \frac{2(n+1-Ranking)}{n(n+1)} \tag{10}$$

Method 2:

$$Weight = \frac{Rating\ score}{Total\ rating\ score} \tag{11}$$

Method 3:

$$Weight = \frac{1}{n} \tag{12}$$

Three methods were chosen because this number strikes a balance between ensuring robustness and avoiding excessive complexity. Using only two methods might not provide enough variability to fully understand the impact of different weighting schemes, while using more than three (such as seven) could introduce unnecessary complexity and make the analysis cumbersome without significantly improving the reliability of the results. The first method considers both the ranking and the number of criterion elements. The second method divides the rating score of each element by the total rating scores of all elements, ensuring that the total sum of the weights ideally equals 1. The third method assigns an equal weight to each element by dividing 1 by the number of criterion elements. This process involved several steps:

1. Relevant criteria had identified for evaluating the oil spill models based on the specific needs and preferences of Norrvatten and Stockholm Vatten och Avfall.
2. Experts from both organizations provided their insights on the relative importance of each criterion. This input was crucial in understanding the practical significance of each criterion in real-world scenarios.
3. The criteria were then ranked and rated collaboratively. The rating score from 1 to 3 was chosen to simplify the assessment, focusing on the three most important elements. This approach allowed us to highlight key differences in model performance clearly.
4. Weight Calculation Methods:
    - Method 1: This method considers the ranking and the total number of criteria, providing a balanced perspective.
    - Method 2: This method uses the proportion of the rating score to the total rating scores, ensuring the weights sum to 1, reflecting proportional performance.
    - Method 3: This method assigns equal weight to each criterion, providing a baseline comparison.

The weighted score for each model was calculated by multiplying its scores against each criterion by their corresponding weights and summing up the results using the formula:

Weight for each element:

$$w_i = \frac{\sum_{j=1}^{m} r_{i\ j}}{\sum_{i=1}^{n} \sum_{j=1}^{m} r_{i\ j}} \tag*{13)}$$

Calculate the score for each element:

$$\mathbf{8}_{\boldsymbol{i}} = w_i \times \frac{\sum_{j=1}^{m} r_{i\ j}}{\boldsymbol{m}} \tag*{14)}$$

Total Score:

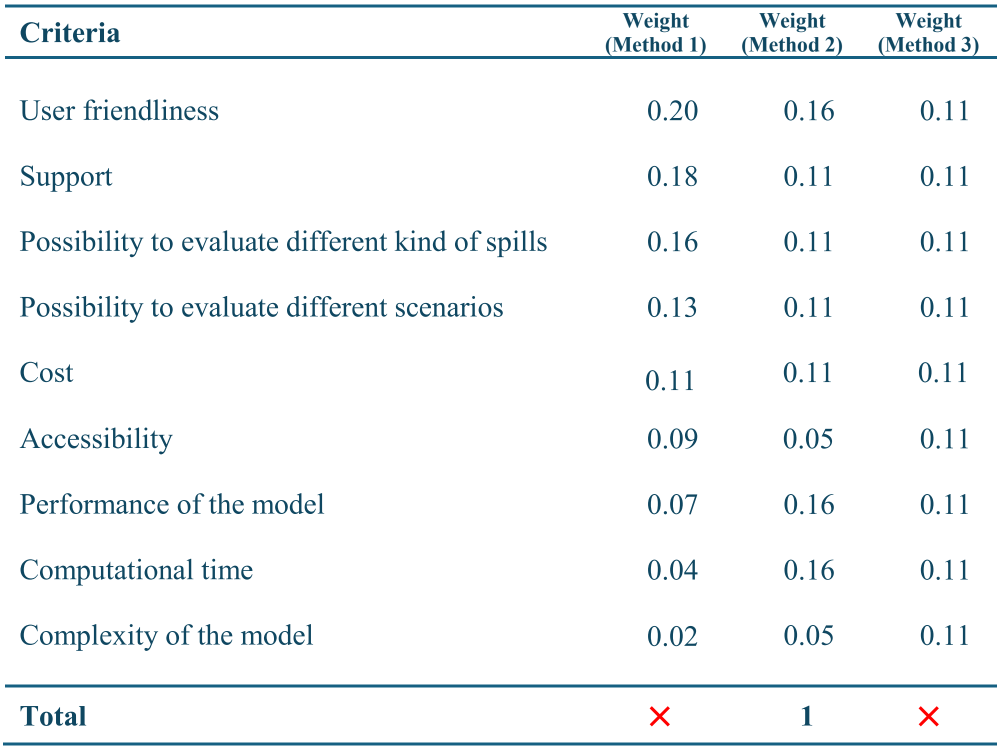
$$\sum_{i=1}^{n} 8_{\ i} \tag*{15)}$$

- $r_{i\ j}$ as the rating score for the i-th element and the j-th sub-element,
- w_i as the weight for the i-th element,
- n as the total number of elements (8 in this case), and
- m as the total number of sub-elements for each element (5 in this case).

to each assessment criterion element and its accompanying subelements, providing insight into the important factors driving Norrvatten's decision-making process.

Using three different methods allows us to capture the uncertainty and variability in the weighting process, ensuring that the final decision is robust and not overly dependent on a single method. This combination of methods helps in understanding how different weighting schemes can affect the overall ranking and ensures the credibility of the MCDA outcomes. The resulting weights are summarized in Table 3.

Table 3. Criteria weights based on their relative importance.



Criteria	Weight (Method 1)	Weight (Method 2)	Weight (Method 3)
User friendliness	0.20	0.16	0.11
Support	0.18	0.11	0.11
Possibility to evaluate different kind of spills	0.16	0.11	0.11
Possibility to evaluate different scenarios	0.13	0.11	0.11
Cost	0.11	0.11	0.11
Accessibility	0.09	0.05	0.11
Performance of the model	0.07	0.16	0.11
Computational time	0.04	0.16	0.11
Complexity of the model	0.02	0.05	0.11
Total	✗	**1**	✗

Uncertainty

To assess the uncertainty in our model comparisons, standard deviation of scores across all sub-elements for each criterion was calculated. This provides a measure of variability in performance across different aspects of each model. The average of these standard deviations for each model was then used as an overall measure of uncertainty.

Scores for sub-elements under the 9 main elements for each of the 3 models (Seatrack, DHI, IVL) were gathered and organized in Excel. The average score of sub-elements for each main element was calculated using the AVERAGE function The resulting average scores were 4.08 for Seatrack, 2.83 for DHI, and 3.51 for IVL. The standard deviation for sub-elements of each main element was calculated using the STDEV.S function. The resulting STDEV.S were 0.79 for Seatrack, 1.20 for DHI, and 1.43 for IVL. A box-and-whisker plot was created to visualize the distribution of average scores for each element and Error bars were added to represent data variability. This shows the median, quartiles, and outliers of average scores, indicating data spread and illustrating uncertainty around average scores, with longer bars indicating greater variability.

Application of One-Way ANOVA for Method Comparison

To assess the differences between the three oil spill evaluation methods (Seatrack, DHI, and IVL), a one-way Analysis of Variance (ANOVA) test was employed. ANOVA is a statistical method used to determine whether there are significant differences between the means of multiple groups. In this case, it was applied to compare the average performance of the three methods across a set of evaluation criteria.

The test works by comparing two types of variances:

- Between-group variance, which measures how much the means of the groups (in this case, the methods) differ from each other.
- Within-group variance, which measures the variability within each group (i.e., the variation in individual scores within each method).

ANOVA calculates an F-statistic, which is the ratio of between-group variance to within-group variance. A higher F-statistic suggests a greater degree of difference between the groups compared to within the groups. The F-statistic is then compared to a critical value from the F-distribution, based on the degrees of freedom of the dataset. This comparison determines whether the observed differences in group means are statistically significant. Based on these assumptions, the ANOVA test is suitable for analysing whether there are significant differences between the three methods across the evaluation criteria. The test results indicate whether the variation in scores can be attributed to differences in the methods or if it is due to random chance.

Result

Visual Comparison of Oil Spill Modeling Outputs

Although the three oil spill models (Seatrack, DHI, and IVL) produce distinct results, visual representations of their outputs have been incorporated into this research to enhance understanding of the outcomes. These visualizations facilitate the comparison of predictions across different models by illustrating both similarities and differences in their outputs. For the Seatrack and DHI models, geographical distribution is represented through maps showing the predicted spread of oil over time and space within Lake Mälaren. These maps provide insights into the models' projections of oil movement, affected areas, and potential impact zones. In contrast, the IVL model presents its results as graphs of oil concentration versus distance from the spill point, which, while not geographically explicit, offer valuable information about the extent of oil dispersion. Temporal aspects of the spill are represented in time-series graphs for all models, showing how oil volume, concentration, or distribution changes over the duration of the simulated spill event. These graphs allow for comparison of the models' predictions regarding the evolution of the spill over time.

While these visual representations significantly aid in understanding each model's predictions, direct comparison remains challenging due to the heterogeneous nature of the outputs. Each model emphasizes different aspects of the spill (e.g., surface spread, concentration at depth, or distance-based dispersion), reflecting their distinct approaches to oil spill modeling. Table 4 complements these visualizations by providing key variables for each model simulation, including the model's name, scenario details, coordinates (where applicable), simulation timeframes, duration, depth considerations, and oil properties. This tabular summary allows for a structured comparison of the simulation setups across models, providing context for interpreting the visual outputs.

Table 4. Keys variables for each model simulation

Simulation	Model	Start date	End Date	Scenario	Coordinate	Duration (h)	Depth (m)	Volume (m³)	Oil	Result
1.a	Seatrack	06.02.2024	06.02.2024	C	2	5	17	10 000	medium	✓
1.b	DHI								Oil	×
1.c	IVL	×	×	×	×	×			**Octane 98**	✓
2.a	Seatrack	15.02.2024	17.02.2024	C	3	1	0	1000	Jet fuel	✓
2.b	DHI								Oil	×
2.c	IVL	×	×	×	×	×			HVO	✓
3.a	Seatrack	24.03.2024	26.03.2024	C	2	2	0	1000	Jet fuel	✓
3.b	DHI								Oil	✓
3.c	IVL	×	×	×	×	×			HVO	✓
3.d	DHI	01.05.2024	06.05.2024	C	2	2	0	Concentration =1000 µg/l	Tracer	✓
4.a	Seatrack	26.03.2024	28.03.2024	A	3	3	0	100	Heavy	✓
4.b	DHI								Oil	✓
4.c	IVL	×	×	×	×	×			Diesel	✓
5.a	Seatrack	04.04.2024	12hours	A	3	3	0	100	Medium	✓
5.b	DHI								Oil	✓
5.c	IVL	×	×	×	×	×			**Octane 98**	✓
6.a	Seatrack	24.04.2024	26.04.2024	B	1	3	1	500	Bunker C	✓
6.b	DHI								Oil	✓
6.c	IVL	×	×	×	×	×			Diesel	✓

The figure 9 represent the graphs which are different from the graphical outputs generated by the models themselves. Instead, they are created by excel utilizing the data supplied by the models. These personalized visualizations provide a customized viewpoint on the model's results, offering improved clarity and assisting in comparison analysis.

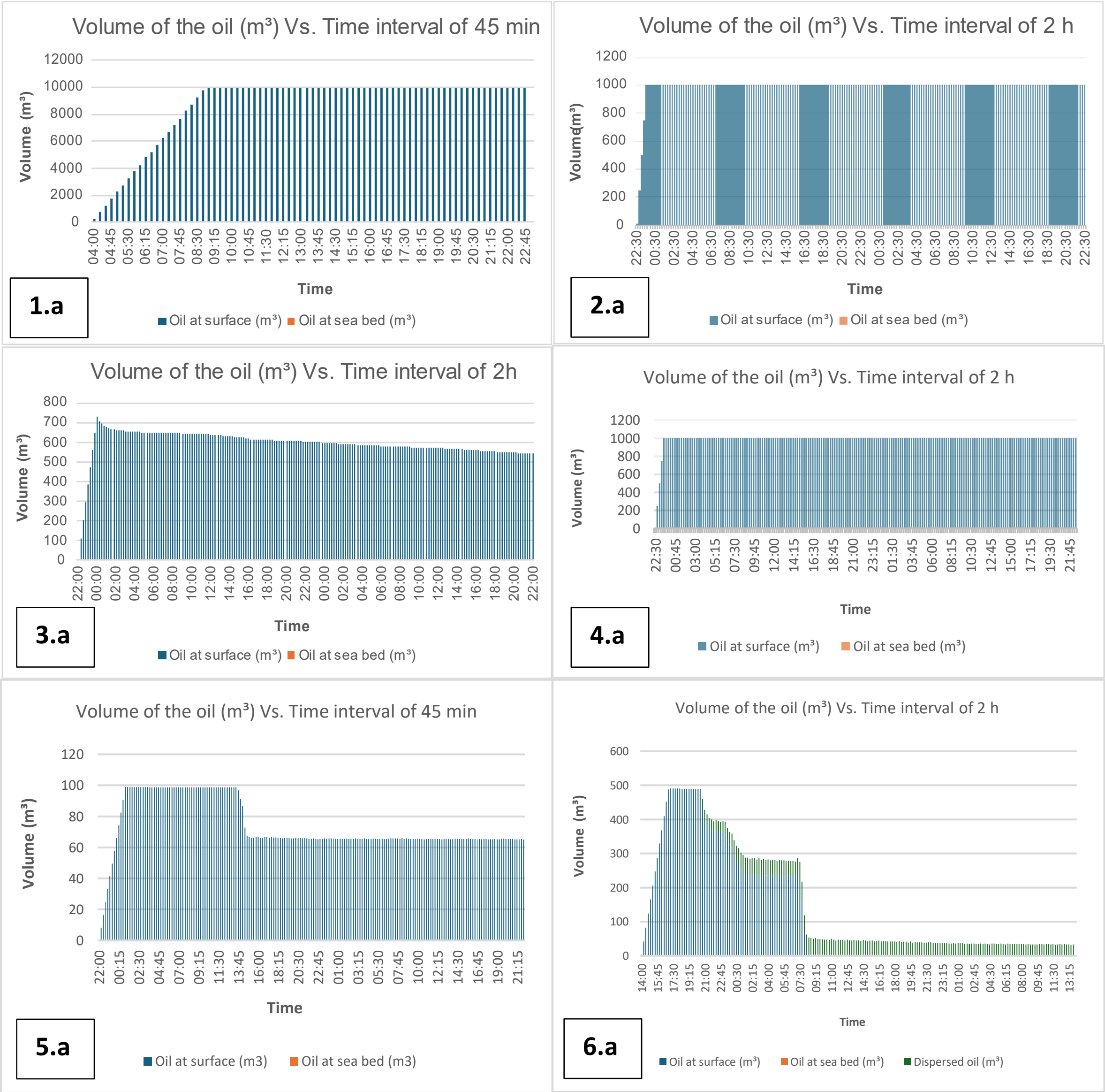


Figure 9. Simulation results of oil volume over time using the Seatrack model for six different scenarios. Each graph presents the volume of oil at the seabed and at the surface, under varying conditions. The scenarios highlight in table 4.

Figure 10 represent the results of oil spill modeling simulations conducted at different times using the Seatrack model. Each image represents a unique scenario of oil spreading within the lake, offering valuable insights into the dynamic nature of oil dispersion and its environmental implications in aquatic ecosystems.

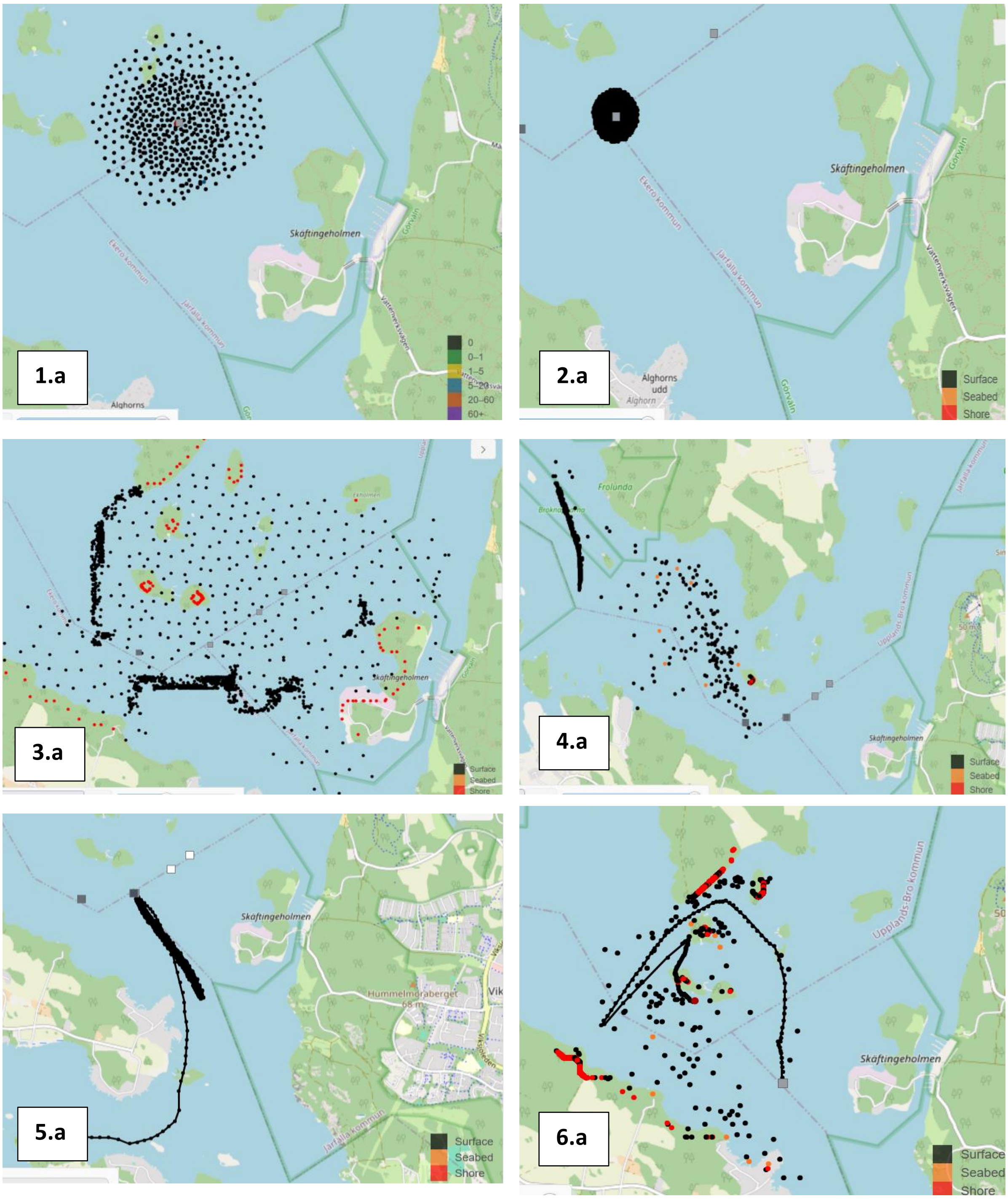


Figure 10. Visualizations of oil plume spreading using the Seatrack model for the six different simulation scenarios described in table 4. Each visualization depicts the spatial distribution and movement of the oil plume over time.

Figure 11 represent graph outputs generated by the DHI models and figure 12 shows the results of oil spill modeling simulations conducted at different times using the DHI model. Each image represents a unique scenario of oil spreading within the lake.

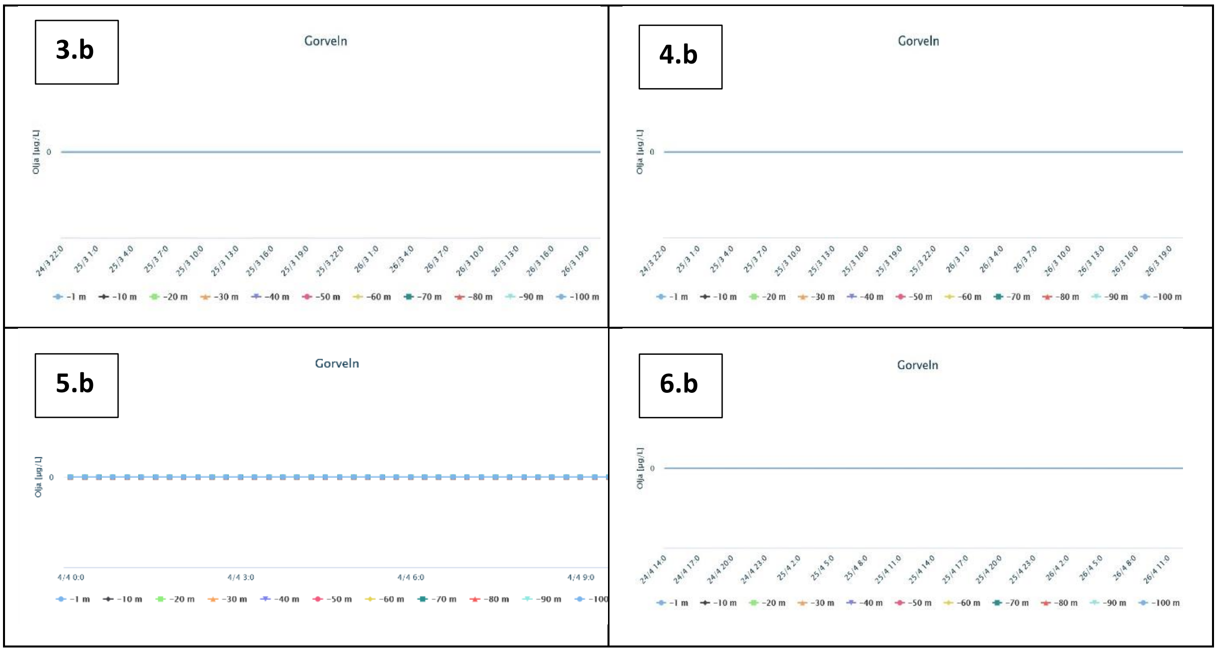


Figure 11. Simulation results of oil concentration over time using the DHI model for 4 different scenarios. Each graph presents the concentration of oil at the seabed and at the surface, under varying conditions. The scenarios highlight in table 4.

Figure 12. Visualizations of oil plume spreading using the DHI model for the six different simulation scenarios described in Table 4. Each visualization depicts the spatial distribution and movement of the oil plume over time. The water plant point has been removed from the visualizations for security reasons.

The DHI model offers versatile capabilities, allowing for comprehensive testing with tracers, oil, and bacteria. To explore these capabilities, a test simulation (3.d) was conducted (table 4), and the results are presented in the figure 13. This simulation provides valuable insights into the behaviour and interactions of tracers within the aquatic environment, offering a deeper understanding of environmental processes and potential mitigation strategies.

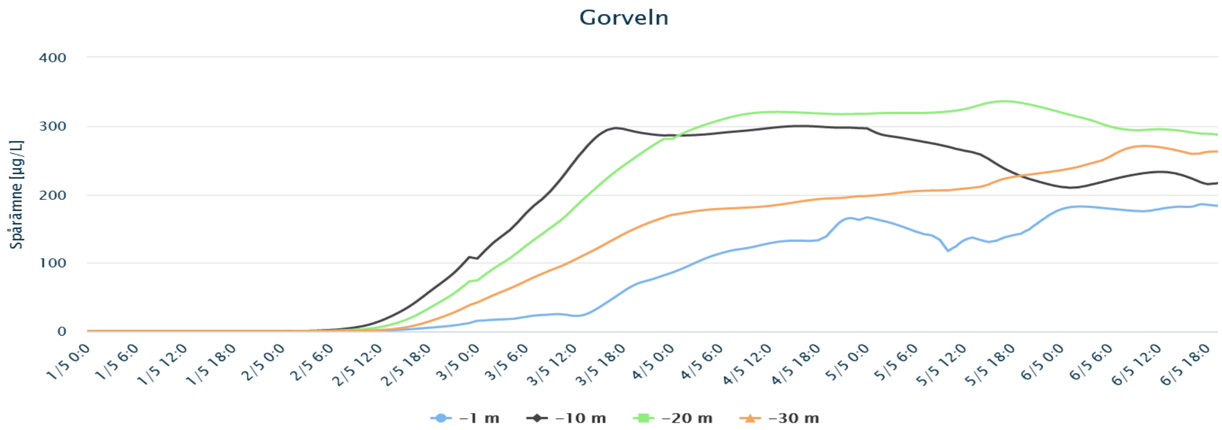


Figure 13. DHI tracer modeling output for simulation 3.d from table 4. This graph illustrates the concentration of oil over time. The simulation highlights the temporal changes in oil.

Figure 14 represent the outputs generated by the IVL models for different scenarios (see table 4).

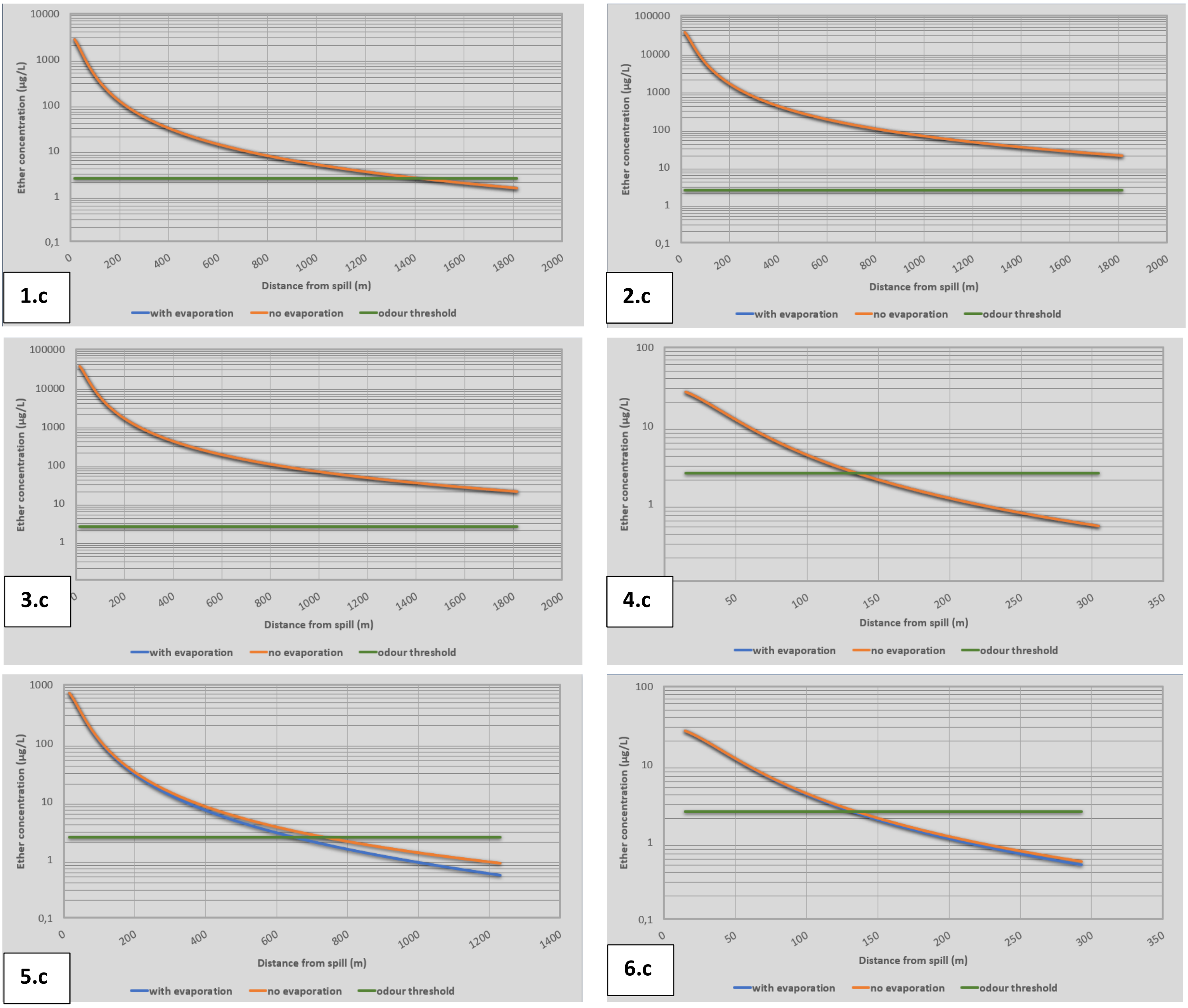


Figure 14. IVL model simulation results showing the concentration of oil with and without evaporation versus distance from the oil spill for six different scenarios described in table 4.

Qualitative analysis

The qualitative analysis of the DHI, Seatrack, and IVL models involves evaluating their performance based on various criteria. These criteria include model selection flexibility, coordinate and timeframe customization, simulation options, oil type selection, parameter customization, output representation, data output options, simulation time, flexibility in analysis, and the presence of limitations and errors. Each model's advantages and disadvantages are assessed to provide a comprehensive understanding of their functionality and limitations. This evaluation aims to highlight the strengths and weaknesses of each model in order to determine their suitability for predicting oil spill scenarios and aiding decision-making processes. The following sections detail the specific advantages and disadvantages of each model based on the aforementioned criteria.

DHI

The simulation (Scenario A) for both the DHI and sea track models commenced with a designated start date of 04.04.2024 at 00:00 and concluded on 04.04.2024 at 12:00, spanning a duration of 3 hours in coordinate 3. For the evaluation, a volume of 100 m³ was chosen. The resulting figure 15 depicting the model outputs are presented below:

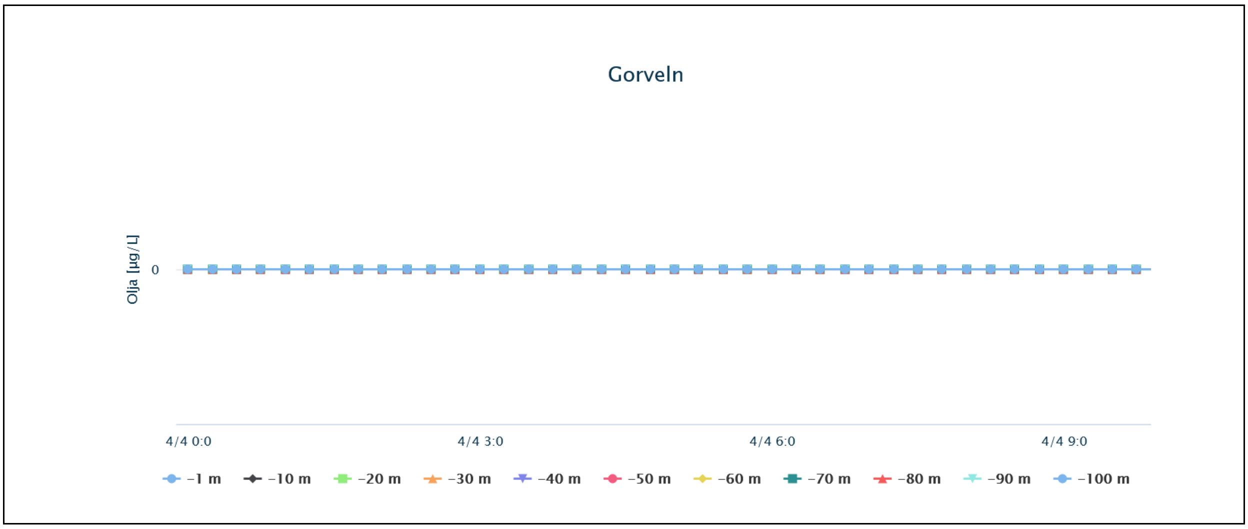


Figure 15. Output simulation of DHI model. Oil concentration at various depths in Görveln

The oil concentration, expressed in micrograms per liter (µg/L), is displayed against time intervals of every 3 hours on the graph in the figure 15. The data, using Görväln as a reference point, shows differences in oil content at various depths below the surface. From -1 meters to -100 meters, every colour on the graph (-1m = blue, -10m = black, -20m = green and so on) denotes a distinct depth inside the water column. Interestingly, no identifiable oil concentration at any depths below the surface water has been found and as shown in figure there is only one graph which is blue, and it belongs to 1 meter below surface water.

After conducting simulations using the DHI model, it is essential to evaluate its performance based on various criteria. Before delving into the advantages and disadvantages of the model, it is crucial to acknowledge the context and purpose of the analysis. The simulations aimed to assess the effectiveness of the DHI model in predicting oil spill scenarios, considering factors such as model flexibility, user friendliness, and accuracy in depicting pollutant spread. The following sections present the advantages and disadvantages of the DHI model, providing detailed insights into its capabilities and any potential shortcomings.

Advantages of DHI model

- Flexible Model Selection: Users can easily select the desired model.
- Convenient Coordinate Selection: Coordinates can be chosen either manually or by selecting directly on the map, enhancing user convenience and accuracy.
- Customizable Timeframe: Users have the freedom to select start and end dates within a specific timeframe, such as between 4 days before the current day and one day after the current day, facilitating tailored simulations.
- Multiple Spill Options: The model accommodates various spill types, including oil, bacteria, and tracer, providing flexibility in analysis.
- Parameter Customization: Users can input parameters such as waste depth, volume, and flow rate, allowing for precise simulation configurations.
- Enhanced Data Representation: The model generates visual representations of pollutant spread, aiding in comprehensive analysis and decision-making.
- Graphical Output with Download Option: Users receive graphical outputs depicting oil concentration and simulated pollutant depth, with the added convenience of data download capabilities.
- Time Series Marker Addition: The model offers the capability to add a new marker for time series data, enhancing the depth of analysis.

Disadvantages of DHI model

- Long Simulation Times: After running the model, users often experience significant delays, sometimes exceeding 14 hours, without obtaining results. Furthermore, the inability to remove simulations during calculations exacerbates this issue.
- Project Limitation Error: The model may encounter a "Maximum number of projects reached 400" error, necessitating the removal of saved scenarios, which is not an optimal solution.
- Limited Oil Variety: The model lacks options for selecting specific types of oil, such as three main oil classes (light, medium, and heavy) or specific oils from a list, which restricts the range of spill scenarios that can be accurately simulated.

- Error Prone: The model frequently encounters errors where it fails to complete the calculation and simulation, which are not conducive to obtaining quick answers during time-sensitive situations.

Seatrack

Simulations were run using the same parameters as were used for the DHI model in order to evaluate the Sea Track model. During the course of the simulations (Scenario A), which began at 00:00 on April 04, 2024, and ended at 12:00, a total of three hours passed, and a volume of 100 m³ was chosen in coordinate 3. The results of these simulations are shown in Figure 16.

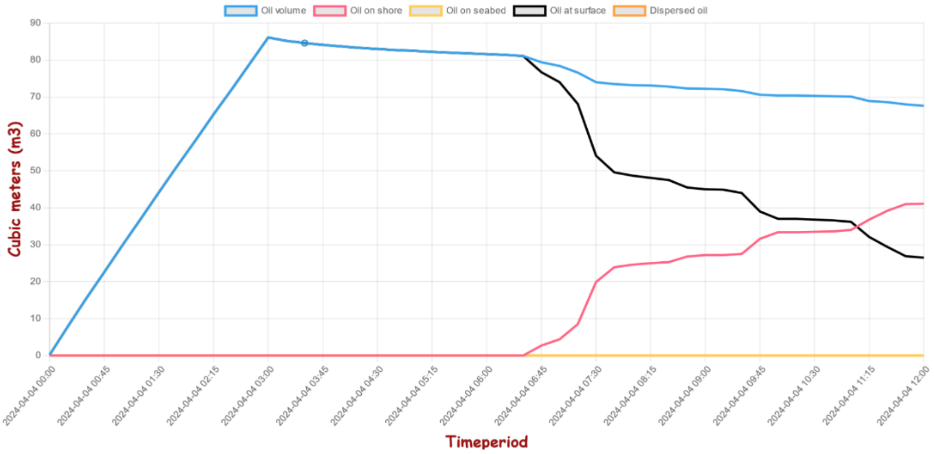


Figure 16. Output simulation of Seatrack model. Oil spill simulation results over a 12-hour period. The graph shows the distribution of oil volume (m³) over time, including total oil volume, oil at surface, oil on shore, oil on seabed, and dispersed oil.

Figure 16 shows how the volume of oil changed over time in the simulation, measured in cubic meters (m³). The graph reveals that the oil volume increased from zero to its highest point after 3 hours (blue line). However, the model always kept the oil volume at zero below the water surface, and it never reached the intake of Norrvatten or the seabed (orange line). This indicates a limitation of the model in accurately representing oil dispersion. Black line shows the amount of oil floating on the water's surface. It remains high for a while before dropping significantly. Pink line indicates oil that has washed up on land. It starts to increase later in the timeline as oil reaches the shore. Additionally, the model consistently showed zero oil volume at various depths, suggesting no detectable oil concentration. The following advantages, and disadvantages of the Seatrack model are presented to provide insights into its functionality and limitations.

<u>Advantages of Seatrack model</u>

- Fast Simulating and Real-Time Progress Tracking: Simulations are completed rapidly (within a maximum of 5 minutes), and users can track progress in real-time, enhancing efficiency and user experience.

- Versatile Simulation Options: Users have three simulation options: oil observation, continuous oil, and floating object tracking. Notably, Norrvatten frequently employs the oil observation feature to monitor oil spills along Lake Mälaren, crucial for identifying and addressing potential sources of contamination.
- Flexible Model Selection: Users can select the desired model, providing flexibility in simulation choices.
- Convenient Coordinate Selection: Coordinates can be chosen manually using two different systems, DDM and DD, or by clicking directly on the map, enhancing user accuracy and convenience.
- Distance Measurement: The model allows users to measure the distance between two points on the map, aiding in spatial analysis and planning.
- Extended Observation Period: Users can specify observation dates and times for up to 20 days before the current day and 7 days after, enabling comprehensive data collection and analysis.
- Forward/Backward Simulation: Users can choose between forward and backward simulation modes, facilitating predictive and retrospective analysis.
- Customizable Simulation Period: Users can select the start and end dates of simulation within a period of 10 days before the current day and 4 days after, tailoring analyses to specific timeframes.
- Diverse Oil Class Options: Users can choose from three main oil classes (light, medium, and heavy) and select specific oils from a list of 11 options, each with fixed densities ranging from 700 kg/m^3 to 1000 kg/m^3, enhancing simulation accuracy and realism.
- Parameter Customization: Users can input outlet depth, volume, and duration, allowing for precise simulation configurations.
- Calculation Mode Options: Users can select from three calculation modes (fast, normal, and detailed), providing flexibility based on computational requirements and accuracy needs.
- Time Series Selection: Users can choose between single or multiple selections for time series data, facilitating diverse analytical approaches.
- Visual Representation of Results: The model provides visual representations of oil spread, aiding in interpretation and decision-making.
- Comprehensive Data Output: Users receive a variety of graphs and can export simulation data to file, including date, time, latitude, longitude, current speed, direction, wind speed, wind direction, volume, viscosity, density, evaporated oil percentage, oil distribution, dispersed oil volume, oil at seabed and shore percentage and volume, and water content percentage.

Disadvantages of Seatrack model

- Limited Graphical Output: The Sea Track model's output offers various graphs, including an Oil Percentage graph. However, this graph only provides the total percentage of oil on the surface without specifying its exact location. Norrvatten's requirement to ascertain if the oil reaches the intake, and if so, the percentage, remains unmet due to this limitation in the model's output.
- Lack of Spill Options: Users can only select oil as a spill option; the model does not include tracer or bacteria simulations. This limitation restricts the versatility of the model, particularly in scenarios where the analysis of tracer or bacteria movement is crucial for comprehensive spill management and mitigation strategies.

IVL

The IVL model was evaluated using the same input parameters as the Seatrack and DHI models. The spill simulation (Scenario A) used MK1 diesel as the spill type, with a predefined volume of 100 m^3. As the IVL model requires water intake depth as an input, this parameter was set after consultation with Helene Ejhed, a specialist at Norrvatten, who recommended using a depth of 8 meters (m) and the water temperature was kept at 2 degrees Celsius (∘C). Notably, the water velocity directed towards the intake point was set at 1 (Cm/s). However, it's important to note that the IVL model lacks options for selecting coordinates and duration time, and it doesn't provide a time period for simulation. To illustrate the temperature value, data was sourced from the Swedish environmental monitoring database, Miljödata-MVM (miljodata.slu.se, 2024). The temperature data spans from February to September 2023 and originates from various monitoring stations situated within Lake Mälaren. Specifically, measurements were taken at a depth of 0.5 meters from the lake's surface. Due to the unavailability of 2024 data, the temperature data for 2023 was utilized to facilitate the execution of the IVL model. Based on this data and analysis, a water temperature of 2 degrees Celsius was assumed for the model inputs. The outcome of the simulation is shown in Figure 17.

Advantages and disadvantages of IVL model

The IVL model presents a simple and straightforward approach to simulating lake conditions, which can be advantageous in certain situations. Its simplicity makes it effective for modeling completely mixed lakes and conducting worst-case scenario simulations. However, this model has several significant limitations that should be carefully considered. A major drawback is its inability to handle thermocline effects, which are thermal stratifications that can profoundly impact mixing and distribution within a water body. Neglecting these effects can lead to inaccurate representations of real-world conditions.

Moreover, the IVL model has a limited capacity for simulating dispersed compounds, failing to capture the complex dynamics involved in the spread of contaminants. There is a potential for underestimating the extent of mixing, which could result in an inaccurate assessment of the reach of contamination. While the model's simplicity can be beneficial in specific contexts, it comes at the cost of overlooking critical factors that govern mixing and dispersion processes in natural water systems. Careful consideration of these limitations is crucial when determining the suitability of the IVL model for a given application.

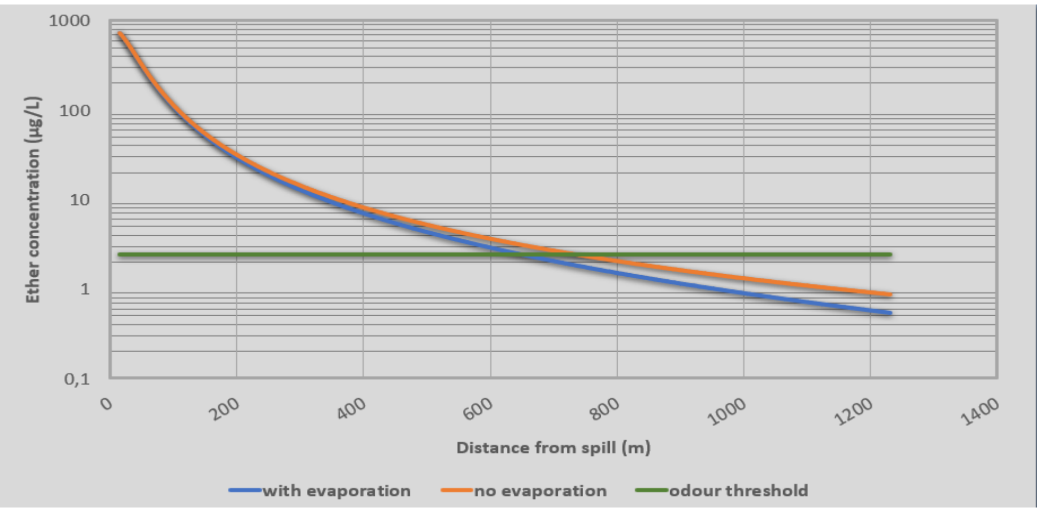


Figure 17. Ether concentration as a function of distance from oil spill point. The graph compares scenarios with and without evaporation and includes the odor threshold level. The x-axis shows distance from the spill in meters, while the y-axis displays ether concentration on a logarithmic scale in µg/L.

The graph demonstrates the oil concentration in micrograms per liter (µg/L) vs distance from the spill location in meters (m). Furthermore, the model output contains the odour threshold, which indicates the concentration level at which the odour is detected. Furthermore, the graph shows the time it takes from the actual spill till the oil concentration falls below the odour threshold value. The effect of evaporation becomes more pronounced at greater distances, where the "with evaporation" scenario shows slightly lower concentrations. A horizontal green line represents the odor threshold for ether, indicating the concentration at which it becomes detectable by smell. Both scenarios intersect this threshold around 600-700 meters from the spill point. The logarithmic scale on the y-axis helps visualize the significant concentration changes, from high levels near the spill point to much lower levels at greater distances.

This graph is valuable for understanding ether dispersion in water following an oil spill, the impact of evaporation, and the distances at which ether might be detectable by odor. This image helps to comprehend the regional distribution of oil concentrations and the time dynamics of odour dispersion after an oil spill.

Comparison

The comparison table 5 provides a detailed assessment of the DHI, Seatrack, and IVL models, focusing on their respective advantages and disadvantages. It is important to note that the criteria for qualitative analysis differ from those in multicriteria analysis, which were chosen by Norrvatten. For qualitative analysis, the criteria are more based on the functionality, attributes, and features of the model. By reviewing this comparison, it becomes clear what the specific strengths and weaknesses of each model are in terms of model selection, coordinate selection, timeframe customization, simulation options, oil type selection, parameter customization, output representation, data output options, simulation time, flexibility in analysis, and limitations/errors. This detailed evaluation aids in making informed decisions about which model is best suited for specific needs in predicting and managing oil spill scenarios.

Table 5. Comparison table for qualitative analysis of DHI, Seatrack and IVL models.

Criteria	DHI Model	Sea Track Model	IVL Model
Model Selection	- Users can select the desired model.	- Users can select the desired model.	- Users can select the desired model.
Coordinate Selection	- Coordinates can be chosen manually or by clicking on the map.	- Coordinates can be chosen manually using two different systems (DDM and DD) or by clicking directly on the map.	✗
Timeframe Customization	- Users can select start and end dates within a specific timeframe.	- Observation dates and times can be specified for up to 20 days before the current day and 7 days after, enabling extended data collection and analysis.	✗
Simulation Options	- Offers various spill types including oil, bacteria, and tracer.	- Provides three simulation options: oil observation, continuous oil, and floating object tracking.	- Offers only oil spill
Oil Type Selection	- Limited oil variety, lacks options for selecting specific types of oil.	- Offers a range of oil classes (light, medium, heavy) and specific oil options with fixed densities, enhancing simulation accuracy.	- Offers various spill types including Ethanol 85, Petrol95 and 98, MK1 Diesel and HVO
Parameter Customization	- Users can input parameters such as waste depth, volume, and flow rate.	- Allows input of outlet depth, volume, and duration, enabling precise simulation configurations.	Users can input parameters such as waste depth, volume, velocity toward intake and water temperature.
Output Representation	- Provides visual representations of pollutant spread.	- Offers visual representations of oil spread and various graphs, facilitating interpretation and decision-making.	- Offers a graph which represent concentration of oil VS distance from spill
Data Output Options	- Generates graphs and allows data download.	- Provides a variety of graphs and enables export of simulation data, including date, time, location, and pollutant parameters, for further analysis.	Generates a graph
Simulation Time	- Simulation times can be lengthy, exceeding 14 hours. Without result	- Fast simulating, completing within a maximum of 5 minutes, with real-time progress tracking.	- Fast simulating
Flexibility in Analysis	- Flexible in analysis but may encounter errors.	- Offers versatile analysis options.	✗
Limitations and Errors	- Encounters errors and limitations in user experience.	- Limited graphical output may not fully meet user requirements.	Limited graphical output may not fully meet user requirements
Spill Options	- Provides various spill options but lacks versatility in oil type selection.	- Offers three simulation options but restricts spill type to oil only.	- Offers spill type to oil only

Multi Criteria Decision Analysis (MCDA)

Score Calculation

Each model undergoes a comprehensive evaluation against every criterion element, utilizing a rating score from 1 to 3 (as shown in Table 2), and against each sub-element, employing a scale from 1 to 5 (as illustrated in Table 6). The rating scales were chosen after consulting with Helene Ejhed, a specialist at Norrvatten, and Frida Ekman at Stockholm Vatten och Avfall. The assigned scores reflect the performance of each model against the selected criteria. For criterion elements, a score of 1 indicates low performance, 2 represents medium performance, and 3 signifies high performance. Similarly, for criterion sub-elements, a score of 1 indicates the lowest performance, while a score of 5 represents the highest performance. Figure 18 shows the average scores for each criterion elements that Seatrack, DHI and IVL model have received.

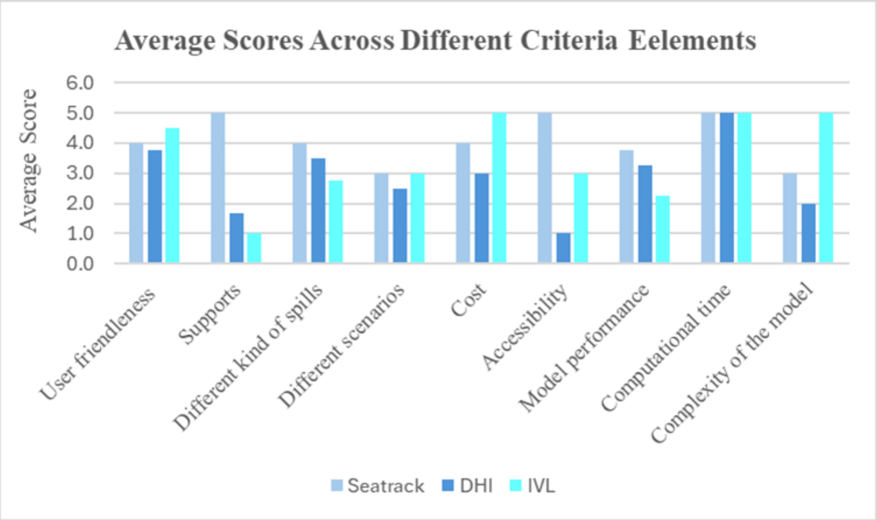


Figure 18. Average scores across different criteria elements for Seatrack, DHI and IVL model.

Table 6 compares the performance of each model based on Method 1 (ranking and number of criterion elements), Method 2 (ratio of individual rating score to total rating score), and Method 3 (equal weighting). This table highlights the impact of different weighting strategies on the overall assessment of each model. Based on the weighted scores, Seatrack received the highest score, indicating its overall suitability for the specified criteria. Therefore, Seatrack is the preferred option for oil spill modelling in this analysis as shown in table 6.

Table 6. Multi criteria decision analysis (MCDA) of Seatrack, DHI and IVL model.

Ranking	Rating score	Method 1	Method 2	Method 3	Evaluation criteria elements	Evaluation criteria subelements	Seatrack		DHI		IVL	
		Weight (using rank sum method)	Weight (using rating score over total score)	Weight (using equal probabilities 1/n=1/9)			Score 1-5	Comment	Score 1-5	Comment	Score 1-5	Comment
2	3	0.18	0.16	0.11	**User friendleness**	Easy to implement	5	Provides implementation guide	5	Provides implementation guide	4	Needs input data (Water temp & current)
						Easy to get the result	3	Gives ranges for oil concentration	4	Gives exact oil concentation on spot	5	Gives exact oil concentation after reaching odor threshold
						Result presentation	3	Extensive	5	developed for norrvatten and SVOA	4	Fit for purpose
						Error / Bugs	5	No errors	1	Unsuccesful computing and simulation saving	5	No errors
						Average score	4.0		3.8		4.5	
6	2	0.09	0.11	0.11	**Supports**	During working hours	5	Offer technical support	3	Offer technical support with extra charge	1	No technical support
						Weekend	5	Offer technical support	1	No technical support	1	No technical support
						Red days	5	Offer technical support	1	No technical support	1	No technical support
						Average score	5.0		1.7		1.0	
4	2	0.13	0.11	0.11	**Possibility to Evaluate different kind of spills**	Tracer and Bacteria	1	Can not be simulated	5	Can be simulated	1	Can not be simulted
						Oil obsevation	5	Can be simulated	1	Can not be simulated	1	Can not be simulted
						Oil	5	3 categories: light, meduim, heavy	5	Can be simulated with no categories	5	Simulating ether (diesel, octane 98, octane 95,…etc)
						Different kind of oils	5	Specific oils: jet fuel, diesel, …etc	3	Only diesel	4	Several oil types
						Average score	4.0		3.5		2.8	
5	2	0.11	0.11	0.11	**Possibility to Evaluate different scenarios**	Prognosis	5	Possible	4	Possible	1	Not possible
						Worst case	1	Not possible	1	Not possible	5	Possible
						Average score	3.0		2.5		3.0	
7	2	0.07	0.11	0.11	**Cost**	The cost of model tool	4	Better	3	The most expensive	5	Best
						Average score	4.0		3.0		5.0	
9	1	0.02	0.05	0.11	**Accessibility**	Coast guard accessibility and usage of the model	5	Seatrack web is used for the entire Baltic and now is set up for Mälaren.	1	Not accesable	3	As the IVL model is an offline excel file, coast guard has access .
						Access to model tool (student, researchers..)	5	Accessable	1	Not accesable	3	Accessable
						Average score	5.0		1.0		3.0	
1	3	0.20	0.16	0.11	**Performance of the model**	Close to reality	4	Responds well to the meteorological driving	4	Responds well to the meteorological driving	2	Offline (no meteorological drving updates)
						Using the temperature measurements	5	Yes	5	Yes	5	Yes
						Possibility to access data from owner	5	SMHI's data on water levels from Mälaren and temperature data via Norrvatten.	3	Partially accessable	1	Not accessable
						PH response	1	No pH response	1	No pH response	1	No pH response
						Average score	3.8		3.3		2.3	
3	3	0.16	0.16	0.11	**Computational time**	Time to obtain the result	5	Around 5 minutes	5	Around 10 minutes	5	Around 1 minute
						Average score	5.0		5.0		5.0	
8	1	0.04	0.05	0.11	**complexity of the model**	Estimation of uncertainty	3	Good	2	Fair	5	Very good
						Average score	3.0		2.0		5.0	
Total Score	19	**Method 1**					**4.06**		**3.30**		**3.44**	
		Method 2					**4.12**		**3.18**		**3.51**	
		Method 3					**4.08**		**2.85**		**3.50**	

Uncertainty

In this study, the performance of three different methods (Seatrack, DHI, and IVL) across various evaluation criteria has compared. To determine whether there are statistically significant differences between the methods, an Analysis of Variance (ANOVA) test has performed.

The data collected included the average scores of the three methods across nine different criteria as shown in table 6. The first step was to calculate the mean score for each method and the overall mean of all scores. Seatrack mean was 4.08, DHI mean was 3.08, IVL mean was 3.50 and overall mean was 3.56. Next, the between-group variability (SSB), and the within-group variability (SSW) was calculated Where k is the number of per group (in this case k=3), and n is the total number of observations (scores) across all groups. Since each method has 9 scores, and there are 3 groups, n=9×3=27.

Degrees of Freedom (DF)

- Between-Groups DF: degrees of freedom between groups (k-1) is 3−1= 2.
- Within-Groups DF: degrees of freedom within groups (n-k) is 27−3= 24.

$$SSB= n\times\sum (Group\ Mean-Overall\ Mean)2= 4.6089 \tag{16}$$

$$SSW=\sum (Individual\ Score-Group\ Mean)2= 30.271 \tag{17}$$

The F-statistic is calculated using the ratio of the Mean Square Between Groups (MSB) to the Mean Square Within Groups (MSW):

$$F = \frac{MSB}{MSW} = \frac{SSB/(k-1)}{SSW(n-k)} = \frac{4.6089/2}{30.271/24} = 1.827 \tag{18}$$

Where:

MSB (Mean Square Between) is the sum of squares between the groups (SSB) divided by its degrees of freedom:

$$MSB = \frac{SSB}{Between - Groups\ DF} = \frac{4.6089}{2} = 2.30445 \tag{19}$$

MSW (Mean Square Within) is the sum of squares within the groups (SSW) divided by its degrees of freedom:

$$MSW = \frac{SSW}{Within - Groups\ DF} = \frac{30.271}{24} = 1.2613 \tag{20}$$

Using an F-distribution table or software (like statistical tools in Python, R, or online calculators), the p-value corresponding to F=1.827 with degrees of freedom 2 and 24 can be calculated. The calculated p-value is approximately 0.180, which suggests there is no statistically significant difference between the group means at the 0.05 level. Since the p-value is greater than 0.05, we conclude that there is no statistically significant difference between the group means at the 95% confidence level. Consequently, there was no need to proceed with Tukey's HSD test for pairwise comparisons, as the ANOVA did not indicate significant differences among the means.

The plot (Figure 19) illustrates the distribution of average scores and the associated uncertainty, highlighting areas where assumptions significantly influence the outcomes. This approach helps in understanding the robustness of the MCDA results.

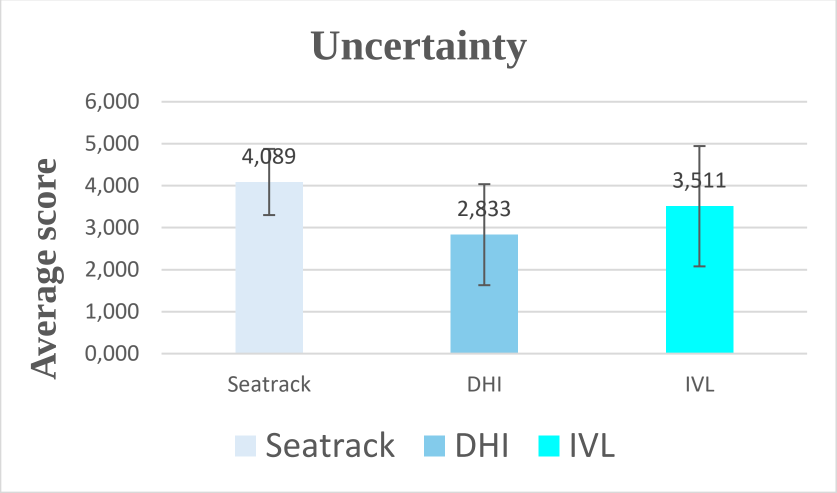


Figure 19. Distribution of average scores and the associated uncertainty for Seatrack, DHI and IVL model.

The Seatrack model achieved the highest overall score of 4.08 (± 0.79), followed by the IVL model with a score of 3.51 (± 1.43), and the DHI model with a score of 2.83 (± 1.20), where the values in parentheses represent the uncertainty in each score. This report clearly shows the ranking of the models based on their overall scores while also indicating the level of uncertainty associated with each score. The higher uncertainty values for the IVL and DHI models suggest that their performance was more variable across different criteria compared to the Seatrack model.

the practical significance of the differences between models can be interpreted. The Seatrack model outperformed the others by 0.57 points compared to the IVL model and 1.25 points compared to the DHI model, which represents a substantial improvement in several key areas. Specifically, Seatrack showed superior performance in user friendliness, simulation options, oil type selection, and output representation. This difference, when considered alongside the uncertainty in our scores, suggests that Seatrack offers meaningful advantages over the other models for our specific use case of oil spill modeling in Lake Mälaren, particularly in terms of operational efficiency and comprehensive analysis capabilities.

Discussion

This research aimed to compare three distinct models (Seatrack, DHI, and IVL) for simulating oil spill scenarios in Lake Mälaren. The study focus on cold weather and ice conditions aligns with the work of Afenyo et al. (2016), who emphasized the importance of considering these factors in oil spill modeling, particularly in northern regions. The models' predictions have direct implications for the management of oil spills in lake Mälaren, particularly for Norrvatten's water intake. Understanding these models' strengths and weaknesses helps in choosing the most appropriate tool for different spill scenarios, ensuring the protection of water resources.

The results demonstrated that the Seatrack model excelled in real-time oil spill response scenarios due to its ability to provide quick simulations and visual maps. This makes it ideal for immediate decision-making during emergency situations. Its ability to respond appropriately to meteorological inputs aligns with the findings of Cucco et al. (2012), who stressed the importance of integrating real-time weather data in oil spill forecasting. The model's fast simulation times (within 5 minutes) and real-time progress tracking enhance its operational efficiency, a critical factor in emergency response scenarios. However, it shows decreased reliability with depth due to simplified inflow and outflow representations. This issue reflects a common challenge in hydrodynamic modeling, as noted by Wang et al. (2008) in their study of oil spill transport in seas. The model's strength in surface oil spread forecasting, particularly its responsiveness to wind-driven surface currents, corroborates the work of Reed et al. (1999), who emphasized the critical role of wind forcing in determining the trajectory of oil slicks. In contrast, the DHI model, while offering more detailed and comprehensive simulations of both surface and subsurface oil movement, requires more computational time, which limits its applicability in urgent scenarios. The IVL model's focus on specific pollutants such as ethers provided valuable data on chemical contamination, complementing the other two models in terms of long-term environmental assessments. Overall, combining the strengths of these models would lead to a more robust oil spill response strategy, integrating real-time response with long-term environmental impact evaluations.

The Seatrack and DHI models provide geographical maps that show the predicted spread of oil over time and space within Lake Mälaren, highlighting areas affected by the spill and potential impact zones. The IVL model, in contrast, represents its results as graphs showing oil concentration versus distance from the spill point, which offers insights into the extent of oil dispersion but does not provide geographic visualization. Although visualizations significantly aid in understanding model predictions, direct comparison remains challenging due to the heterogeneous nature of outputs. Each model focuses on different aspects (e.g., surface spread vs. concentration at depth), which complicates a straightforward comparison of their efficacy in predicting oil spills. The IVL model, while simple and straightforward, demonstrated effectiveness for modeling completely mixed lakes and worst-case scenarios. This aligns with the principle of parsimony in environmental modeling, as discussed by Jakeman and Hornberger (1993). The model's ability to specify wind speed and direction makes it particularly useful for worst-case computations, a feature does not present in the other models. However, the IVL model's inability to handle thermocline effects and limited capacity for simulating dispersed compounds represent significant limitations. These shortcomings reflect the ongoing challenges in balancing model complexity with practical applicability, a theme explored by Solic and Krstulovic (1992) in their work on environmental modeling. The model's use of a single input temperature works well for completely mixed lakes but may lead to inaccuracies in deeper, stratified water bodies.

Comparing the three models reveals significant discrepancies in their approaches and outputs. The multicriteria decision analysis (MCDA) conducted in this study provides a quantitative basis for model comparison, an approach supported by Nissanka and Yapa (2018) in their review of oil spill modeling techniques. The Seatrack model achieves the highest overall score (4.08 ± 0.79), indicating strong performance in operational efficiency and comprehensive analysis capabilities, particularly in real-time spill response scenarios. The IVL model follows with a score of 3.51 ± 1.43, reflecting moderate performance but with higher uncertainty, suggesting variability in performance across different criteria. The DHI model has the lowest score (2.83 ± 1.20), showing significant operational challenges, including errors and simulation archiving issues, which align with computational limitations noted in hydrodynamic modeling literature.

The DHI model encountered significant operational challenges, including technical errors and issues related to simulation archiving. These challenges are consistent with the findings of Guo and Wang (2009), who reported that the hydrodynamic models often experience computational limitations and errors. In this study, the errors refer to model bugs that affected the successful completion of simulations, while the simulation archiving issues resulted from insufficient storage capacity, requiring the removal of previous simulations to run new ones. Despite attempts by the model's owners to upgrade the system, its performance remained constrained, particularly during the January and February simulations. The term "performance" here refers to the model's ability to accurately simulate oil spills in real-time, using available environmental and hydrodynamic data to produce reliable results. The continued limitations in computing and archiving highlighted the need for more robust error handling, which includes managing system bugs and ensuring that simulations do not diverge from expected outputs, as emphasized by Li et al. (2016). While the DHI model primarily focuses on showing oil concentrations over time at selected points of interest, this feature—though useful for limited applications—proves insufficient in scenarios requiring comprehensive spatial analysis. In summary, the model's inability to compute, calculate, and finalize simulations efficiently, compounded by storage capacity limitations, severely impacted its effectiveness in providing timely results for oil spill management.

This study demonstrates that models requiring detailed hydrodynamic simulations, such as DHI, are more prone to errors and longer computation times. These findings align with the work of Guo and Wang (2009), who also highlighted the computational limitations of complex hydrodynamic models. However, while Guo and Wang's research focused on broader hydrodynamic models, this study specifically explored models for oil spill simulation in Lake Mälaren. Similarly, the challenges observed with storage capacity and error handling in this study resonate with the conclusions of Hodges et al. (2011), who discussed the computational difficulties in modeling complex aquatic systems. Other studies, like Li et al. (2016), which rely on a single model for oil spill simulation, tend to overlook the advantages of combining different models. In contrast, this study highlights the importance of integrating models to address both immediate response needs and long-term environmental impacts, offering a more comprehensive approach.

Uncertainties and recommendations

Despite the valuable findings, the study encountered several uncertainties and limitations that should be acknowledged. First, the DHI model faced significant operational challenges, including technical errors and storage capacity issues, which limited the ability to run continuous simulations. These challenges were particularly apparent during simulations conducted in January and February, when the model's performance was constrained. Additionally, the models were tested using hypothetical spill scenarios; while these provide useful insights, the lack of real spill data for validation adds uncertainty to the results. Another limitation relates to the spatial resolution of the models, especially Seatrack, which provided less detailed subsurface data compared to DHI. This limitation could impact the accuracy of predictions, particularly in scenarios where detailed vertical oil movement is crucial.

A few studies have attempted to compare different models, but often in different contexts or using different evaluation criteria. Liu et al. (2013) compared the performance of hydrodynamic models in predicting oil spills in Arctic environments, noting that model outputs can vary significantly based on ice coverage and water temperature. Their findings also demonstrate that different models have distinct strengths and weaknesses, depending on the specific environmental conditions and types of oil spills.

Future studies should focus on improving model integration and addressing the technical limitations encountered, particularly with the DHI model. Enhancing the storage capacity and error-handling capabilities of complex hydrodynamic models is essential for more reliable simulations. Additionally, further research should involve the use of real spill data to validate the models' predictions, reducing the uncertainties observed in this study. Combining Seatrack's real-time capabilities with DHI's detailed hydrodynamic modeling and IVL's focus on chemical contamination would offer a powerful tool for oil spill management in Lake Mälaren. Future applications should also consider incorporating advanced machine learning algorithms to improve prediction accuracy and computation speed, particularly in scenarios where rapid decision-making is critical.

The recommendation to combine models, leveraging the IVL model's ability to display ether concentration in oil alongside the dispersed oil representations of other models, aligns with the integrated modeling approach proposed by Zhu et al. (2018). They argued for combining multiple models to capture different aspects of oil spill behaviour comprehensively. The varying complexities of these models, from the intuitive understanding offered by the IVL model to the intricate systems of Seatrack and DHI, reflect the spectrum of approaches in environmental modeling. This diversity echoes the findings of Reed et al. (1999), who noted the trade-offs between model complexity and practical applicability in oil spill response.

Conclusion

The Seatrack model demonstrated superior performance in real-time simulation and operational efficiency, making it particularly useful for emergency spill response. Its ability to provide rapid surface oil movement predictions is an essential feature when immediate decisions are necessary. However, Seatrack's limitations in subsurface analysis should be acknowledged when deeper water dynamics are critical. The DHI model, while more advanced in hydrodynamic simulations, faced operational challenges, particularly with storage capacity and error handling. These computational limitations reduced its effectiveness in scenarios where rapid response is needed, although it excelled in providing detailed subsurface data, useful for long-term environmental assessments. The IVL model proved to be simple yet effective for worst-case scenario predictions in completely mixed lakes. Its ease of use and ability to simulate specific chemical contaminants make it a valuable tool in specific contexts, though its lack of detailed spatial analysis limits its broader applicability.

In conclusion, all models have limitations, strengths, and weaknesses; hence, they do not get a complete score. Multicriteria scoring is an effective way to communicate, distinguish, and prioritize among models. Seatrack received the best grade owing to its performance of the model features. The IVL model received the first grade owing to its simplicity, user friendliness, and ability to simulate worst-case scenarios. The DHI model requires model tweaks to function effectively and provide reliable, meaningful findings, which accounts for the lowest overall score. However, this study also revealed that no single model provides a complete solution for all oil spill scenarios in Lake Mälaren. Each model has its limitations, whether in depth reliability, computational demands, or specific environmental factors. This finding highlights the potential benefits of an integrated approach, combining the strengths of multiple models to achieve a more robust and comprehensive oil spill management strategy.

By advancing our understanding of these modeling approaches, we move closer to creating more resilient, responsive, and effective systems for managing environmental risks, not just in Lake Mälaren, but in similar aquatic environments worldwide.

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Examensarbete vid Institutionen för geovetenskaper
ISSN 1650-6553