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Combined oil spill modelling and shoreline sensitivity analysis for contingency planning in the Irish Sea

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ABSTRACT

Offshore oil spills often result in severe environmental and socio-economic consequences. This work focuses on a busy, yet poorly studied part of NW Europe, the Irish Sea, to assess the impact of future oil spills on the nearby coast. By integrating numerical models and shoreline sensitivity analyses for two confined areas, Liverpool Bay and Milford Haven, this work acknowledges wind direction and speed as principal controls on the movement of oil under winter/storm conditions and in shallow waters. Ocean currents play a secondary role, but are significant in deeper waters and in low-wind summer conditions. The temporal elements used in the modelling thus stress that when the spill occurs is just as important as where. As a corollary, the fate of spilled oil is determined in this work for distinct scenarios and types. Response strategies are recommended to minimise the impact of future spills on coastal populations.

1. Introduction

Oil is a key factor in the economic development of a country, having recorded a rise in demand since the 1940s due to population growth and subsequent technological advances (Chen et al., 2019). As the production, transport and consumption of oil has risen in time, so has the underlying risk of offshore oil spills. At present, almost 60 % of the world's oil is transported by tankers (Burgherr, 2007; Wang et al., 2022), with many traffic routes located near biodiversity hotspots and marine protected areas (Roberts et al., 2002). Paradoxically, global increases in the volume of oil transported by marine vessels have not resulted in more frequent offshore oil spills (ITOPF, 2021). A progressive decline in the total number of oil tanker spills has been recorded since the mid-1970s due to: a) the imposition of more stringent regulations against ship-derived pollution, b) the introduction of double hull tankers, and c) significant improvements in marine traffic surveillance and monitoring (Eide et al., 2007; ITOPF, 2021). Yet, major oil spills from maritime accidents still occur due to human error and unforeseen circumstances.

The 2018 *Sanchi* oil spill was one of the largest maritime accidents of the early 21st century, and saw the *Sanchi* tanker collide with another vessel to cause extensive oil pollution (Zhang et al., 2021). The tanker exploded after the accident and sank, highlighting the lack of emergency procedures for gas condensate pollution accidents, which release relatively new types of chemical feedstock (Qiao et al., 2019). The *MV Prestige* oil spill was another remarkable accident of the 21st century in which a severe North Atlantic storm led to the rupture and sinking of what was, at the time, an aged single-hull tanker. The vessel was carrying 77,000 tons of crude oil, of which 37,000 tons sank inside its hull and continued to be released into the sea after the arrival on the coast of a first slick on 19 November 2002 (Montero et al., 2003). A total of 63,000 tons of oil are suspected to have been released by the *MV Prestige*, mostly comprising a heavy oil type that favoured a strong emulsification and very minor evaporation (Carracedo et al., 2006; Penela-Arenaz et al., 2009). In Northern Europe, major offshore oil spills affecting the United Kingdom include those of the *SS Torrey Canyon* in 1967, *MV Braer* in 1993 and *MV Sea Empress* in 1996 (Harris, 1995; Law, 2011; Law and Kelly, 2004). The supertanker *SS Torrey Canyon* ran aground in March 1967 near Land's End and spilled its entire cargo of 119,000 tons of crude oil, plus a quantity of bunker fuel, making it the largest ever spill in the United Kingdom and the first major oil tanker disaster in history (Law, 2011). Another example is the *MV Braer*, which ran aground offshore the Shetland Islands in January 1993 in severe weather conditions, spilling 84,700 tons of crude oil and 1500 tons of bunker fuel oil (Harris, 1995). The most recent large-tanker (>700 tons) oil spill in UK waters, that of the *MV Sea Empress*, occurred in February 1996 near Milford Haven, southwest Wales. It released 72,000 tons of crude oil and

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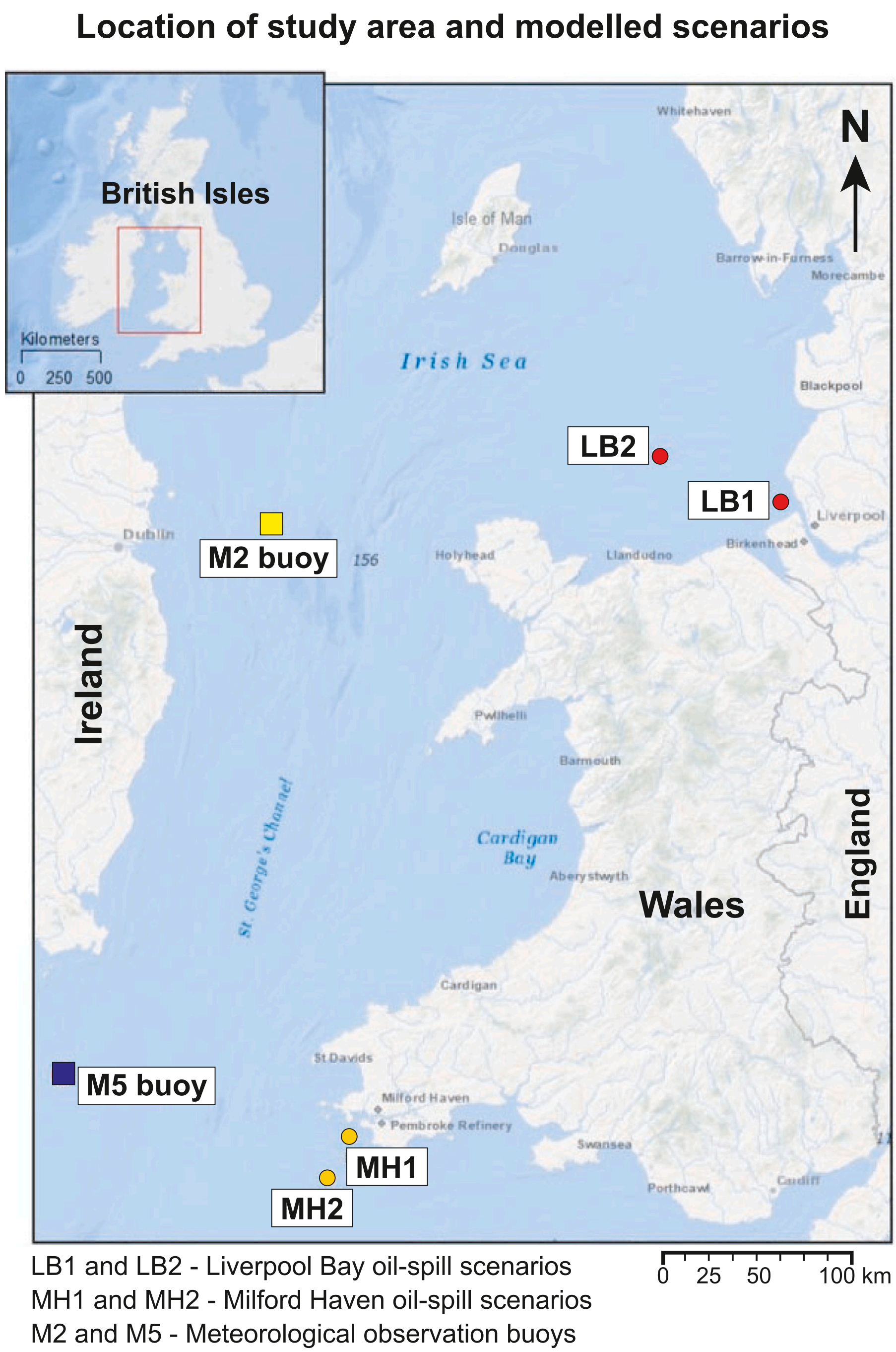

Fig. 1. Map showing the oils spill sites modelled in this work and the location of the M2 and M5 buoys from which key metocean data were collected. Inset highlights the location of the Irish Sea in between the islands of Great Britain and Ireland.

480 tons of heavy fuel oil (Law and Kelly, 2004).

All in all, the severity of an oil spill depends on a combination of factors, including: 1) the quantity and chemical composition of the spilled oil, 2) the prevailing metocean conditions at the time of the spill, 3) the sensitivity of the environment affected, and 4) the effectiveness of the chosen clean-up strategies (ITOPF, 2011). These factors require significant consideration in any offshore oil spill contingency plan (Ornitz and Champ, 2007; Beyer et al., 2016; Flores-Medina et al., 2022). The presence of oil in the marine environment can negatively impact the abundance and diversity of benthic communities, at the same time compromising the water repellency of seabirds, damaging the insulating ability of marine mammals, and contaminating fish and shellfish (Teal and Howarth, 1984; Peterson et al., 2003). Human health is another concern in the aftermath of an oil spill, not only through the consumption of contaminated seafood, but also due to the potential inhalation of toxic fumes by coastal populations. For instance, people living in areas exposed to oil spilled by the *MV Sea Empress* experienced acute health effects including anxiety, depression, decreased mental health, headaches, sore eyes and sore throats (Lyons et al., 1999). Contaminated food sources, combined with the loss of certain marine organisms, can also destabilise the food chain to cause long-term problems for both wildlife and humans, as recorded after the *Exxon Valdez* (Peterson et al., 2003) and *Deepwater Horizon* (Abbriano et al., 2015; Sumaila et al., 2012) oil spills.

This paper investigates the fate of oil for specific accident scenarios in the Irish Sea. It aims at becoming a basis for future offshore oil spill

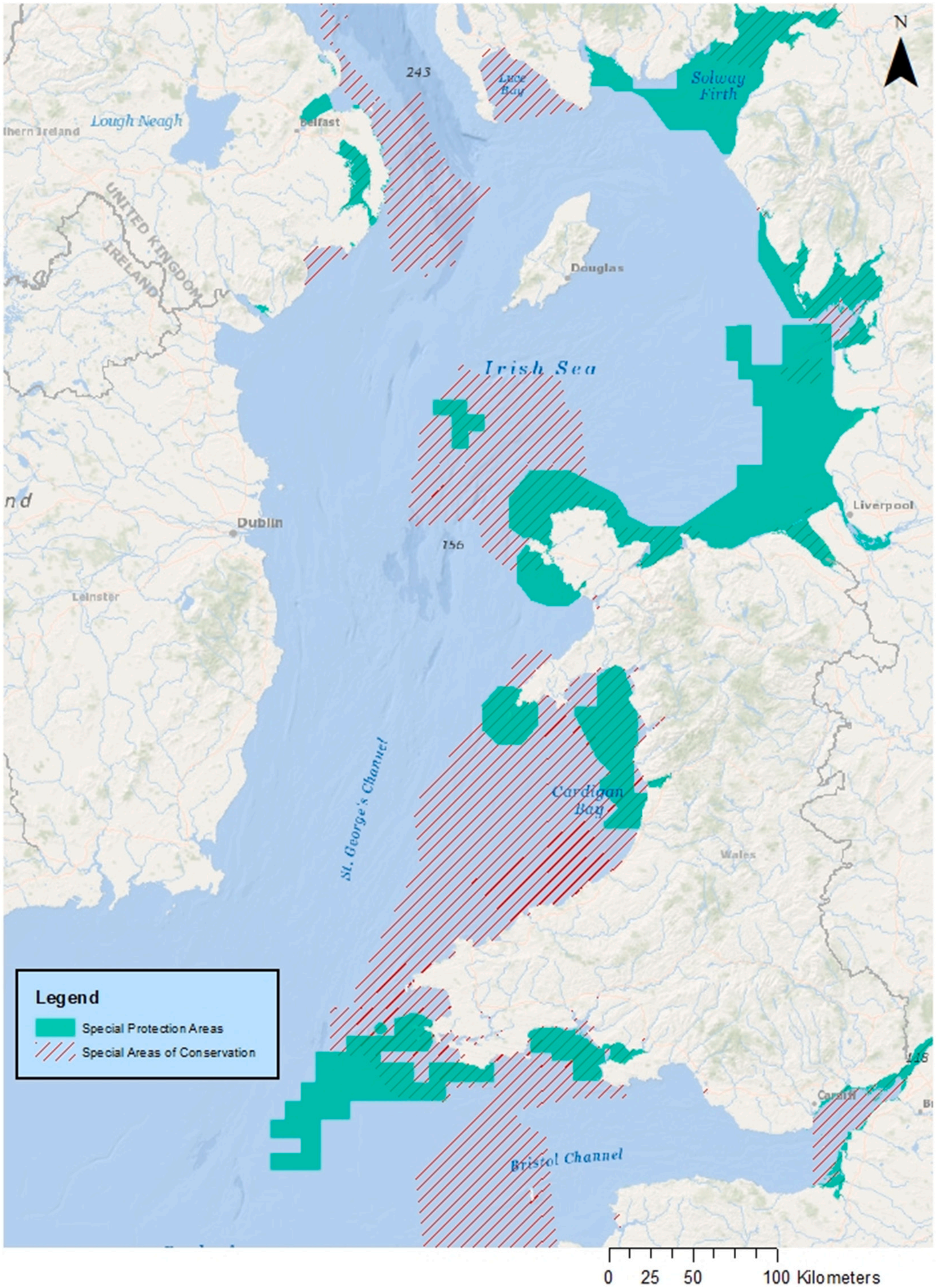

Fig. 2. Map highlighting the location of Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) in the Irish Sea. The information shown is based on JNCC (2022).

contingency planning in the confined seaway that separates the islands of Great Britain and Ireland (Fig. 1). Notwithstanding the accidents in UK waters previously mentioned, the oil spill literature for the Irish Sea tends to focus on the effects of oiling on marine organisms, particularly after the *MV Sea Empress* accident, which severely impacted what are protected natural areas of the Welsh coast (Batten et al., 1998; Lancaster et al., 1998; Fernley et al., 2000). More information on the potential impacts of an Irish Sea oil spill will be beneficial to support future contingency plans for the whole region spanning the islands of Great Britain and Ireland (Fig. 1). Hence, research questions addressed in this work include:

1. What are the dominant meteorological and oceanographic conditions influencing the movement and weathering of oil spills in the Irish Sea?
2. How important is the location of an oil spill, relative to the metocean conditions at a time of an accident, in controlling oil drift and fate?
3. Which shorelines around the Irish Sea are most sensitive to the arrival of oil, and thus must be prioritised by contingency plans?

Table 1
Summary of the input data used in ADIOS.

ADIOS input data	Summer	Winter	Storm
Wind speed (knots)	8	16	20
Wind speed uncertainty (knots)	2	2	2
Wind direction (degrees true)	180	210	245
Wave height (m)	0.7	2	3
Temperature (°C)	16	11	9
Salinity (ppt)	34	32	25
Oil spilled (metric tons)	70,000	70,000	70,000
Duration of release (days)	5	5	5

2. The Irish Sea

The semi-enclosed Irish Sea is located on the Northwest European Continental Shelf, between Ireland and Great Britain (Fig. 1). Main topographic features in the region include the deep and narrow North Channel and a wider, shallower St. George's Channel (Dabrowskia et al., 2003). The Irish Sea has a mild maritime climate, with annual mean temperatures of ~10 °C at the south end of St. George's Channel and ~11 °C in the North Channel (Bowden, 1980). Westerly winds are common in the region and influence water-mass circulation (Hadziabdic and Rickards, 1999). Wind forcing can occasionally induce large storm surges, though atmospherically forced currents only exceed tidal-current amplitudes under storm conditions (Flather, 1987). In parallel, near-inertial oscillations promoted by sudden changes in wind direction cause wind-driven mixing of water masses (Olbert et al., 2012). Semi-diurnal tides also drive water circulation, with these same tides entering through both the St. George's and North Channels and meeting south of the Isle of Man (McKay and Pattenden, 1993). As a result, strong tidal currents of around 1–1.5 m/s are recorded at both entrances and in the vicinity of headlands (Olbert et al., 2012), as shown in Supplementary File 1.

A final factor governing circulation in the region is summer solar heating (Dabrowskia et al., 2003), which causes important stratification in the water column to the southwest of the Isle of Man and, to a lesser degree, in Liverpool Bay itself (Widdows et al., 2002) (Fig. 1). Water column stratification also occurs in the winter and spring, promoted by the influx of low-salinity water sourced from rivers in the northwest of England (Widdows et al., 2002).

The Irish Sea supports a variety of ecologically and commercially important marine species and habitats, many of which are protected by international and national conservation designations. Priority habitats include *Sabellaria alveolata* reefs, estuarine rocky cliffs and knolls, salt marshes, seagrass beds, maerl beds, horse mussel beds, and fragile sponge communities on subtidal rocky habitats (Irish Sea Maritime Forum, 2013). Marine mammals such as the harbour porpoise, grey seals, common seals and bottlenose dolphins also occupy the region. Additionally, there are several critically endangered species within the Irish Sea, including the Portuguese dogfish, common skates, flapper skates, porbeagle sharks, white skates and angel sharks (IUCN, 2022). Many of these species occur in: a) Special Areas of Conservation (SACs; sites designated under the European Habitats and Species Directive), b) Special Protection Areas (SPAs; sites which protect vulnerable bird species in the UK), c) Marine Conservation Zones (MCZs; protecting species and habitats in UK waters), and d) marine nature reserves (JNCC, 2019). Fig. 2 highlights the location of SPAs and SACs in the Irish Sea.

3. Data and methods

Six hypothetical oil spill scenarios are considered in this work based on summer, winter and storm conditions for Liverpool Bay (near buoy M2) and Milford Haven (near buoy M5) (Fig. 1). The MH1 and MH2 spill sites are respectively located 2.7 miles and 11.3 miles offshore Milford Haven. The LB1 and LB2 spill sites are located 2.9 miles and 19 miles off

Table 2
Summary table of data sets and sources utilised in this work.

Data	Source	Methodological approach
Coastline morphology	GNOME Online Oceanographic Data Server 'GOODS' Database: Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS)	Oil spill trajectory modelling
Currents	HYCOM (Hybrid Coordinate Ocean Model) Dataset: GOFS 3.1: 41-layer HYCOM + NCODA Global 1/12° Analysis (NRL)/GLBy0.08/expt_93.0/Hindcast Data: Dec-04-2018 to Present *3-hourly*/GLBy0.08_expt_93.0 (ssh, ts3z, and uv3z aggregated)	Oil spill trajectory modelling
Wind speed Wind direction Wave height Salinity Ocean temperature	Marine Institute Dataset: Irish Marine Data Buoy Observation Network Real Time Data 2002 – Present	Oil spill trajectory modelling Oil spill weathering and fate modelling
Oil type	ADIOS Oil Database	Oil spill weathering and fate modelling
Vessel information	MarineTraffic.com	Oil spill trajectory modelling Oil spill weathering and fate modelling
ESI	Adler and Inbar's (2007) Environmental Susceptibility Index (ESI)	Shoreline sensitivity assessment

the Wirral Peninsula, respectively (Fig. 1). The port of Milford Haven is the UK's largest energy port (Milford Haven Port Authority, 2022), whilst Liverpool Bay is home to the Liverpool Bay Oil and Gas Development Project (LBODP), making them logical areas for our hypothetical oil spill scenarios. In addition, the LBODP consists of four oil and gas fields, as well as significant offshore and onshore facilities (BHP, 2014). Oil movement was simulated using GNOME and ADIOS software from NOAA (ADIOS, 2022). The models compiled use high temporal and spatial resolution data for wind, wave, sea surface temperature and current conditions (Tables 1 and 2).

Three main methodological approaches are therefore used within this paper: 1) oil spill trajectory modelling, 2) oil spill weathering and fate modelling and 3) shoreline sensitivity assessment. Collectively, these approaches can address important questions that arise during an oil spill incident; where it will end up, when it will arrive and what damage it will cause. We therefore present GNOME and ADIOS models for known metocean scenarios together with coastline environmental sensitivity maps for hypothetical oil spill scenarios along the coasts of Wales and NW England. Fig. 3 summarises the approach followed in this work. Full descriptions of the methods used are also given in Supplementary Table 1 and Supplementary File 2.

3.1. Oil spill simulations (GNOME)

The simulations in this work use GNOME (General NOAA Operational Modelling Environment), an Eulerian/Lagrangian trajectory model chosen on the basis of its high prediction accuracy (Farzingohar et al., 2011; Xu et al., 2013). Previous studies have found it to be an effective and low-cost tool for oil spill risk management (Cheng et al., 2011; Marta-Almeida et al., 2013; Toz et al., 2016; Prasad et al., 2020).

The main components of GNOME as a modelling tool are maps,

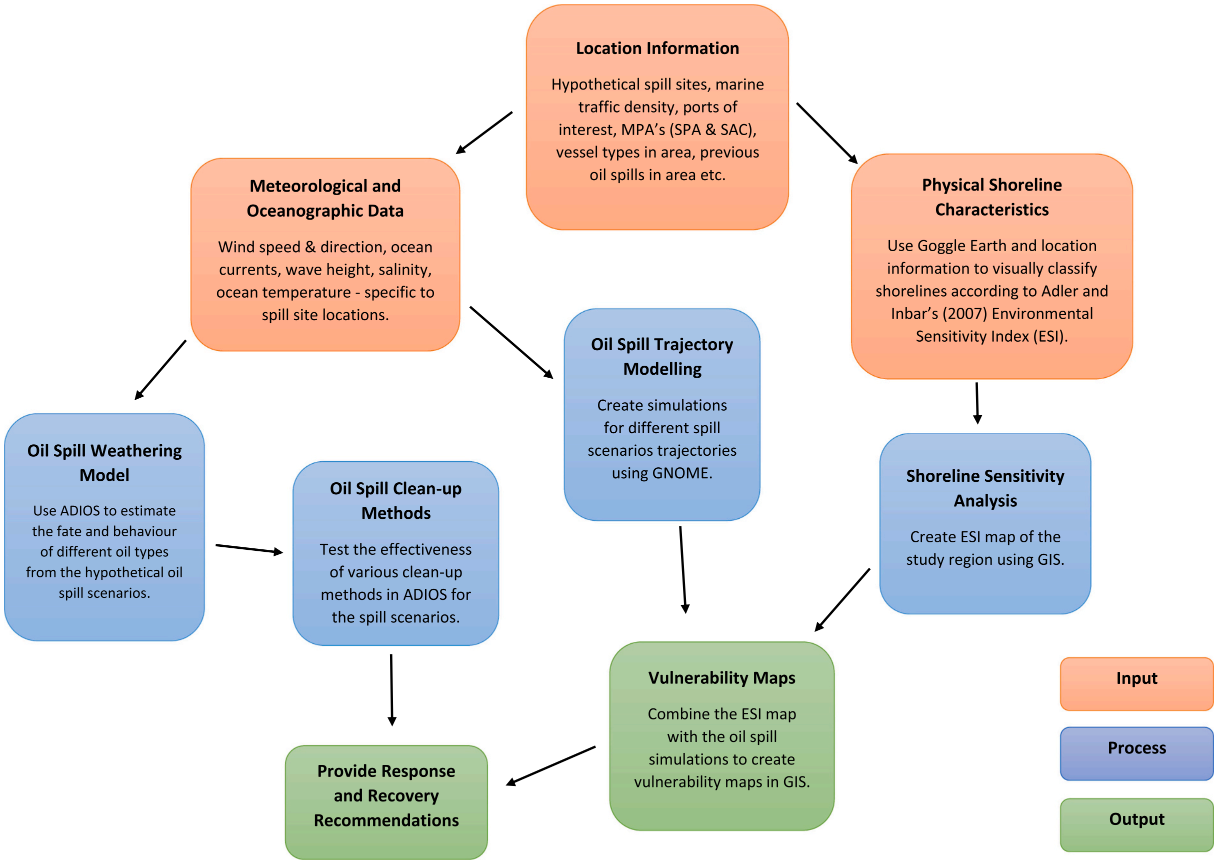

Fig. 3. Workflow diagram summarising the methodology adopted in this work.

movers and spills. Map files are accessible through the GNOME Online Oceanographic Data Server 'GOODS', where vector shoreline 'BNA' maps can be downloaded for a specific location (Zelenke et al., 2012). Movers are any physical parameters that cause oil to move in water such as wind and currents. In this work, movers were added at each time step to show the overall movement of oil using a forward Euler scheme, specifically a 1st order Runga-Kutta method (Beegle-Krause, 2001). In addition, oils are typically grouped into five categories by GNOME, and spill responders, ranging from light non-persistent oils (Group 1) to heavy and sinking oils (Group 5) (NOAA, 2020). Oil types from the first four groups used within this work include gasoline, Brent crude oil, Gullfaks crude oil and bunker C fuel oil (Supplementary File 2).

The oil spill's Lagrangian Elements (LEs, or splotts) are modelled within continuous flow fields by GNOME, and create an oil spill 'movie' animation displaying the predicted movement of the spill within 1-hour time steps (adjustable). During each time step, the LEs have a known starting point and query each mover to find out what direction, and how far, a LE has moved within that time step. The steps are then added in a vector sum to calculate the new LE location (Beegle-Krause, 2001). In this work, snapshots of the oil spill trajectories are taken at various time steps.

GNOME provides a limitation in terms of the volume of oil that can be modelled. A maximum volume of 70,000 metric tons of oil is achievable in GNOME and, although this volume equates to a large oil spill of a similar size to the *MV Prestige*, previous tanker spills in the UK such as the *SS Torrey Canyon*, *MV Braer* and *MV Sea Empress* are known to have exceeded such a volume.

3.2. Oil weathering and fate modelling (ADIOS)

ADIOS (Automated Data Inquiry for Oil Spills) is the oil spill weathering and fate model used within our analysis. It is used in conjunction with GNOME to give more accurate estimates of oil behaviour in the marine environment (Zelenke et al., 2012). ADIOS has been used by multiple authors to quickly estimate the weathering and fate of an oil spill, using mathematical equations to predict changes in oil properties such as density, viscosity and water content (Lehr et al., 2002; Zhao et al., 2015; Toz et al., 2016). ADIOS estimates oil evaporation rates from the sea surface, dispersion in the water column and the formation of oil droplets that become emulsified/suspended in water from the oil property changes (NOAA, 2022b). As with this work, several studies have previously used ADIOS alongside GNOME to better understand the behaviour of offshore oil spills (Yang et al., 2013; Toz et al., 2016; Bassey et al., 2017; Elizaryev et al., 2018; Akinbamini et al., 2022).

ADIOS provides best-guess predictions for oil processes such as dispersion, evaporation and emulsification. For evaporation, a pseudo-component evaporation model is used by the software (Jones, 1997). This approach models oils as non-interacting components and the sum of the individual component rates is calculated as the total evaporation rate. In addition, ADIOS uses the asphaltene fraction when estimating emulsification, based on results from a study by Fingas et al. (1996). Additionally, a hydraulic model developed by Delvigne and Sweeney (1988) is used to estimate dispersion, which measures the number/size distribution of oil droplets dispersed into the water column by breaking waves (Lehr et al., 2002).

ADIOS requires input data about the oil spill, environmental conditions, and the planned clean-up strategy. For the oil spill itself, information regarding the type of oil, the quantity of oil spilled, as well as the rate and duration of release, is provided for the scenarios considered in this work. For the oil type, the ADIOS Oil Database is used as it contains data for over a thousand different oil types (ADIOS, 2022). Environmental conditions such as wind speed and direction, wave heights, water temperature and water salinity are also provided. Finally, clean-up

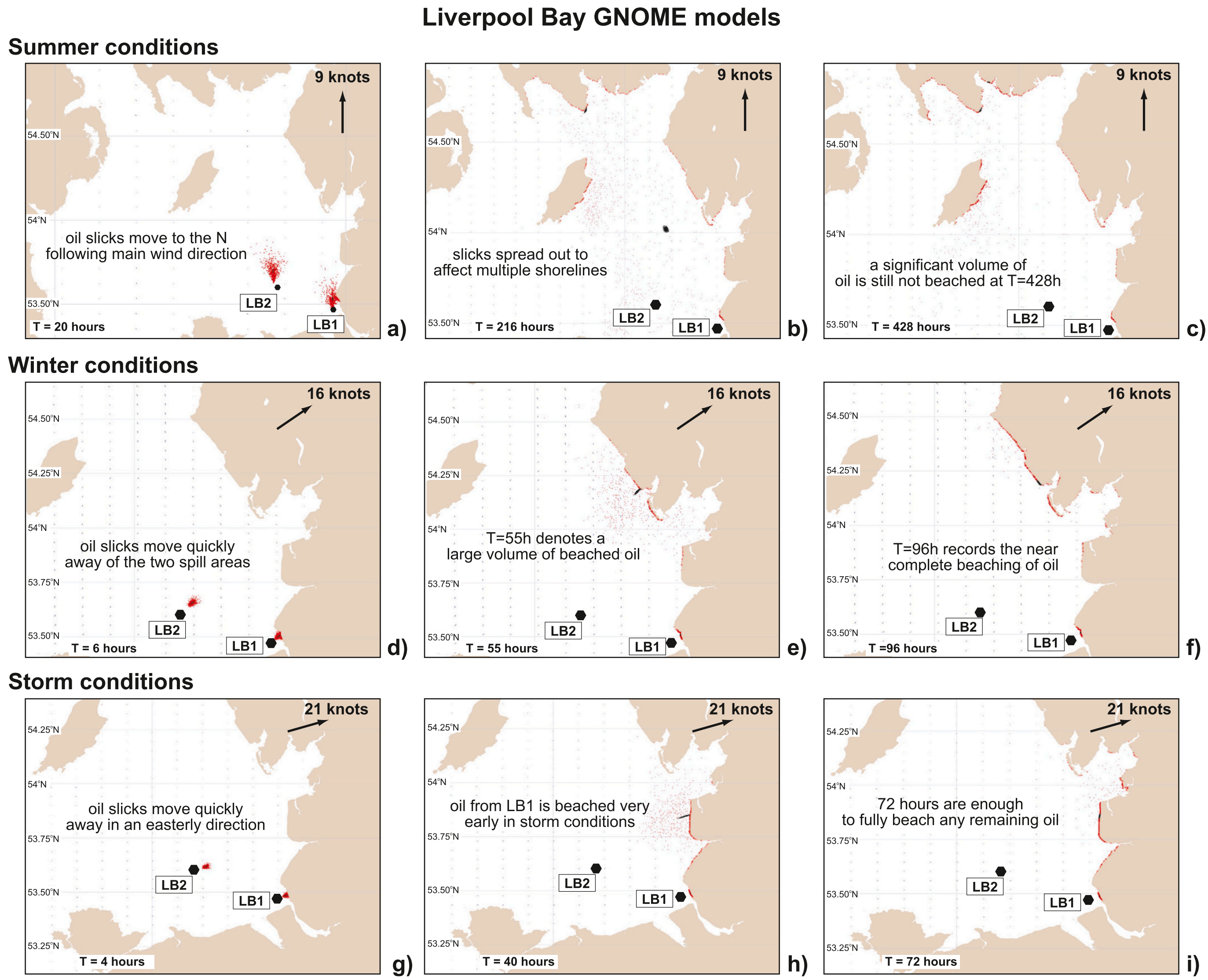

Fig. 4. GNOME modelling results for oil movement in the northern part of the Irish Sea, near Liverpool Bay. In all the images shown, the large black dots are the spill sites. a), b), c) GNOME simulation results for the Liverpool Bay Summer scenario. d), e), f) GNOME simulation results for the Liverpool Bay Winter scenario. g), h), i) GNOME simulation results for the Liverpool Bay Storm scenario.

options are considered in the oil spill scenarios, including the use of dispersants and skimming (Lehr et al., 2002). The ADIOS input data are provided in Table 1.

Output information from ADIOS is represented by a range of graphs, including oil budget graphs, which help to visually understand how long the spilled oil should remain in the marine environment for different accident scenarios. Output information such as the amount of oil evaporated, dispersed and remaining within the marine environment is collated in this work, and oil budget graphs compiled based on these data.

The main limitation of ADIOS is that it can only predict oil behaviour for a maximum of five days, missing out the effects of longer-term processes. Oxidation, sedimentation and biodegradation are longer term processes that happen in the later stage of a spill, determining its ultimate fate. These processes are not accounted for in ADIOS.

3.3. Shoreline sensitivity analysis

The Irish Sea shoreline is analysed according to its sensitivity to oil, using Google Earth and Adler and Inbar's (2007) Environmental Sensitivity Index (ESI). ESI approaches are used by many authors to combine the physical features of a shoreline with biological information and anthropogenic uses of an area (Nansingh and Jurawan, 1999; Adler and Inbar, 2007; Peterson, 2022). In this work, only the physical characteristics of the shoreline are accounted for; we classify a range of shoreline types from rocky cliffs and headlands to beaches with high environmental or biological importance (Fig. 2).

Google Earth is used to visually determine shoreline types and classify them following the ESI. A limited timeframe and the huge extent of the study area restricted the ability to gather filed observations. Nevertheless, the estimated ESI values provide a good indication of the potential harm oil can pose to a shoreline. ESI maps are compiled in this work to provide responders with a visual indicator of environmental damage susceptibility (see Nelson and Grubesic, 2017).

In a later stage in our analysis, oil spill trajectory results from GNOME are aggregated with the ESI maps to create environmental vulnerability maps. Vulnerability maps can act as a quick reference during an oil spill incident, identifying high priority areas to protect (Balogun et al., 2021). They also allow for clean-up equipment to be strategically placed prior to an incident, so that it can be dispatched in

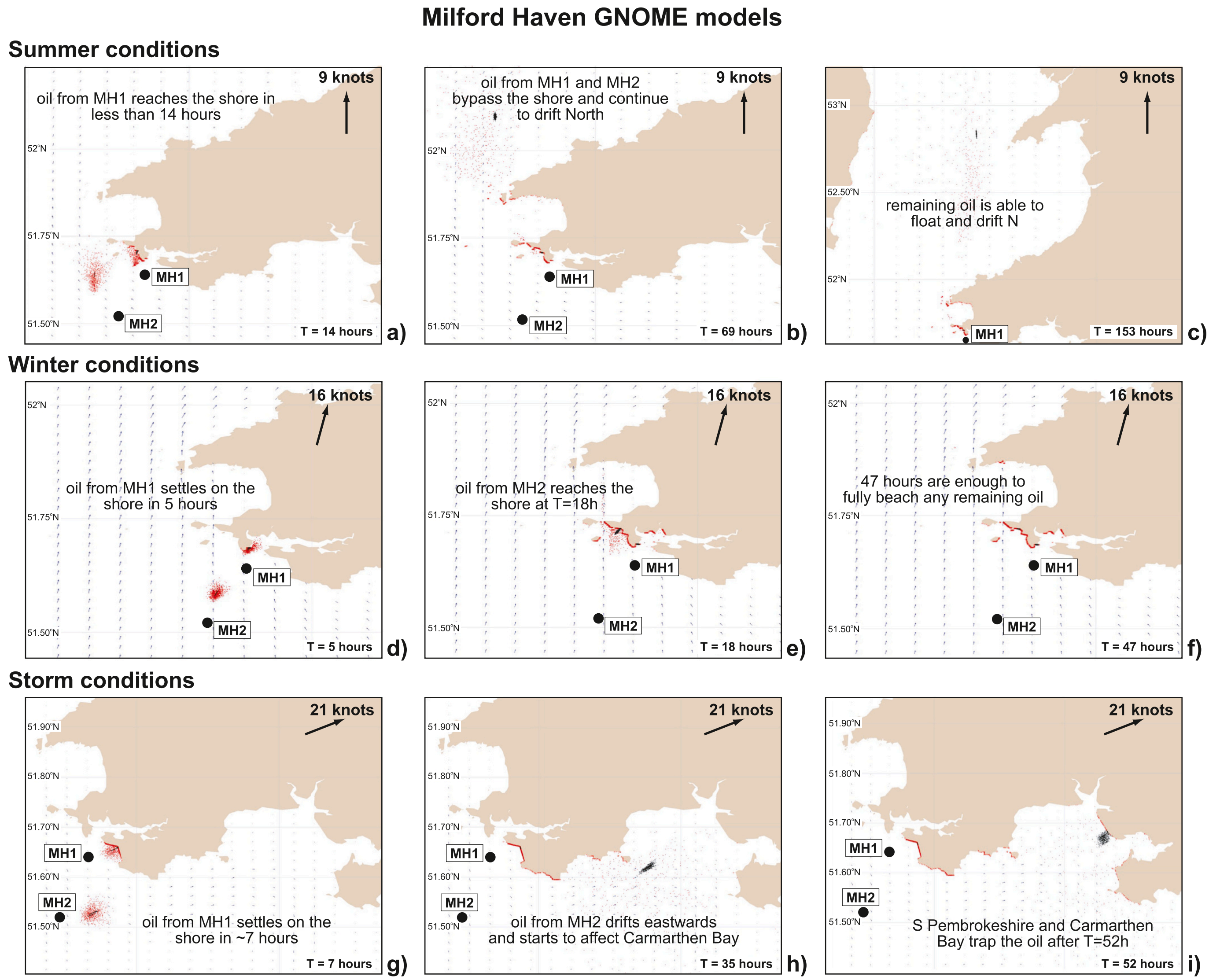

Fig. 5. GNOME modelling results for oil movement in the southern part of the Irish Sea, Near Milford Haven. In all the images shown, the large black dots are the spill sites. a), b), c) GNOME simulation results for the Milford Haven Summer scenario. d), e), f) GNOME simulation results for the Milford Haven Winter scenario. g), h), i) GNOME simulation results for the Milford Haven Storm scenario.

minimal time to effectively tackle an oil spill (Adler and Inbar, 2007) (Fig. 3).

4. GNOME simulations

This section presents GNOME oil spill simulations. GNOME results are shown for the six oil spill scenarios using a medium crude oil type and displaying the model's best guess estimate of the location of the oil slick (small black dots), as well as its uncertainty (red dots).

4.1. Liverpool Bay's summer scenario

Initially, winds blowing from the south play an important role in the movement in summer oil spills, especially within the first 20 h (Fig. 4a–c). Ocean currents become more of an influence as the spilled oil drifts farther from Liverpool Bay into deeper waters near the Isle of Man (Fig. 4b, c). After 216 h, the oil first released at LB2 reaches the shoreline in southern Scotland. However, the drift rate of oil released by LB1 was significantly slower than that from LB2; oil derived from LB1 only reaches southern Scotland after 411 h (Fig. 4c). As wind speeds remain constant, different current velocities influence the drift rate as time progresses.

4.2. Liverpool Bay's winter scenario

Fig. 3d–f shows that oil released by both LB1 and LB2 follows the predominant wind direction at first, with LB1 oil reaching the shore after 6 h. Wind speed and direction are key factors influencing the trajectory of oil at this point in the model. The movement of oil released by LB2 becomes influenced by ocean currents after 6 h, slowing in speed and drifting slightly towards the north (Fig. 4e). At 96 h, oil first released at LB2 settles just north of Barrow-in-Furness. The short arrival time of LB1 oil to the shore results in much less uncertainty when compared to the LB2 spill.

4.3. Liverpool Bay's storm scenario

Similarly to the winter scenario above, the oil released at LB1 reaches the shore in a short time (Fig. 4g–i). The greater wind speed results in a faster drift, and LB1 oil takes only 4 h to reach the coast. Oil movement is

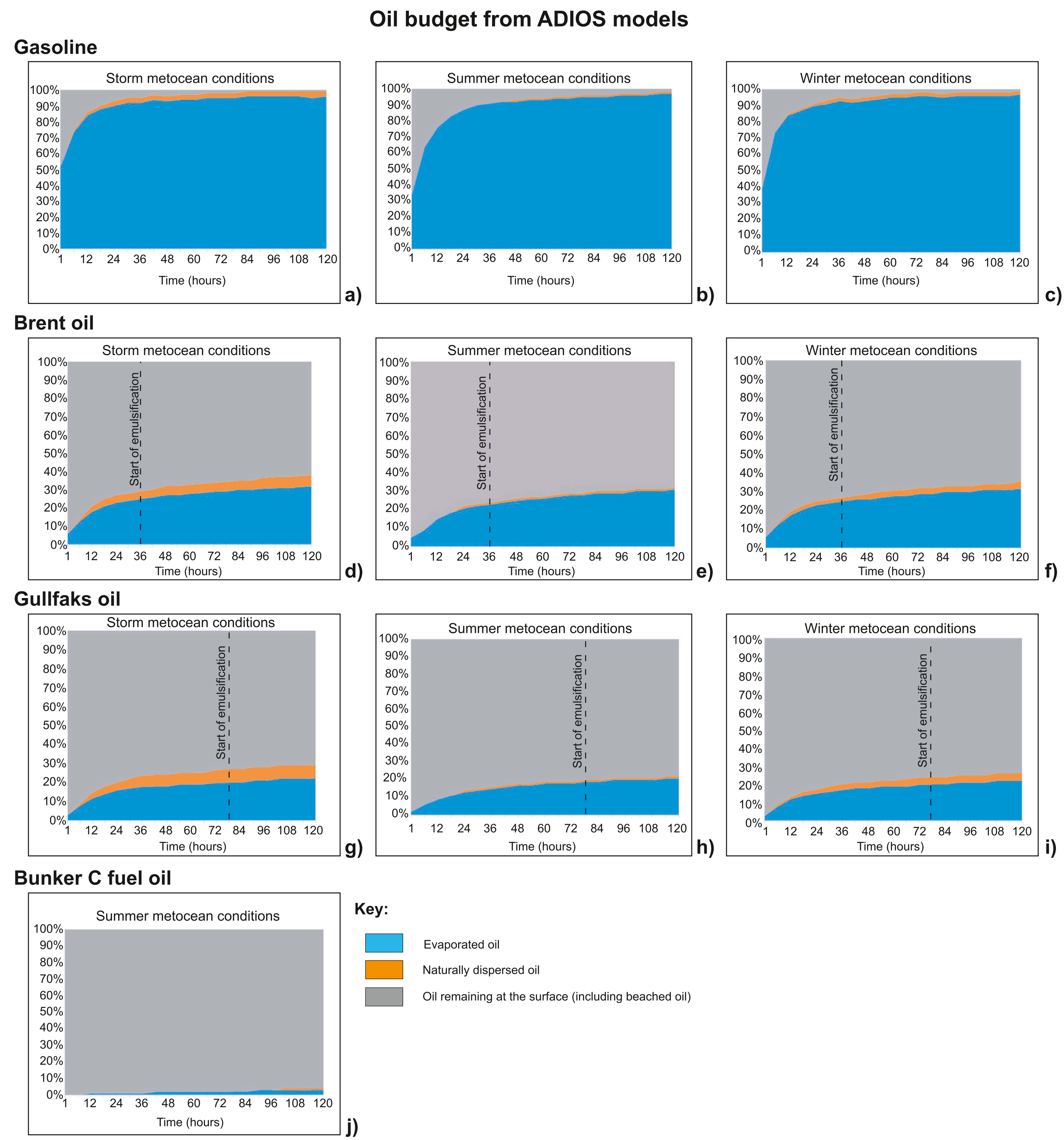

Fig. 6. Oil budget graphs showing ADIOS results for: a), b) and c) gasoline under summer, winter and storm conditions, d) e) and f) Brent Crude oil for summer, winter and storm conditions, g), h) and i) Gullfaks crude oil under summer, winter and storm conditions, and j) bunker C fuel oil under summer conditions. Black dotted line represents the formation of stable water-in-oil emulsions.

mainly influenced by wind direction (Fig. 4h, i). This shows that at greater wind speeds the direction of the oil spill trajectory is less influenced by ocean currents. Oil released by LB2 reaches Blackpool after 40 h, following the predominant wind direction. However, ocean currents still have an influence, directing the oil further north. At 72 h, both spills settle on the northwest coast of England (Fig. 4i).

4.4. Milford Haven's summer scenario

Oil derived from MH1 reaches the Dale shoreline within 14 h (Fig. 4a–c). Southerly winds transport the oil northwards before ocean currents alter its trajectory. Oil from MH2 also follows these same ocean currents to the west, bypassing Skokholm Island, which lies directly north of the spill site (Fig. 5b). Whilst oil from MH1 settles on the west coast of Pembrokeshire, that of MH2 drifts northwards - following the

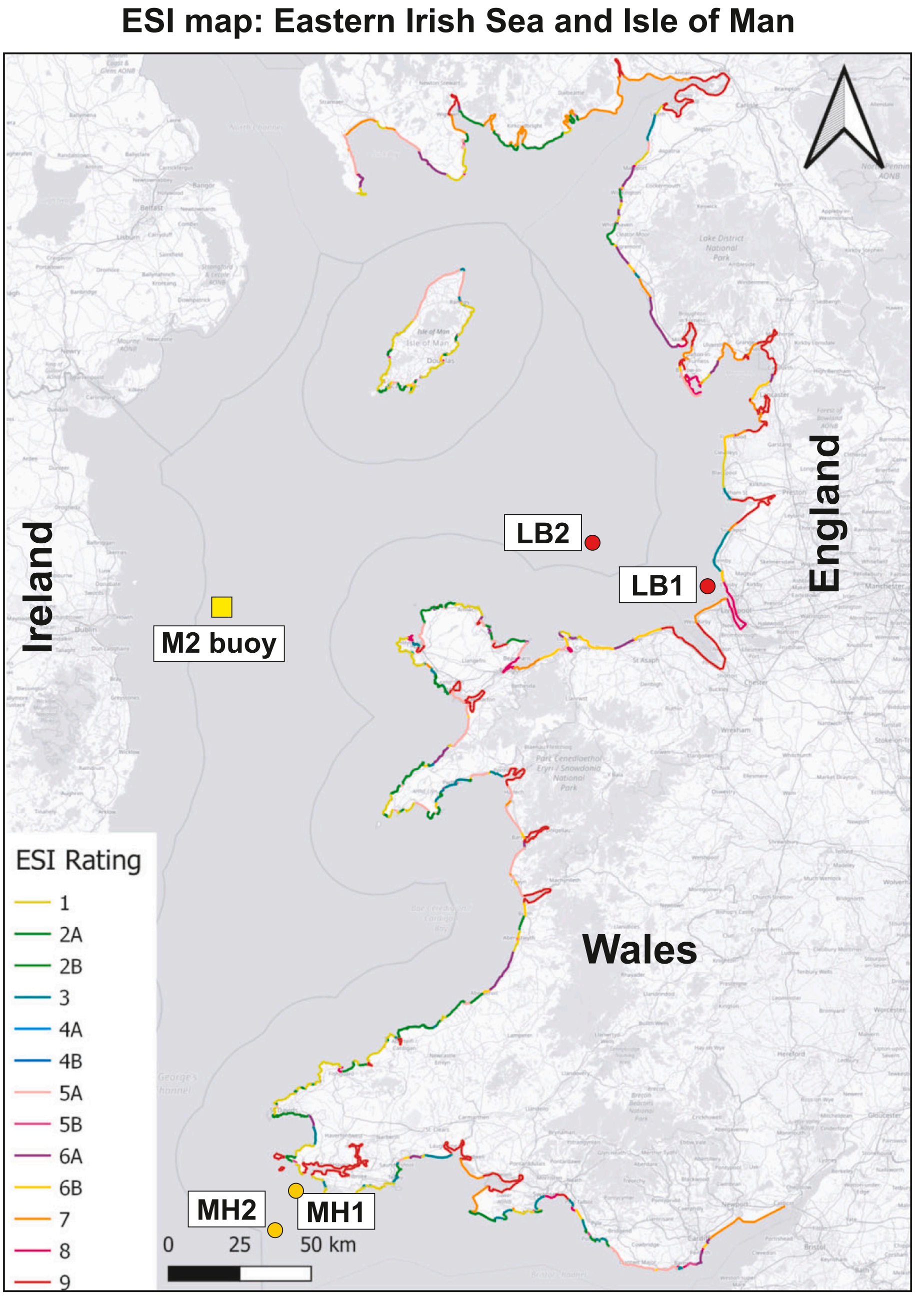

Fig. 7. ESI map for the eastern coast of the Irish Sea and the Isle of Man. Note the high sensitivity of low-lying estuaries in bays near environmentally protected parts of Wales and England.

ocean currents - into the deeper St. George's Channel. Overtime the MH2 oil continues its movement north, following the northerly flow of water coming from the Celtic Sea (Bowden, 1980). Although not shown in Fig. 5, oil released at MH2 reaches the Kilclief shore of Northern Ireland after 380 h.

The trajectory of oil released at MH2 is influenced by both wind direction and currents. The southerly winds allow it to cover a large distance. However, the oil also drifts east and west due to the changing current direction. This factor causes greater uncertainty in oil distribution in North Wales and along the coastline of Ireland. The final beaching of MH2 oil (seen at 401 h) is ultimately determined by ocean currents. Specifically, a near-surface gyre in the western Irish Sea is present in spring and summer (Hill et al., 1997), and is seen to control the movement of oil in the MH2 spill.

4.5. *Milford Haven's winter scenario*

Under winter conditions, oil derived from MH1 reaches St. Anne's Head after 5 h (Fig. 5d–f). The slick follows the predominant wind direction. Oil from MH2 spreads over the water surface in the direction of the wind but is influenced by currents. It reaches the Dale shoreline after 18 h (Fig. 5e). A combination of both wind and currents influence determines the endpoint of the spill. Importantly, oil from MH1 enters the Milford Haven Waterway.

4.6. *Milford Haven's storm scenario*

During storm conditions, the wind plays the primary role in the movement of oil released at both MH1 and MH2 (Fig. 5g–i). Oil from both spill sites moves in a northeast direction, despite the prevalence of

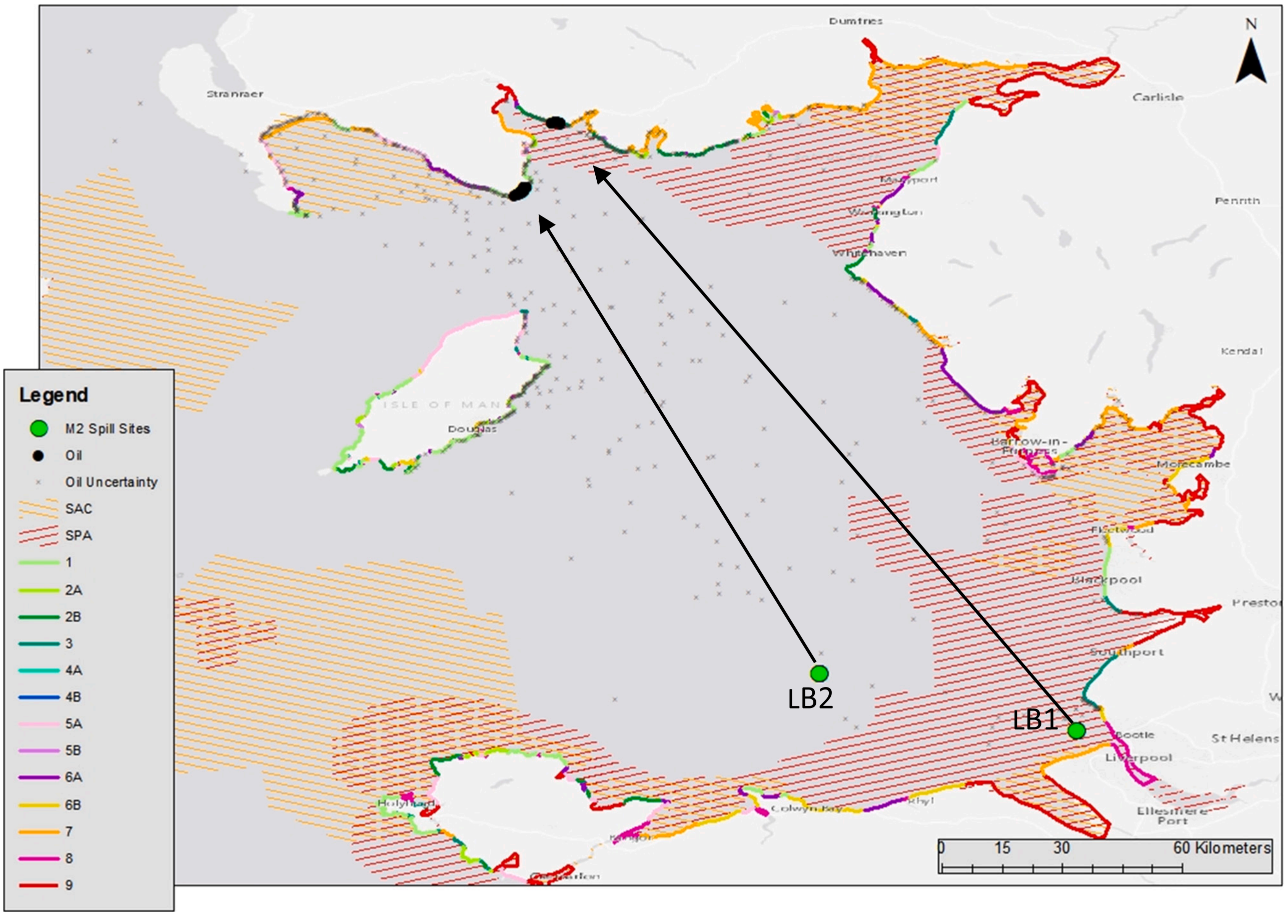

Fig. 8. Vulnerability map for Liverpool Bay's summer scenario.

southeast ocean currents in the first 7 h. Oil from MH1 reaches the shoreline between Angle and Freshwater West after 7 h (Fig. 5g). At 35 h, oil spilt by MH2 enters Carmarthen Bay, bar a certain degree of uncertainty. Variable wind and current directions are usually identified off the Pembrokeshire coast when compared with Carmarthen Bay (Supplementary File 1). At 52 h, MH2 oil reaches the Pembrey shore. At this point, the oil spreads out significantly on the flat, shallow areas off Carmarthen Bay. At 58 h, oil from MH2 is spread over a much larger area than MH1, though still topographically confined within Carmarthen Bay (Fig. 5i).

5. ADIOS weathering and fate results

Following the GNOME modelling concerning oil-spill movement, below is given an account of oil weathering and fate for the six modelled scenarios. In all models, beached oil was considered as a constituting part of naturally dispersed oil, as shown in Fig. 6. Fig. 6 highlights that beached oil is considered as a constituting part of the oil remaining at the surface, not naturally dispersed oil.

5.1. Gasoline (57 API)

As expected, gasoline has very high evaporation rates, as shown in Fig. 6a–c, and no marked seasonal differences are recorded. However, a difference in the natural dispersion of gasoline is observed. The percentage of gasoline dispersed increases with wave height and wind speed (see Supplementary File 3).

5.2. Brent crude oil (light 37.8 API oil)

In contrast to gasoline, the amount of Brent crude oil evaporated is just over 30 % of the total oil released (Fig. 6d–f). Summer conditions record a slightly lower percentage of oil evaporated, showing that temperature is not a major influence. Higher wind speeds can also increase evaporation (ITOPF, 2002), which explains the slight increase in evaporation for winter and storm conditions.

5.3. Gullfaks oil (medium 29.3 API oil)

Gullfaks crude oil – a medium oil in terms of its API density - shows similar results to the lighter Brent crude oil (Fig. 6g–i). They are the only oil types to form stable emulsions (dark dashed lines in Fig. 6d–i). However, evaporation is lower and dispersion is marginally increased for Gullfaks oil when compared to Brent oil.

5.4. Bunker C fuel oil (heavy 12.3 API oil)

Bunker C fuel oil can only be simulated for summer conditions as its pour point is 15 °C, a value higher than the sea temperatures for the winter and storm scenarios. Based on the results provided for the other oil types, it can be assumed that the evaporation and dispersion of bunker C can only slightly decrease the amount of remaining oil, even when considering increased wind speeds, wave height and sea turbulence (Fig. 6j).

Overall, there is very little seasonal variability in evaporation for all oil types (Supplementary File 3). The chemical composition of the spilled oil has a more significant influence on the amount of oil evaporated. In contrast, a seasonal difference is identified for dispersion, with

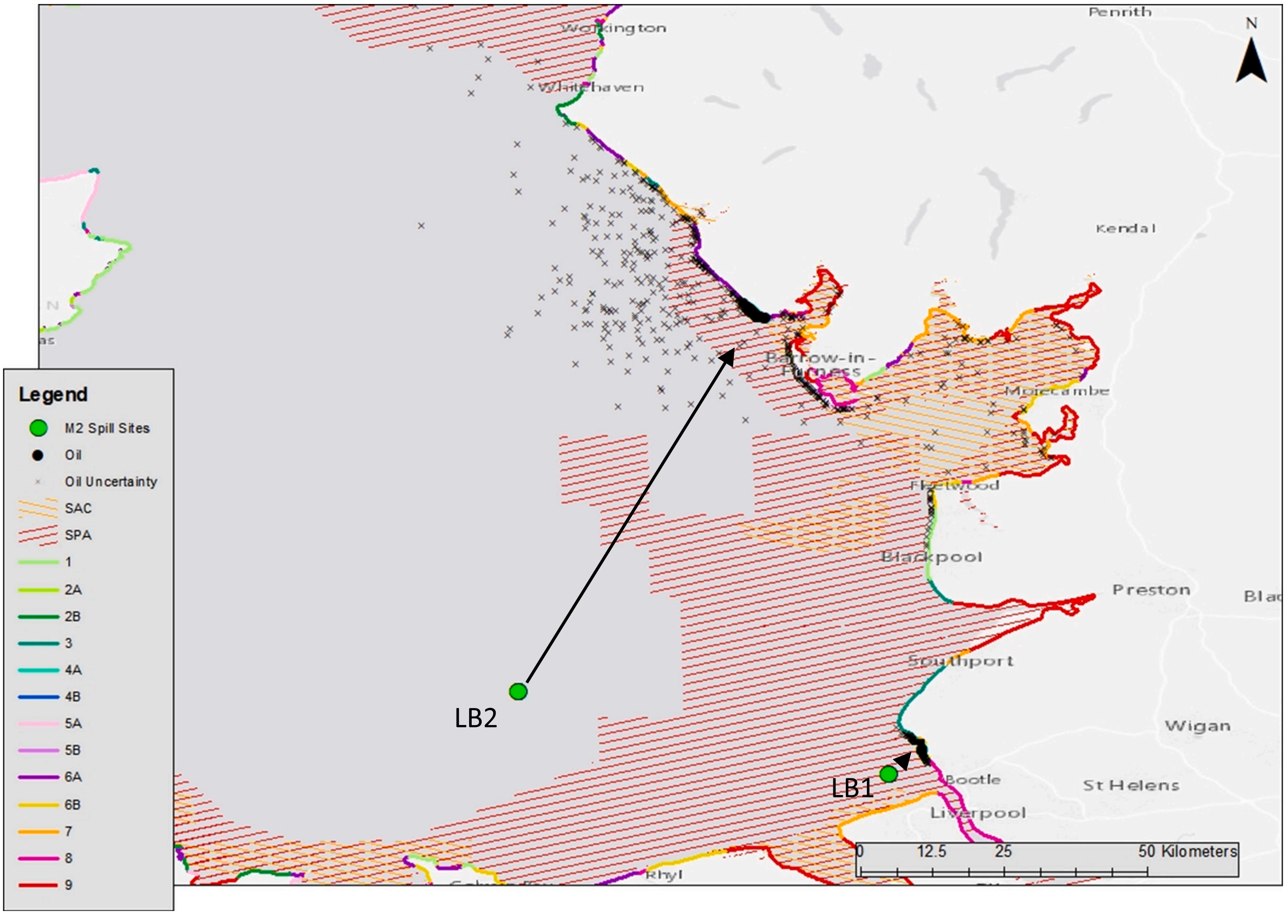

Fig. 9. Vulnerability map for Liverpool Bay's winter scenario.

increases in dispersion being recorded with increased wind speeds and wave heights. The distance covered by the oil slick increases with wind speed. Stable emulsions only form for the crude oil types after a specific amount of evaporation has taken place. For example, a stable emulsion 'mousse' begins to form at the sea surface when 23 % of the spill is evaporated for Brent (at 36 h), and 19 % for Gullfaks (at 78 h) (Fig. 6f, i).

6. Regional environmental sensitivity index (ESI) analysis

Fig. 7 shows an ESI map for the eastern coast of the Irish Sea and the Isle of Man. Shorelines least sensitive to oil (ESI 1 to ESI 2B) include exposed headlands, exposed rocky cliffs, wave cut platforms or exposed large boulder beaches, which are mostly impermeable. In contrast, the most sensitive shores (ESI 9) consist of nature reserves, beaches with high environmental or biological importance, saltmarshes, estuaries and other specially protected areas. A large proportion of the ESI 9 rated shorelines can be seen to protrude inland on the ESI map through estuaries (Fig. 7). Due to the predominant wind direction in the region, and the easterly locations of the spill sites, the east coast of Ireland is mostly unaffected according to our models, so it has not been classified.

The Liverpool Bay and Milford Haven spill sites are highlighted in Fig. 7. The shorelines near these sites are particularly susceptible to oil pollution. Liverpool Bay is known for its Dee Estuary and Mersey Estuaries, low-lying parts of the coastline where busy shipping lanes and economic activity are historically located. Close to these estuaries are located SPAs and SACs that may be heavily impacted by spilt oil (Fig. 2). The Milford Haven Waterway is also known as the largest estuary in Wales and one of the deepest natural harbours in the world, with great environmental and economic value (Milford Haven Port Authority, 2022). Further detail concerning shoreline sensitivity to oil spills in summer and winter conditions is provided in Supplementary Table 2 and the following section.

7. Vulnerability maps for the modelled scenarios

7.1. Model #1 - Liverpool Bay's summer scenario

A vulnerability map for the Liverpool Bay Summer scenario is shown in Fig. 8. Oil derived from LB1 covers the sandy shores of Kirkdale, whereas oil from LB2 impacts the Isle of Whithorn. Kirkdale has an ESI rating of 3, characterised by a low to medium penetration of oil. However, Kirkdale is also located within the Solway Firth Special Protection Area (SPA), which consists of tidal rivers, estuaries, mud flats, sand flats, lagoons and salt marshes, increasing the sensitivity of the area (JNCC, 2022).

For the most part, the Isle of Whithorn has an ESI rating of 1 due to its exposed headlands. However, the Isle of Whithorn harbour brings the ESI rating up to 8 due to its sheltered position, which enables the trapping of large volumes of oil. Oil spill uncertainty also entered the Luce Bay and Sands Special Area of Conservation (SAC), which comprises a large shallow inlet and bay (Fig. 8). The sediments within the SAC also support rich plant and animal communities (JNCC, 2022).

7.2. Model #2 - Liverpool Bay's winter scenario

Under winter conditions, oil from both LB1 and LB2 ended up in SPAs (Fig. 9). Oil from LB1 covered the Crosby and Hightown shorelines, located in the Liverpool Bay SPA. The Liverpool Bay SPA is classified for the protection of red-throated diver, common scoter, the little gull in the non-breeding season and the common tern and little tern in the breeding

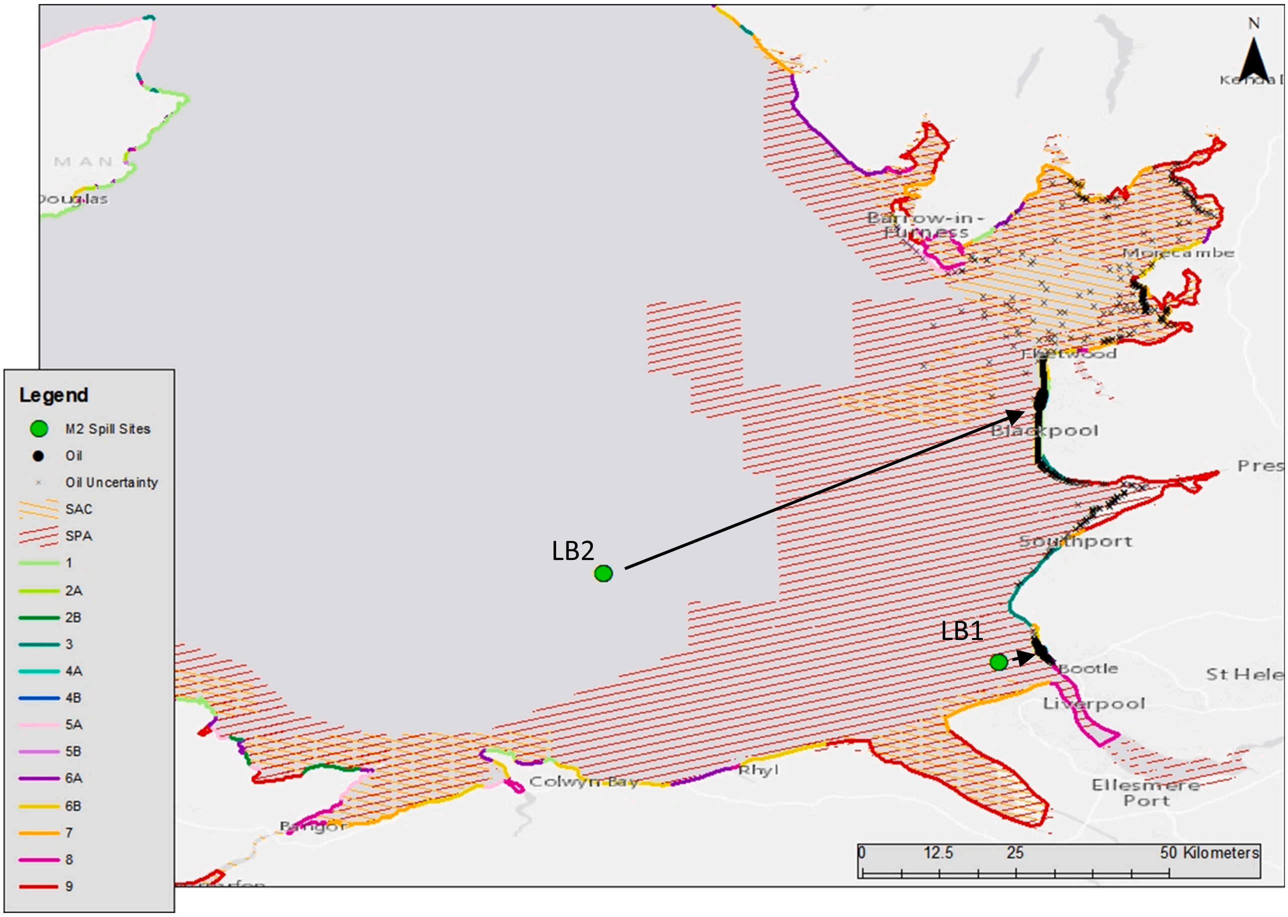

Fig. 10. Vulnerability map for Liverpool Bay's storm scenario.

season (JNCC, 2022).

Oil from LB2 impacts the moderately sensitive, gravel/pebble shores of Haverigg and Silecroft, which are located in the Morecambe Bay and Duddon Estuary SPA (Fig. 9). The Morecambe Bay and Duddon Estuary SPA supports internationally important waterbird and seabird assemblages (JNCC, 2022).

7.3. Model #3 - Liverpool Bay's storm scenario

Fig. 10 shows how oil released at LB1 impacts the shore near Seaforth and Crosby. The Seaforth Nature Reserve is also impacted, which provides special protection for a variety of waders, seabirds and ducks (Lancashire Wildlife Trust, 2022).

The LB2 spill covers the shoreline of Blackpool and its surrounding areas. Blackpool was classified with a low ESI rating of 1 based on the high-tide images provided in Google Earth, which highlight the presence of a vertical seawall along the whole of Blackpool. However, at low tide, a vast area of sand becomes exposed, increasing the sensitivity of the region. One limitation of using Google Earth is the difficulty in classifying shorelines as images taken at a particular point in the tide cycle, missing the full details of the shoreline and the tidal range it experiences.

Oil derived from LB2 is likely to spread over a vast area, including the extremely vulnerable areas of Morecambe Bay SPA and the Ribble and Alt Estuaries SPA (Fig. 10). Morecambe Bay SPA is one of the best examples in the UK of an area with a variety of protected features, including sandbanks, estuaries, mudflats, sandflats, coastal lagoons, reefs and Atlantic salt meadows (JNCC, 2022). The Ribble and Alt Estuaries SPA contain tidal flats and saltmarshes that support internationally important populations of waterfowl in winter months (JNCC, 2022).

7.4. Model #4 - Milford Haven's summer scenario

Oil from MH1 covers St Annes Head and the Dale shorelines, spreading to near the Skomer and Skokholm Islands (Fig. 11). These areas are all part of the Skomer, Skokholm and the Seas off Pembrokeshire SPA, which supports the largest concentration of breeding seabirds in England and Wales, together with the largest breeding colony of Manx shearwater in the world (JNCC, 2022).

In the MH2 spill scenario, a range of protected areas are impacted by both the model's best-guess estimate and its uncertainty (Fig. 11). The spill ended up off the coast of Northern Ireland near the Strangford Lough Marine Conservation Zone (MCZ) and SPA. Strangford Lough comprises protected species and habitats that include tidal rivers, estuaries, mudflats, sandflats, lagoons, salt marshes, reefs and the harbour seal (JNCC, 2022). It also qualifies as a Ramsar site due to its internationally important wetland, which supports large numbers of wintering and breeding birds (JNCC, 2022). The oil uncertainty also spread either side of Strangford Lough, into the North Channel SAC and Murlough SAC, which are home to the protected Harbour porpoise and common seal, respectively (JNCC, 2022) (Fig. 11).

7.5. Model #5 - Milford Haven's winter scenario

Oil from MH1 reaches Mill Bay, located just off St Annes Head (Fig. 12). In terms of ESI, the area has a low sensitivity rating due to its greater exposure to wave action. Oil spill uncertainty is slightly different in this map as the slicks have completely settled on the shoreline, which can be seen as thin grey lines. Oil from MH1 also enters the Milford Haven waterway with most of it covering the shoreline of St Ishmaels, which consists of small bays with gravel/pebble beaches. This area is

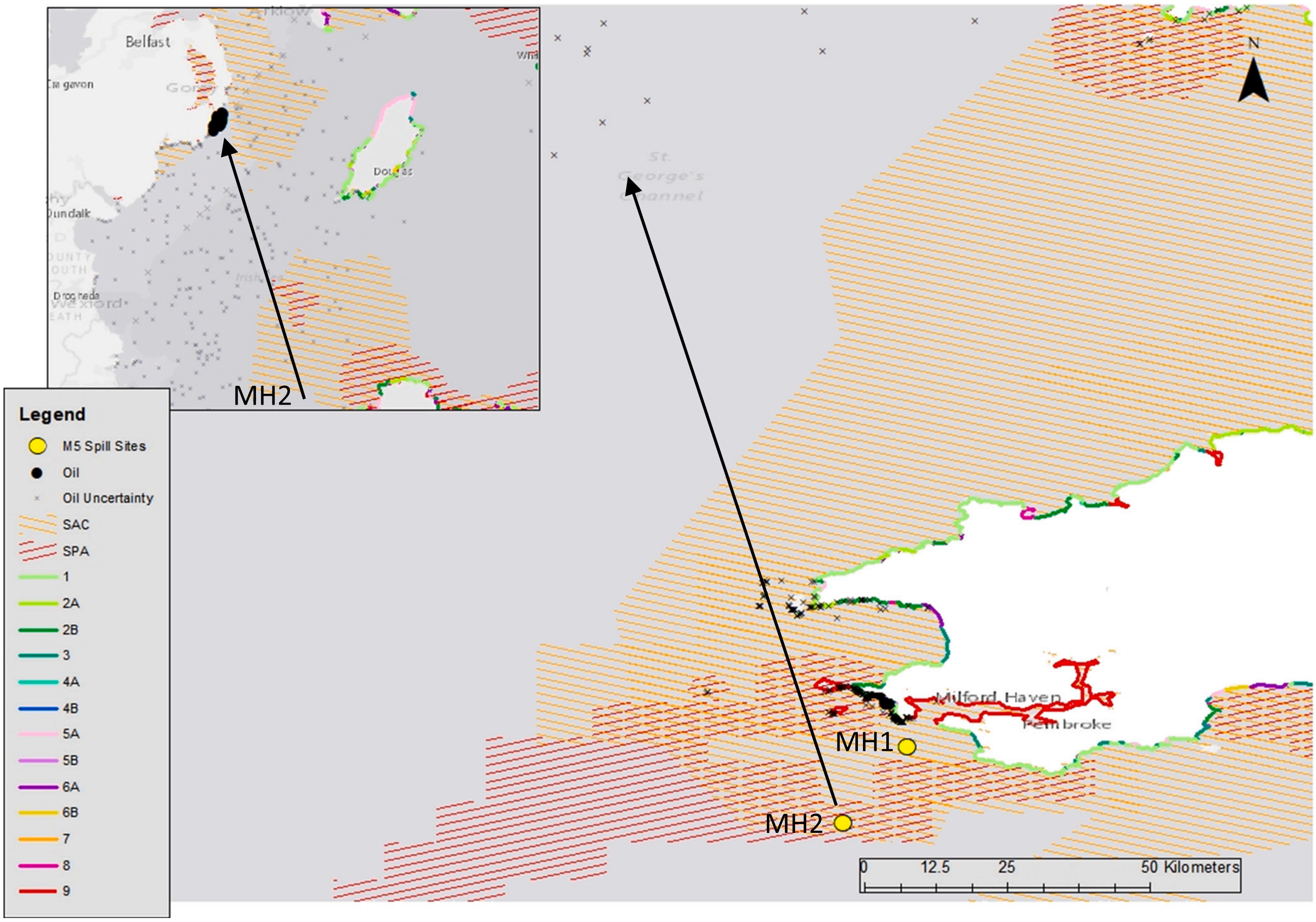

Fig. 11. Vulnerability map for Milford Haven's summer scenario. Top left box highlights the final beaching of MH2 oil in Northern Ireland.

also part of the Pembrokeshire Marine SAC, which has protected populations of allis shad, grey seal, otter, river lamprey, sea lamprey, and twaite shad (JNCC, 2022).

Oil from MH2 covers the entirety of the Marloes Sands beach, spreading also over rocky headlands and wave cut platforms (Fig. 12). Therefore, the best-guess estimates for the MH2 spill scenario highlight a low-moderate sensitivity rating for the region. However, oil may also reach the Skomer and Skokholm Islands, which are highly vulnerable areas, as previously stated.

7.6. *Model #6 - Milford Haven's storm scenario*

Under storm conditions, Fig. 13 shows the Angle shoreline and Freshwater West beach to be impacted by oil derived from MH1. The area rates low on the ESI classification, and is characterised by its natural exposed rocky cliffs (ESI 1) and fine to medium grained sandy beaches (ESI 3). Similarly to the previous Liverpool Bay oil spill scenarios, oil from MH1 also moves swiftly towards environmentally protected shorelines under storm conditions, in this case towards the Pembrokeshire Marine SAC (Fig. 13).

Oil released by MH2 impacts large areas of the Carmarthen Bay SPA, with the best-guess estimate reaching the Pembrey shoreline and spreading to the Gower Peninsula (Fig. 13). The Pembrey shoreline has an ESI rating of 7 due to its 'wet' sandy beaches and the possible entry of oil into rivers. Western areas of the Gower Peninsula also have an ESI rating of 7. However, exposed rocky cliffs and headlands are present on the eastern side, and classify as low sensitivity shores. Nevertheless, an oil spill in this area would be devastating, especially as the Gower Peninsula is Britain's first designated Area of Outstanding Natural Beauty (Gower Peninsula, 2022). The Carmarthen Bay and Estuaries SAC was also impacted by the spill, potentially impacting various protected species and habitats (JNCC, 2022).

8. Discussion

8.1. *Influence of wind and currents on oil spill trajectories*

The results in this work can be discussed under the scope of Elliott and Jones (2000) hindcast study of the *MV Sea Empress* oil spill, as it is particularly relevant for the Milford Haven sites (Figs. 1 and 5). The MH1 scenarios affect an area very close to the actual spill site of the *MV Sea Empress*, which hit rocks off St Annes Head on route to Milford Haven's port (Winterton, 2021). However, Elliott and Jones (2000) found wind, currents and tides to have closely influenced oil spill trajectory in the latter accident. They identified wind to have had the greatest effect on the movement of oil, with tides and residual currents due to freshwater inflows having a smaller influence (Elliott and Jones, 2000). These results contrast with the Milford Haven scenarios presented in this paper, in which the bulk of oil was transported towards the shore, whereas wind direction and tides carried most of the oil from the *MV Sea Empress* into deep waters to the south of Milford Haven (Law and Kelly, 2004). This permitted the use of dispersants in areas far from the shore, reducing the overall impact of the spill (Law and Kelly, 2004). However, based on our simulation and the exceptional environmental value of the area near MH1, impacts may be much more severe in case of a future oil spill (Figs. 5, 11–13).

Wind action plays a significant role in the shallow eastern Irish Sea, as highlighted in the Liverpool Bay scenarios (Figs. 4, 8–10). Liverpool

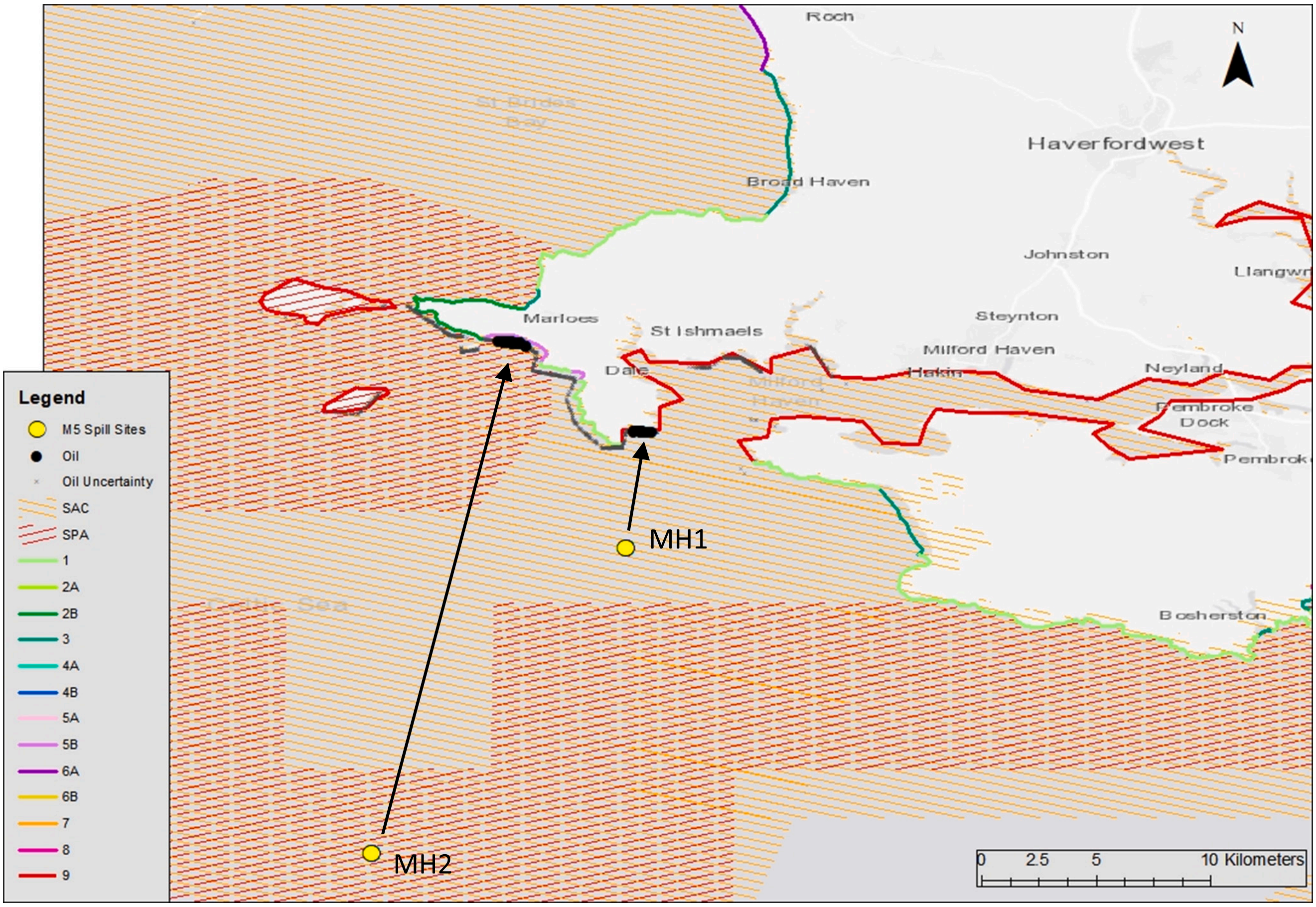

Fig. 12. Vulnerability map for Milford Haven's winter scenario.

Bay's winter and storm spills near the LB1 and LB2 buoys quickly drift towards the shoreline, following the predominant winds. Near-surface flows within the eastern Irish Sea are also approximately in the direction of the wind in such a scenario, highlighting the significance of wind-induced oil movement (Barnes, 1984). Under storm conditions, oil spills were found to move at the greatest velocity due to the high winds. A study by Youseff and Spaulding (1994) also found the drift factor of an oil slick to increase with wind speed in shallow water, as exemplified in the Liverpool Bay's winter and storm scenarios (Fig. 4d–i). Storm surges pose an additional risk under these conditions as they can transport oil spills at even greater velocities, allowing little time for response and clean-up operations (Trevors and Saier, 2010). This could become an issue for the UK as predictions of changes in local climate and sea level consider future increases in the frequency of storm surges (Lowe et al., 2001).

In what ocean currents are concerned, they had a significant influence in both Liverpool Bay's and Mildford Haven's summer scenarios due to calmer sea conditions and lower wind speeds (Figs. 4 and 5). This clearly stresses the fact that when an oil spill occurs is just as important as where. The influence of ocean currents is particularly noted in the Milford Haven summer scenario, during which oil from MH2 drifts past the west coast of Pembrokeshire following currents and the general northerly flow of water coming from the Celtic Sea (Bowden, 1980) (Figs. 5a–c and 11). GNOME simulations also highlight that ocean currents have a greater influence over the oil spill trajectories in deep waters, away from the shore. In summer conditions, oil spilt by both LB2 and MH2 drifts into deep-water areas primarily influenced by currents (Figs. 4 and 5). MH2 oil enters an area close to St. George's Channel (>80 m deep), whereas oil released at LB2 enters the middle of the eastern Irish Sea, which is deeper than nearshore areas but still relatively shallow (around 30 m deep). A study by Naidu et al. (2012) also supports these findings, recognising that the strength of ocean currents is stronger in open-sea areas than near the shore. In the particular case of the western Irish Sea, the cyclonic circulation of a gyre influenced the final beaching of oil in the MH2 summer spill (Fig. 4c). Future spring/summer oil spills within the vicinity of the gyre will likely have the same outcome. Additionally, the gyre will retain pollutants, increasing the risk of environmental damage (Hill et al., 1997).

8.2. Oil spill fate and response

Oil spill prevention remains the most important part of oil-spill risk management, as no fool-proof clean-up methods have been discovered yet (Othumpangat and Castranova, 2014). However, when a spill does occur several measures can be implemented, with the main options comprising dispersant spraying, in-situ burning and mechanical countermeasures (e.g., booms, skimmers, current busters and sweeping arm systems).

The shorelines surrounding the spill sites considered in this work are similar to the Cantabrian coast of N Spain an area affected by the *MV Prestige* oil spill in November 2002. The main types of environments in Cantabria include estuaries, rocky shores and sandy beaches (Castanedo et al., 2009). Oil spill assessments carried out by Castanedo et al. (2009) after the *MV Prestige* released 63,000 tons of bunker C oil into the marine environment have suggested that estuaries comprised the most vulnerable habitats, especially from a physical point of view (González et al., 2006; Penela-Arenaz et al., 2009). The same assessments also found that, in coastal areas, oil quickly adheres to intertidal vegetation with a very low self-cleaning capacity. This agrees with the information gathered after *MT Hebei Spirit* oil spill in South Korea, occurred in December 2007,

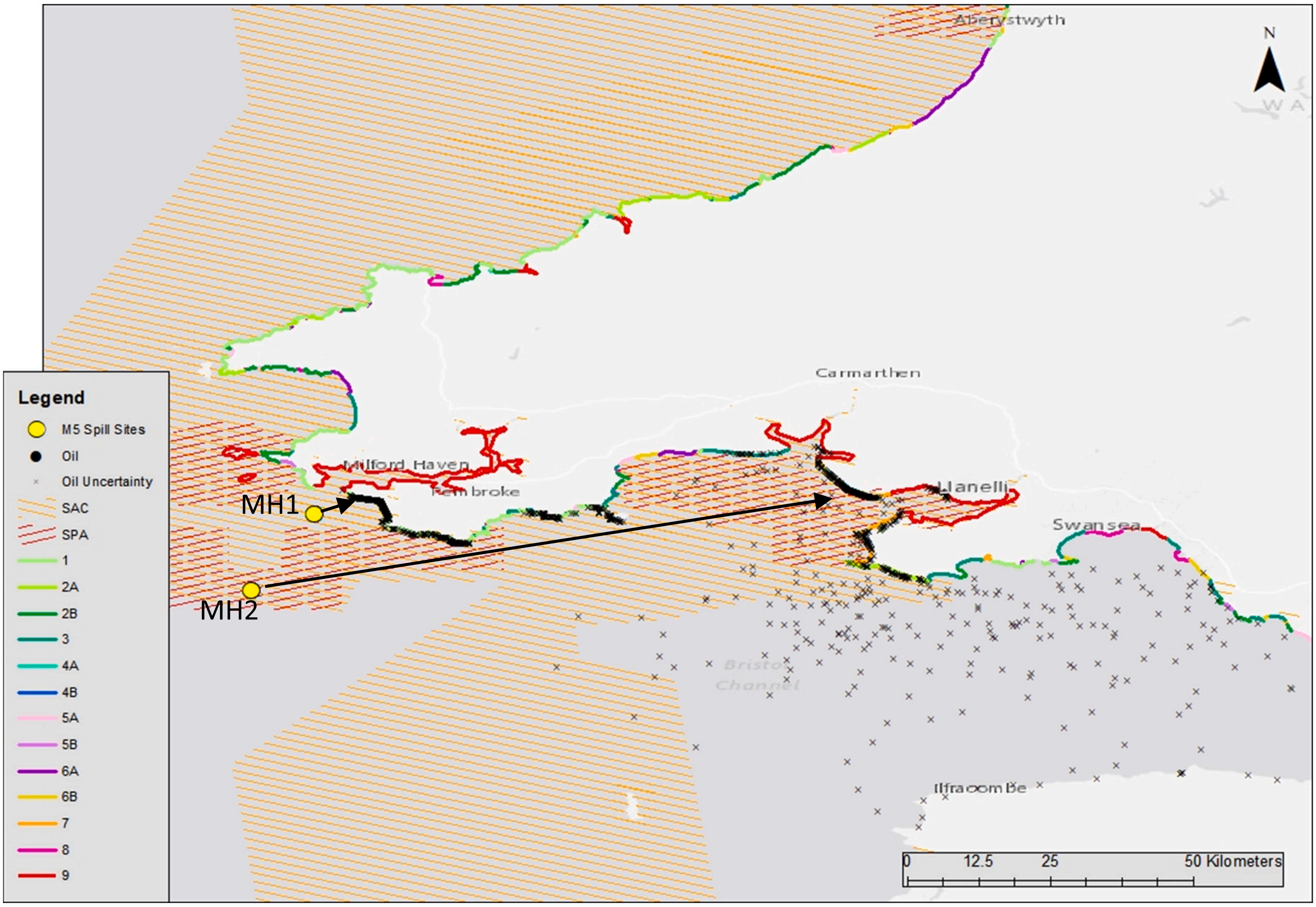

Fig. 13. Vulnerability map for Milford Haven's storm scenario.

where oil was found to persist for longer within low energy regions such as intertidal areas of mudflats (Barron et al., 2020).

In this work, vulnerability maps for all Irish Sea scenarios identified at least one impacted shoreline with the highest sensitivity rating (ESI 9) (Figs. 7 to 13). These same maps highlight a large proportion of ESI 9 areas as comprising estuaries, which are common features around the Irish Sea (JNCC, 2022). Estuaries are sheltered low-energy environments that connect freshwater rivers or streams to the ocean. They are also closely associated with a wide range of sensitive habitats such as sand and mud flats, sand banks, reefs and salt marshes (JNCC, 2022). Multiple authors have previously found low energy coastal ecosystems, such as salt marshes and wetlands, to be particularly vulnerable to the presence of oil, taking up to 50 years to recover from a spill (Gundlach and Hayes, 1978; Kingston, 2002; Ornitz and Champ, 2007). These areas also contain productive aquatic environments that are easily damaged (Nelson and Grubesic, 2017). Therefore, estuaries and their associated low-energy habitats should be regarded as high priority areas to protect in the event of an oil spill. Additionally, the Skomer and Skokholm Islands should also be prioritised by response and recovery plans. The islands support huge numbers of breeding seabirds and other protected species (JNCC, 2022). An oil spill in the vicinity of these islands could be as severe as the *MV Erika* oil spill was in France in 1999, in which 42,000 seabirds were killed (Neuparth et al., 2012).

Our ADIOS results for different oil types are in line with the changing laws of oil spill weathering for evaporation, dispersion, and emulsification processes (ITOPF, 2002). For instance, evaporation played the greatest role in naturally removing oil from the water surface for all oil types considered in our scenarios (Fig. 6). In our models, the main factor controlling evaporation is the composition of the spilled oil; a higher API gravity oil with more volatile components increases the extent and rate of the evaporation process (Fingas, 2021). Dispersion had a less significant role in the natural removal of oil. The process was found to largely depend on the sea state, with increases in dispersion correlating with higher wave height and wind speed (Fig. 6). Stable water-in-oil emulsions only formed for Brent and Gullfaks during the 5-day timescale, due to the specific compounds (e.g., asphaltenes) in these crude oils that promote and stabilise emulsions (Lee, 1999). In terms of oil type, Group 4 heavy oils (e.g., bunker C) proved to be the most persistent and will likely result in the most severe damage to the marine environment (Ansell et al., 2001).

Evaporation is a physical process leading to the removal of the volatile fractions of spilled oil, thus reducing a significant portion of the total mass of the slick within a short time – a rate that depends on oil composition, degree of oil emulsification, and the metocean conditions at the time of the spill (Zodiatis et al., 2017). Therefore, evaporation is revealed as the most important weathering process in our analysis, helping the removal of volatile low-molecular weight components from the spilled oil, components that are especially important in light petroleum products (Mishra and Kumar, 2015). The rate at which evaporation occurs depends upon the volatility of the oil. For example, light products such as gasoline can evaporate almost completely within a few days and do not tend to form emulsions. In contrast, losses in volume of heavy oils (e.g., bunker C) are minor due to their high viscosity and lack of volatile components (Fingas, 2004; El-Fadel et al., 2012).

Our results concerning oil evaporation are here compared to a study by Fingas (2021), as shown in Fig. 14. ADIOS results follow a similar logarithmic curve relative to time when compared with the data in Fingas (2021). According to Fingas (2021) study, around 80 % of the oil evaporation occurs in the first two days (Fig. 14a). Our results also follow this general trend, with 80 % of oil evaporation (for a total of 5

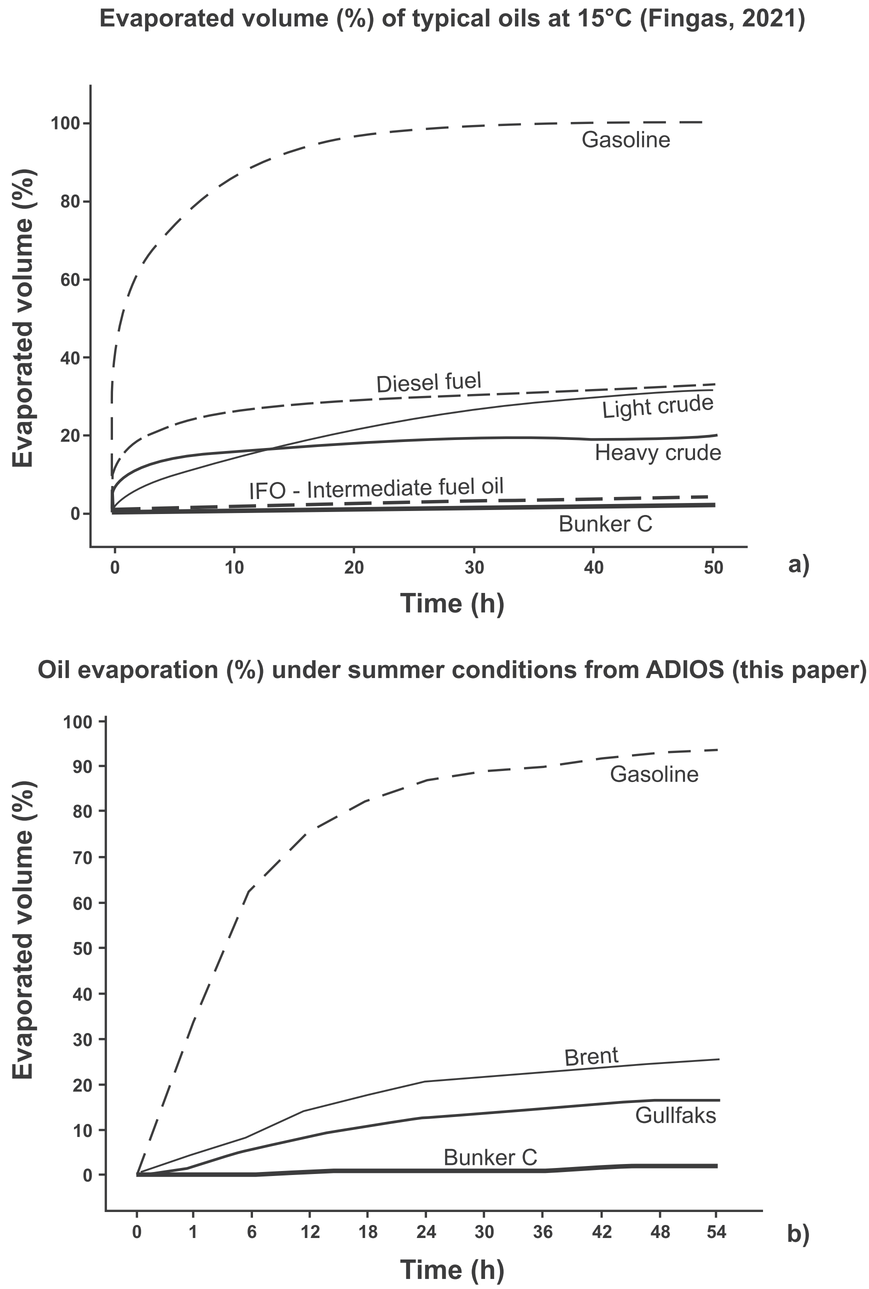

Fig. 14. Comparison between the evaporation of oil in Fingas (2021) and the results of this work. a) Graph showing the evaporation of typical oils at 15 °C (Fingas, 2021). b) Oil evaporation under summer conditions gathered from the ADIOS models completed for this work.

days) occurring at 48 h for Brent, Gullfaks and bunker C (Fig. 14b). It is worth noting that the rate of evaporation also depends on atmospheric and sea temperatures (ITOPF, 2002). However, our results found that sea temperature in the Irish Sea has a smaller influence on evaporation than wind speed. Both factors had a minimal influence compared to that of the oil spill's composition. Overall, the amount of oil evaporation increases in oils with low viscosity, high API gravity and increased volatility (Fingas, 2021).

Dispersion can be defined as the uptake into the water column of oil droplets of diminishing size, until they are no longer part of the slick (Zodiatis et al., 2017). This process is promoted by wave action, which separates the oil in droplets of various sizes and drives them into the water column, thus generating a cloud of droplets beneath the spill. Dispersion is, therefore, a key process in determining the expected lifetime of spilled oil on the surface of the ocean (Johansen et al., 2015). A study by Elizaryev et al. (2018) found wind speed, water temperature and wave height to be main influencing factors in dispersing oil. In our work, dispersion was also found to largely depend on the sea state with increases in dispersion being seen with increases in wave height and wind speed. Similarly to evaporation, sea temperature did not greatly affect the rate of dispersion; summer scenarios had the lowest dispersion of all scenarios, despite the highest sea temperatures. The low sea-energy and a lack of breaking waves associated with summer conditions would have also contributed to the limited dispersion of oil (Yudiana et al., 2018). Interestingly, dispersion was highest for Gullfaks oil, which was also the type of crude oil spilled by the *MV Braer* in 1993. Due to the 'light' properties of Gullfaks oil, and the severe weather conditions at the time of the *MV Braer* spill, oil dispersed naturally with minimal impact on the shoreline (White and Molloy, 2003).

Generally, dispersion will occur most rapidly for lower viscosity oils (ITOPF, 2002). However, our ADIOS results do not support this postulate, with dispersion occurring slowly for gasoline and Brent oil but

Table 3
Summary of the techniques for oil spill removal in water. Table adapted from a study by Qiao et al. (2019).

Techniques	Advantages	Limitations
Booms and skimmers	• Efficient treatment for emulsified oils and oils of variable viscosity • No adverse environmental effects	• Ineffective in rough weather/sea conditions • Time consuming and expensive (on a large scale). • Require significant personnel and equipment
Natural sorbents	• Inexpensive • Eco-friendly and sustainable option	• Less efficient than synthetic options.
Dispersants	• Rapid and effective elimination of large volumes	• Effective for oils with viscosity <2000 cSt • Can be harmful to aquatic creatures • Less effective in calm waters
Bioremediation	• Efficient, cheap and environment friendly	• Limited by nutrient substance, pH and temperature. • Ineffective for large spills

more quickly for Gullfaks oil (Fig. 6, Table 4 and Supplementary File 3). Evaporation occurred first for all oils, removing most of the volatile components and leaving less oil to be dispersed (Supplementary File 3). As Gullfaks oil has low evaporation rates more oil was left to disperse, hence higher dispersion rates. This highlights that dispersion plays a less significant role than evaporation. Although bunker C could not be simulated for winter or storm conditions, a study by Fingas (2021) found that bunker C or heavy crude oils will not disperse naturally to a significant extent.

Emulsification concerns the formation of a water-in-oil emulsion, in which water becomes mixed with oil in the slick (Zodiatis et al., 2017). It does not start until a certain amount of oil has been evaporated, though some data points out to an early emulsification in particular cases. The emulsification process is thus sensitive to the initial oil viscosity and composition of an oil spill (Mishra and Kumar, 2015). Some studies suggest that the relative amount of waxes, resins and asphaltenes in oil plays the dominant role in determining its emulsification (Bobra, 1991). These compounds have high molecular weights, typically found in crude oils (Mansoori, 1996). Additionally, most medium-heavy crude oils will only emulsify after a certain amount of evaporation has occurred (Lehr et al., 2002). Results suggest that gasoline does not create a stable emulsion mousse at the sea surface, due to its low percentage of high molecular weight compounds (Fig. 6, Table 4 and Supplementary File 3). Similarly, Bunker C did not form an emulsion mousse as this oil type tends to take up water slowly due to its high viscosity (ITOPF, 2002).

It is important to note that although evaporation and dispersion remove oil from the sea surface, emulsification increases the persistency and volume of spilled oil (ITOPF, 2002). Emulsification also impedes the weathering abilities of other processes such as evaporation (Fingas et al., 1993). As emulsification depends heavily on water turbulence, water-in-oil emulsions are more likely to appear after storms conditions and can exist in the marine environment for more than three months (Speight and Jauhari, 2012). Additionally, the stability of these emulsions generally increases with decreasing temperature, i.e. emulsification processes are likely to play a larger role within the storm scenarios, due to low temperatures and increased water turbulence.

8.3. Recommendations concerning oil spill response at sea

Table 3 summarises the advantages and limitations of all the recommended techniques thus far discussed. A combination of these methods is advised for maximum clean-up potential. As each oil spill is unique, metocean conditions should be taken into consideration as well as the location, quantity and types of oil spilled.

The first step of response plans should be to prevent the spilled oil from encountering sensitive shorelines, something that requires the oil's physical containment. Oil containment should begin as soon as possible due to the sensitivity of the locations around the Liverpool Bay and Milford Haven scenarios. As our oil spill scenarios assume a continuous leak of oil from a grounded vessel, this same vessel should be towed to a shoreline area where the spill can be contained or securely extracted (Alves et al., 2014, 2015). However, this process can be hindered by poor weather conditions as previously recorded during the *MV Prestige* oil spill, where the tanker had to be towed further offshore instead of the nearest harbour or ria (Liu and Wirtz, 2006). Assuming that a stricken tanker in the Liverpool Bay and Milford Haven scenarios is in a good-enough state to be towed, it should be brought into an appropriate area at the shore. For the Liverpool Bay scenarios, the tanker could potentially be towed into Holyhead port (North Wales). In comparison to the area surrounding Liverpool port, Holyhead has a lower shoreline ESI rating and less shipping traffic, making it a more viable option. The Milford Haven port comprises the necessary equipment available to contain the spill and pump the remaining oil from a stricken tanker. Although the area has an ESI 9 rating, there are no other ports within the region that would be able to handle a large Long Range (LR2 tanker; Supplementary Table 1), turning it into the best option in these circumstances.

Booms are also a go-to approach for containment, which act as floating physical barriers to oil (NOAA, 2019). However, booms are extremely susceptible to weather conditions and will fail at a current of 0.5 m/s due to their inherent hydrodynamic limitations (Fingas, 2011). Boom containment will be only effective within the summer scenarios and calm waters. As the spills sites are located relatively close to shorelines and major ports, response resources will be easily accessible so mechanical recovery options (booms, skimmers, current busters) will be more efficient (Etkin and Nedwed, 2021). Skimmers are devices used for removing oil from the surface of the water but decreases in their recovery potential are observed with increasing wave height (Fingas, 2011), once again limiting their effectiveness in winter/storm scenarios. Current busters are increasingly being used within oil spill containment and recovery as they can withstand currents up to 3,5 knots without gross losses of oil.

Despite their inherent limitations, mechanical countermeasures have been occasionally able to recover large amounts of oil from nearshore spills. For example, the *MV Cosco Busan* oil spill of 2007 released 1260 bbl of heavy fuel oil into San Francisco Bay, and 43 % of the oil on the water surface and land was recovered (Etkin and Nedwed, 2021). In contrast, experience shows that recovery rates are usually low for major oil spills, where a retrieval of around 10–20 % of the spilled oil is expected (Linkov and Clark, 2003). It has also been observed that mechanical oil removal methods can increase the vulnerability of salt marsh vegetation (Andrade et al., 2004). Therefore, skimming is only an option for open waters where sensitive vegetation is not present.

Chemical dispersants are the UK's primary response method to offshore oil spills (ITOPF, 2015). Dispersants can help mitigate impacts on marine mammals and seabirds, as well as prevent the spilled oil from reaching sensitive shoreline (Ghurye et al., 2014). They contain surfactants and/or solvent compounds that break oil into small droplets, encouraging the natural dispersion of oil. Nevertheless, the effectiveness of dispersants is dependent upon metocean conditions and the type of oil spilled. Similar to the natural dispersion of oil, chemical dispersion works better with rough seas and is a more appropriate option for winter/storm scenarios (Obi et al., 2014). Additionally, oil viscosity should be <10,000 cSt as light to medium weight oils disperse better

Table 4
Effectiveness of oil spill countermeasures from ADIOS results. Effectiveness determined from the amount of remaining oil after 5 days at sea, before (no response) and after countermeasures were applied.

		Oil remaining beached and remaining on the sea surface 5 days after the spill			
Season	Clean-up method	Gasoline	Brent	Gullfaks	Bunker C
Summer	No response	2 %	68 %	78 %	96 %
	Skimming	–	62 %	70 %	86 %
	Dispersants	–	68 %	77 %	95 %
Winter	No response	1 %	65 %	74 %	–
	Skimming	–	59 %	66 %	–
	Dispersants	–	64 %	72 %	–
Storm	No response	1 %	62 %	70 %	–
	Skimming	–	57 %	63 %	–
	Dispersants	–	62 %	69 %	–

than heavy crudes (Ghurye et al., 2014).

The *MV Sea Empress* oil spill demonstrated an appropriate, measured use of dispersants, with at least 17,000 tons of crude oil having been prevented from coming ashore (Purnell, 2003). However, a study by Bassey et al. (2017) suggests that dispersants are not a favourable method in ecologically sensitive areas due to their toxicity; dispersants are not recommended for sensitive nearshore areas, being more appropriate for those spills occurring further offshore. In fact, the use of chemical dispersants has been criticised since the *SS Torrey Canyon* accident of 1967, in which the use of first-generation dispersants killed significant numbers of the local fauna (Kleindienst et al., 2015). Another negative example is the *MV Eleni V* spill off the Norfolk coast in May 1978. In this occasion, 900 tons of dispersants were applied to the 7500 tons of heavy fuel oil spill, with no discernable effect (Nichols and Parker, 1985). Advances in modern dispersants have made them no more toxic than the oil itself (Purnell, 2003), improving their ability to treat oils with higher viscosities but, ultimately, dispersants remain relatively ineffective on heavy fuel and crude oils with greater viscosity and density (Ansell et al., 2001).

ADIOS allowed various clean-up options to be added to our oil spill scenarios with the aim of testing their effectiveness on different oil types under summer, winter and storm conditions. The in-situ burning of oil could also be simulated in ADIOS, but the UK contingency plans discourage this option (Morton, 2020). For gasoline, clean-up methods are not generally needed as most will evaporate or dissolve by the time responders reach an accident site (Etkin, 2000). Gasoline has a high natural clean-up ability, with only 1–2 % of gasoline remaining in the water after 5 days (Table 4). In contrast, a no response or 'natural clean-up' option is not feasible for the other oil types due to the sheer volume of oil remaining at the sea surface after a spill (Fig. 6). ADIOS results for summer conditions highlight that skimming decreases the volume of the Brent oil spill by 6 %, 8 % for Gullfaks and 10 % for bunker C oil (Table 4). Therefore, the efficiency of skimming methods increases with the viscosity of the oil type and the associated thickness of the oil slick at the sea surface.

Chemical dispersants are much less effective, only reducing the total volume of oil by a maximum of 2 % in the winter Gullfaks scenario (Table 4). However, the type of dispersant used is known to impact the chemical dispersion of oil. A study by Lunel et al. (2000) found Corexit 9500 to be the most effective dispersant; it is therefore used to treat operational discharges from the Milford Haven refinery. A combination of mechanical methods and dispersants is recommended for Brent and Gullfaks oils, depending upon the local weather and sea conditions at the time of the spill. Due to the greater viscosity of bunker C, dispersants are not expected to be effective and mechanical options must be prioritised (Purnell, 2003).

As a corollary to this work, it is worth stressing that the only weathering process that completely removes oil from the marine environment is biodegradation; the other processes only transform and dilute oil components in the short term (Nordam et al., 2020). Therefore, enhancing the biodegradation of an oil spill through bioremediation is recommended in this work. A study by Andrade et al. (2004) looked at the effects of the Prestige oil spill on salt marsh soils, suggesting that future clean-up methods must focus on bioremediation as an alternative method to the mechanical extraction of oil. Nevertheless, there are some limitations to bioremediation; high molecular weight oils are not readily amenable to microbial degradation, so the effectiveness of bioremediation on oils such as bunker C fuel is often limited (Megharaj et al., 2014). Bioremediation is also recommended as an alternative to mechanical extraction only for sensitive shorelines.

8.4. Uncertainty in oil spill models

The uncertainty of trajectory forecasts is a crucial component in decision making, especially as oil-spill models are sensitive to errors in the initial input data, e.g. oil characteristics, rates, and changing weather/sea conditions (Li et al., 2018). In practice, this means that the oil uncertainty estimated in the GNOME simulations increases with time. This fact is supported by Simecek-Beatty (2011), who found trajectory uncertainty to be low to medium after 24 h, but high after 72 h not because of inconsistencies in the modelling itself, but due to unpredictable changes in wind and current forecasts. In parallel, the rates at which oil spill weathering processes occur are understood at different levels of confidence, causing much uncertainty throughout the published literature (Berry et al., 2012). It is important to stress that most weathering models are based and calibrated on empirical results from small-scale field and laboratory tests, at much smaller volumes to major oil spills (Sebastião and Guedes Soares, 1995; Lehr et al., 2002).

All in all, there will always be a level of uncertainty surrounding oil spill models as they are based on assumptions of processes and cannot entirely replicate the complexity of an environmental system, especially when simulations are hypothetical and there is no real oil spill data to validate model results (Vethamony et al., 2007). Due to the natural variability of metocean conditions, the uncertainty of oil spill trajectories needs to be estimated for the outcome to be as accurate as possible (Uusitalo et al., 2015). Fortunately, GNOME uses uncertainty algorithms for the perturbation of current and wind data, which provided an uncertainty evaluation for the model's best estimate (Keramea et al., 2021). ADIOS also displays output uncertainty, which provides a wider range of possible outcomes.

One of the main limitations of our approach is that tides have not been accounted for within the simulations. Considering that the circulation of the Irish Sea is strongly influenced by tides, oil spill trajectory results may differ substantially with the addition of tidal inputs (Robinson, 1979). Research has shown that the accuracy of oil spill trajectory prediction is higher when tidal currents are included (Buranapratheprat and Tangjaitrong, 1999). Future work would benefit from the addition of tidal information, estimating oil spill trajectories in conjunction with rising and falling tides, which will produce more localised effects (Marghany, 2004).

Another limitation is that only physical shoreline vulnerability is classified (Santos and Andrade, 2009). The ESI approach taken in this work neglects any important socio-economic factors. To fully understand the breadth of impacts associated with an Irish Sea oil spill, the ESI approach should be combined with a full vulnerability assessment, including all physical, biological, social and economic factors involved.

Finally, there is no way of validating the modelling results in this work, as they are hypothetical. However, they do provide a useful guide for future contingency plans. For real oil spill incidents or hindcast studies, oil spill models should be updated by observations from overflights or satellites (Beegle-Krause, 2001). The uncertainty of trajectory forecasts is a crucial component within decision making processes, especially as oil spill models are sensitive to errors in the initial input data (e.g., oil spill details and weather/sea conditions). As a result, responders who solely focus on the single best-guess estimate tend to make less favourable decisions (Simecek-Beatty, 2011).

9. Conclusions

This work supports the use of a combination of methods for maximum oil clean-up potential in the Irish Sea. As each oil spill is unique, metocean conditions should be taken into consideration as well as the location, quantity and types of oil spilled. The main findings in this work can be summarised as follows:

a) Wind has the most significant influence on the trajectory of oil spilled in the Irish Sea, especially with high wind speeds (winter and storm scenario) and in shallow waters. Ocean currents play a secondary role. Ultimately, the results in this work clearly stress that when an oil spill occurs is just as important as where.
b) Evaporation is the dominant weathering process and plays the largest role in the natural removal of oil from the sea surface. Dispersion has a relatively minor influence. The main factor controlling evaporation is oil composition, whilst dispersion largely depends on wave height and wind speed.
c) Stable water-in-oil emulsions only form in crude-oil spills. Evaporation occurs first, followed by dispersion and emulsification, highlighting the importance of a timely response.
d) Low energy and sheltered shorelines were found to have the highest sensitivity ratings, and should be prioritised for protection within contingency plans.

The severity of a future Irish Sea oil spill will also depend on 1) the quantity and chemical composition of the oil spill, 2) the prevailing metocean conditions, 3) the sensitivity of the environment affected and 4) the effectiveness of the chosen clean-up strategies. For the Irish Sea, the effectiveness of containment and recovery options relates to the chemical composition of the oil spill and the prevailing metocean conditions. Booms and skimmers are recommended for oil spills in calm waters and for medium-high viscosity oils. Dispersants are advised for oil spills occurring further offshore, rough sea conditions and for low-medium viscosity oils. Additionally, natural sorbents and bioremediation approaches are recommended as alternative options for areas near sensitive shorelines.

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CRediT authorship contribution statement

Shania Hughes: Writing – original draft, Conceptualization, Investigation. **Tiago M. Alves:** Supervision, Conceptualization, Methodology. **T.C. Hales:** Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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