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Forecasting System for Predicting the Dynamics of Oil Spill in a Tide-Dominated Estuary

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ABSTRACT

Crude oil is predicted to become one of the most detrimental sources of anthropogenic pollution to estuaries. A comprehensive survey of oil spill literature reveals that oil spill transport in estuaries presents a gap in academic knowledge and literature. To address this gap, we present the first detailed analysis of estuarine oil spill dynamics. We develop and analyse a range of simulations for the Humber Estuary, using TELEMAC3D; a coupled hydrodynamic and oil spill models. The river boundary of the Humber Estuary is forced by discharge data, while the offshore boundary is driven by tidal height data, including estuarine water temperature and salinity. The calibrated model shows good agreement with measured data during the validation process. Results show that: (a) the time of oil release within a tidal cycle significantly influences oil slick transport; and (b) the tidal range significantly influences oil slick impacted area and overall distance travelled, as oil slick released under spring tide is approximately double the oil slick size under neap tides and travels on average 71% farther. This study emphasises the need to: a) understand how the interaction of river discharge and tidal range influences oil slick transport; and (b) be aware of the time of release within a tidal cycle, to efficiently deal with oil spills. Findings should be useful for future operational oil spill response and could be equally applicable to other tide-dominated estuaries.

1. INTRODUCTION

Oil spills are a source of worldwide marine pollution due to growing energy demand and consumption which drives petroleum production as well as marine transportation (Chen et al., 2015; Kang et al., 2016). Oil spill impacts include damages to fisheries, water supplies, beaches and the ecosystem (Liu and Sheng, 2014). Consequently, Oil spills cause adverse environmental, social and economic impacts (Bernabeu et al., 2016; Kankara et al., 2016). The unpredictability of oil spills presents considerable oil spill risk around regions surrounding production platforms and along tanker routes (Vethamony et al., 2007). Understanding the oil travel path and oil travel time to receptors is important to mitigate the impact of oil spills (Berry et al., 2012).

Estuaries have very complex hydrodynamic and transport processes, as a result numerical modelling provides a good and effective approach for oil spill predictions to counter pollution threat (Hu et al., 2009; Abascal et al., 2017). Yet, the review of literature reveals that no numerical study has been undertaken to unravel the dynamics of oil spill transport in any tide-dominated estuary; therefore, we aim to address this research gap. Using the Humber Estuary as a case study, this study develops a numerical model for understanding oil spill transport in a tide-dominated estuary.

2. STUDY AREA

The Humber Estuary which is formed by the confluence of two major rivers (Rivers Ouse and Trent) at Trent Falls, is one of the largest estuarine systems in the UK with a mean discharge of ~250 m3/s (Fujii, 2007; Morris and Mitchell, 2013) (Figure 1). Several smaller rivers such as R. Freshney, R. Hull and R. Ancholm also discharge into the Humber Estuary. The estuary meets the North Sea at Spurn Head located approximately 62 km from the confluence (Trent Falls) (Figure 1; Boyes and Elliott, 2006). The distance of tidal influence extends from the mouth to 120 km and 147 km on Rivers Ouse and River Trent respectively (Mitchell 2013; Skinner et al. 2015). The Humber Estuary has a mean spring tidal range of 5.7 m, making the Humber a well-mixed macro-tidal estuary (Skinner et al., 2015).

In the outer Humber Estuary is the Tetney Monobuoy from which crude oil is offloaded and transferred through underground pipelines to the ConocoPhillips Ltd's Humber refinery (Cave et al. 2003). Furthermore, three marine terminal facilities, are located at the Southbank of the Humber (South Killingholme Jetty, Immingham gas jetty and Immingham oil terminal), which provide services to two oil refineries at Immingham (Humber Nature Partnership 2015). Consequently, the Humber Estuary plays host to oil tankers which berth at the oil terminals (Cave et al. 2003). These and other associated facilities at the Humber Estuary highlight the imminent risks of oil spills.

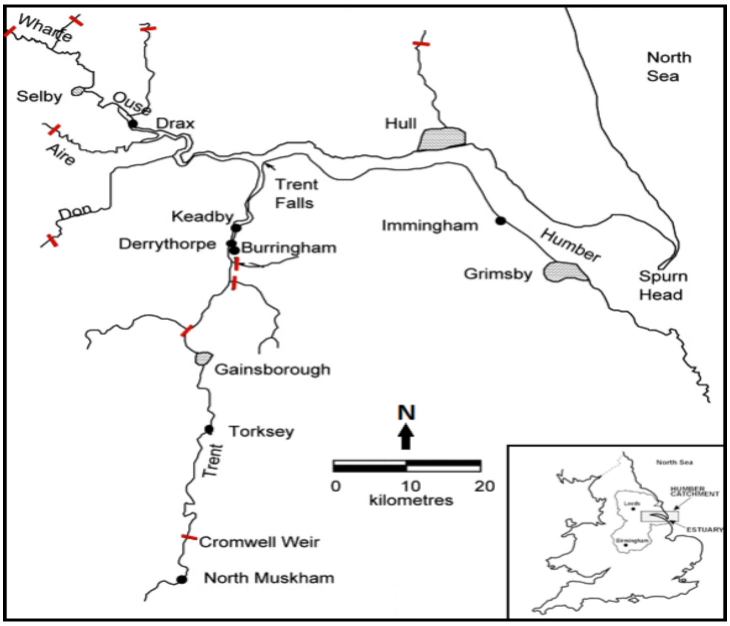

Figure 1: The Humber Estuary system. Inset shows the location of the Humber Estuary in the UK (Mitchell et al. 2003; Edwards and Winn 2006). Tidal limits are indicated as red bars crossing the channel.

3. DATA COLLECTION

3.1 Bathymetry

The bathymetry data for Humber Estuary was provided by the Association of British Ports (ABP), collected in 2008. The data extends from the entrance of the Humber Estuary to Blacktoft on River Ouse and Keadby on River Trent. Bathymetry point data were referenced to a local chart datum and all positions were aligned to Ordnance Survey National Grid 1936/British national grid (OSGB). Because of inconsistency in the reference level, an interpolated grid of values were employed to convert all depths to ODN (Ordnance Datum Newlyn).

3.2 River Input Data

Several rivers drain into the Humber Estuary. However, the largest freshwater discharge comes from Rivers Ouse and Trent (Morris and Mitchell, 2013; Wang and Townend, 2012). Caves et al. (2003) point out that River Hull contributes approximately 1% of the freshwater input while River Ancholme's freshwater contribution is less than River Hull's. Because of limited bathymetric data, this study only considers river input from Rivers Ouse and Trent. The absence of other river inputs (such as R. Hull and R. Ancholme) will not have any significant effect on the results, because of their relatively low freshwater discharge contribution. Due to limited high-resolution freshwater discharge data at the model's river input points, constant discharge obtained from literature is employed to drive the open river boundary for the winter month of February 2010. Consequently, the open river boundary was driven by 800 m^3/s and 400 m^3/s was measured at Blacktoft on River Ouse and Cromwell on River Trent respectively (Mitchell et al., 1999).

3.3 Offshore Input Data

Considering the unavailability of field tidal height measurements at the mouth of the Humber Estuary, 15-minutes tidal height data from the FES2014 model is used for setting the boundary conditions along the offshore input. Mean tidal height data from the interaction of 34 tidal components at the estuary's mouth was extracted from the FES2014 model (at 541049, 402468 and 540841, 409420). FES2014 is the most recent version of the Finite Element Solution (FES) global tidal model following the FES2012 (Carrère et al. 2013) and FES2004 versions (Lyard et al. 2006). FES2014 is based on hydrodynamic modelling with assimilation data (Zawadzki et al. 2016) and takes advantage of more accurate ocean bathymetry, improved modelling and data assimilation techniques, better altimeter standards and longer altimeter time series and a refined mesh in most shallow water regions (Lei et al. 2017). Ranji et al. (2017) and Seifi et al. (2019) compared eight different tide models in the Persian Gulf and Great Barrier Reef, Australia respectively. Both studies agree that FES2014 presents the best tidal prediction for coastal regions. Tidal harmonics obtained from the FES model have compared favourably with model outputs of the Irish Sea (Robins et al. 2013) and the European Shelf (Neil and Hashemi 2013); and has been employed to successfully develop a hydrodynamic model for the Conwy Estuary, UK (Robins et al. 2014).

3.4 Wind Data

Hourly wind data measured at an altitude of 8 m over the sea surface was provided by the UK Met Office. The wind data were recorded for February 2010 from the Donna Nook station (National Grid Reference 542900; 399700) located at the mouth of the Humber River estuary.

3.5 Temperature and Salinity

Temperature and salinity data were obtained from the "UK Environment Agency water quality archive". Analysis of 34 temperature measurements collected in February from various points around the Humber mouth between 2007 and 2014 resulted in an average temperature of 6.62 ^{o}C. While analysis of 61 salinity measurements collected in February from the same points around the Humber's mouth resulted in an average salinity of 27.20 ppt.

4. MATERIALS AND METHODS

4.1 Hydrodynamic Model

TELEMAC3D is a three-dimensional open-source finite element model that solves the Navier Stokes equations with or without hydrostatic pressure approximation (Guillou et al., 2016; Stansby et al., 2016). This study employs the hydrostatic pressure approximation due to the intense computational power demanded by non-hydrostatic pressure models (Botelho et al., 2009; Liu et al., 2016). TELEMAC3D employs a sigma transformation to resolve the vertical direction and unstructured triangular grid in the horizontal direction (Moulinec et al., 2011; Villaret et al., 2013). Sigma coordinate provides a good adaptation to the free surface and bathymetry as it provides an equal number of levels in deep and shallow water (Abascal et al., 2017). This makes TELEMAC3D ideal for this study as sigma models are best suited for coastal regions (Chassignet et al., 2006; Mehra and Rivin, 2010) and unstructured mesh for resolving complex bathymetry and geometry commonly observed in rivers, tidal flats, estuaries and coast in a robust, efficient and adequate way (Zhang and Baptista, 2008; Wang and Shen, 2010). Furthermore, TELEMAC3D provides a wide variety of numerical options to solve various processes within the model (Stansby et al., 2016).

4.1.1 Model Setup

TELEMAC3D requires three input files: the geometry file (a SERAFIN file which contains the information on the model mesh); the boundary condition file (a command-line user interface file which describes the domain's boundary condition); and the steering file (a CASsette file that describes the configuration of the simulation) (Gifford-Miears and Leon, 2013; Rahman and Venugopal, 2015). The geometry and boundary condition files were developed with Blue Kenue; a software developed by the Hydraulic Canadian Centre which proposes a powerful mesh generation and user-friendly pre- and post-processing tool (Pham et al., 2016), while the steering file was developed with a text editor.

Blue Kenue was employed to develop an unstructured mesh with the edge length (mesh resolution). The choice of mesh size was also influenced by computational power demand (Azevedo et al., 2014; Guo et al., 2014). The resulting mesh had a mean mesh size of 54.57 m and had 92,369 nodes and 183,925 elements in the computational domain (Figure 2). Brown and Davies (2009) indicate that a high-resolution mesh ranges between 20 – 100 m as this allows high resolution of the significant bathymetric features. Blue Kenue was used to interpolate the mesh and the bathymetry point dataset to develop the geometry file. Here, "open boundary with prescribed discharge" was added to the river inputs (at Blacktoft and Keadby) while "open boundary prescribed with depth and prescribed tracers" was added to the Humber mouth.

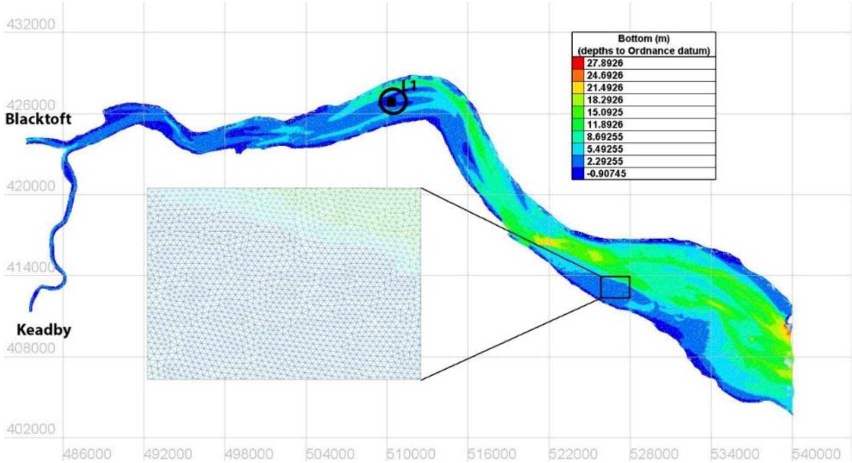

Figure 2: Bathymetry and computational domain for the Humber Estuary simulations. The release point is indicated by the black dot at 510498; 426777 (coordinates are in OSGB 1936). Inset shows the detail of the computational mesh.

The model was implemented with 5 equidistant σ-coordinate layers in the vertical and a time step of 45 seconds. Abascal et al. (2017) indicate that 5 equidistant σ-coordinate levels are efficient for developing an operational oil spill system. To take into account possible dry zones in the domain, TELEMAC3D’s “Tidal Flats” option was activated in this study. Coriolis force was also taken into account in this study as it influences discharge in the Humber Estuary (Pietrzak et al., 2011). For resolving the horizontal turbulence, this study employed the Smagorinksy model as it is best suited for resolving tidal systems with highly non-linear flow (Pham et al., 2016; Rahman and Venugopal, 2017). Nezu and Nakagawa mixing length model was employed to solve the vertical turbulence. Buoyancy forces were taken into account by activating variation of density according to temperature and salinity. Bottom friction was represented using Chezy’s law, because it is ideal for resolving equidistant vertical layering within TELEMAC3D models (Rahmann and Venugopal, 2017). The default Chezy friction coefficient of 60 $m^{0.5}/s$ was employed for the initial simulation (Figure 3a; Table 1).

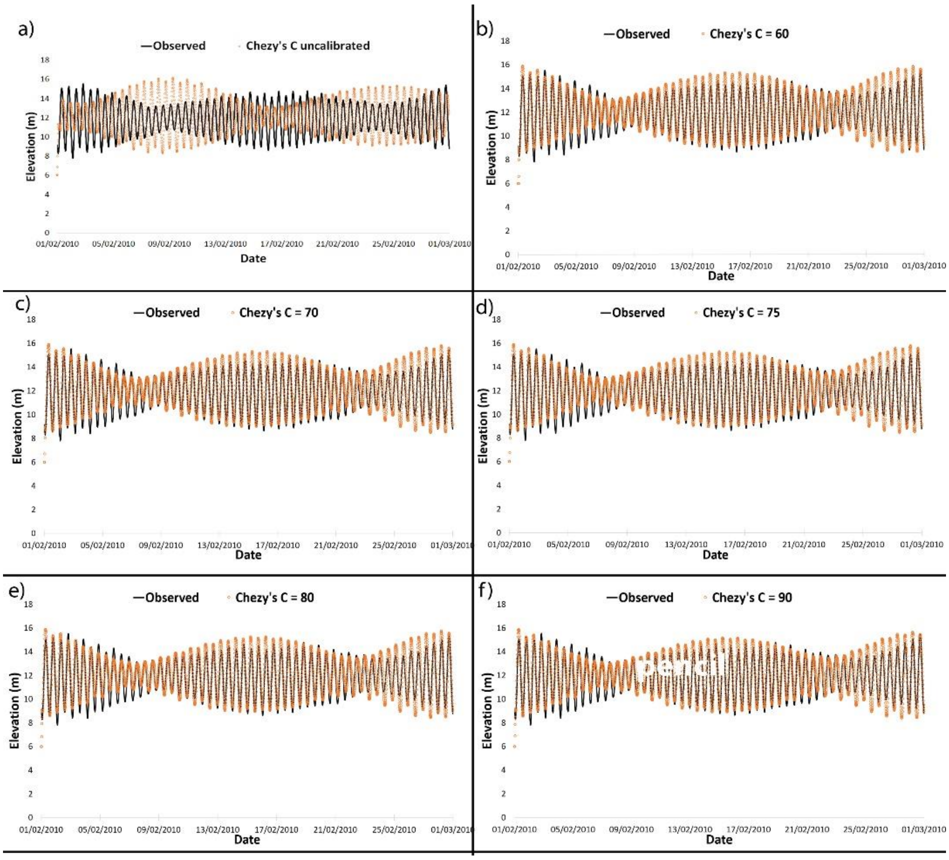

Figure 3: Observed (line) and simulated (points) free surface elevations at Immingham after calibration for February 2010; (a) Uncalibrated Chezy's C = 60 (b) Chezy's C = 60; (c) Chezy's = 70; (d) Chezy's = 75; (e) Chezy's = 80; (f) Chezy's = 90.

Table 1: Calibration metrics comparing observed and simulated tidal heights as a function of Chezy C. Best values for each metric are indicated as underlined italics.

Chezy C ($m^{0.5}$/s)	60 (uncalibrated)	60	70	75	80	90
RMSE (m)	3.046	0.713	*0.709*	*0.709*	0.711	0.722

4.1.2 Calibration and Performance Indicator

Model calibration was undertaken by comparing the simulated water level elevations with tidal level data at Immingham station (located at 520049; 416473) (Figure 1). The British Oceanographic Data Centre (BODC) provided 15-minutes tidal height data for February 2010. Rahman and Venugopal, (2017) TELEMAC3D sensitivity analysis pointed out that Bottom friction (i.e. Chezy's friction coefficient) is an important and sensitive TELEMAC3D model parameter, and as a result, was the main focus of the model calibration. To improve the fit between observed and simulated data, Brown and Davies (2009) recommend adjusting boundary conditions while undertaking model calibration. Because of the fit between observed and simulated data (Figure 3a), the FES2014 tidal height data employed at the offshore boundary was adjusted by 10 days (February 10th, 2010 – March 9th, 2010).

Root Mean Square Error (RMSE) was employed to determine the model performance as it is a suitable qualitative tool to determine the agreement of the model output and measured data (Lindim et al., 2011). Furthermore, the RMSE is appropriate for scalar quantities (e.g. water levels; Brière et al., 2007). Smaller RMSE value indicates better model performance (Umrao et al., 2018). Measured and simulated 15-minutes free surface elevation for the month of February 2010 (2976 values) were compared using RMSE. The calibration result is summarised in Figures 3b – f and Table 1.

4.1.3 Validation

The RMSE analysis indicated the model performs best with Chezy's coefficient for bottom friction of 75 $m^{0.5}/s$ and 10-day adjusted FES2014 tidal height data. Model validation was undertaken with February 2013 tidal height data (February 10th, 2013 – March 9th, 2013) at the offshore boundary. The 15-minutes tidal height data employed in the simulation was extracted from the FES2014 model. The simulated water levels were compared against February 2013 tidal height data at Immingham station. The simulated water level showed good agreement with the recorded data (RMSE = 0.823; Figure 4). Model performance may have been adversely affected by the use of simulated tidal height data rather than measured data to drive the offshore boundary. Due to unavailability of measured current data, we are unable to assess the accuracy of current produced by the hydrodynamic model.

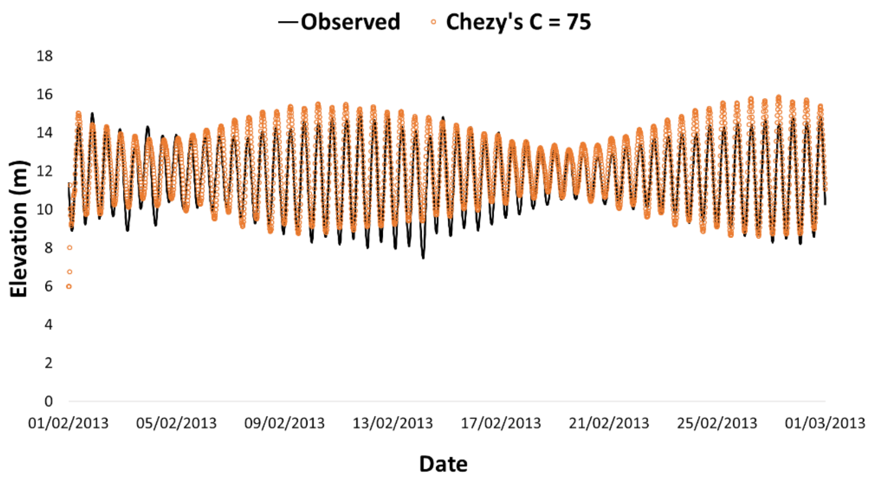

Figure 4: Observed (line) and simulated (points) free surface elevations at Immingham for the validation period (February 2013).

4.2 Oil Spill Model

Integrated into TELEMAC3D is a two-dimensional oil spill module for short-term forecasting. The oil spill module combines the Eulerian/Lagrangian approach to compute oil slick transport (advection-diffusion) (Pham et al., 2016). A set of hydrocarbon particles, considered as a mixture of discrete non-interacting hydrocarbon components (soluble and insoluble components) represents the oil slick (Joly et al., 2014). The TELEMAC3D hydrodynamic model (Section 4.1) provides the hydrodynamic data required for the oil spill model. TELEMAC does not model some key short term weathering processes such as dispersion, emulsification, viscosity, density and buoyancy. The TELEMAC oil spill model can, therefore, be considered as rudimentary with regards to modelling oil weathering processes. Consequently, the focus of this study is on oil spill transport in tide-dominated estuarine environment. Full description and validation of TELEMAC oil spill processes were undertaken by Goeury (2012).

We conducted four instantaneous oil spill scenarios to understand oil spill transport in the tide-dominated Humber Estuary. The oil spill simulations considered spill occurrence at high and low tide (with reference to Immingham station) during neap and spring tide (Table 2). The mean wind speed for February 2010 was employed in simulating the oil spill. A hypothetical spill of 10,000 m^3 of Brent crude at 510498; 426777 (Figure 2) was simulated for a duration of 48 hours. The Brent blend was chosen due to its proximity to the Humber Estuary, as it is located in the North Sea off the United Kingdom's coast.

Table 2: Summary of the oil spill scenarios

Period	Neap tide	Spring tide
Time of oil spill occurrence	High tide (07/02/2010 – 23:15) Low tide (06/02/2010 – 17:30)	High tide (01/02/2010 – 19:30) Low tide (01/02/2010 – 14:00)

5. RESULTS AND DISCUSSION

Unlike spills in oceans, estuarine oil slicks were observed to drift with flood and ebb currents thereby can be characterised by back and forth motions (Figure 5). Results suggest that oil slick transport exhibits trends and patterns based on the prevalent conditions at the time of release. After 48 hours, oil slick impacted area on the water surface was 131% and 86% larger when released under spring tides than under neap tides at high water and low water respectively, with an average of 109% (Table 3; Figure 6). Similarly, after 48 hours, oil slick upstream displacement was 7.50 km farther for oil slicks released under spring tides than under neap tides. While oil slick downstream displacement was averagely 5.82 km farther for slicks released under spring tides than for under neap tides. The overall distance travelled (maximum upstream and downstream displacement from the point of release) by oil slicks released under spring tide was 71% larger than neap tide oil slicks at high and low water (Table 4). Larger oil slick impacted area and overall distance travelled observed under spring tide scenarios can be explained by a larger current magnitude governing oil sick transport.

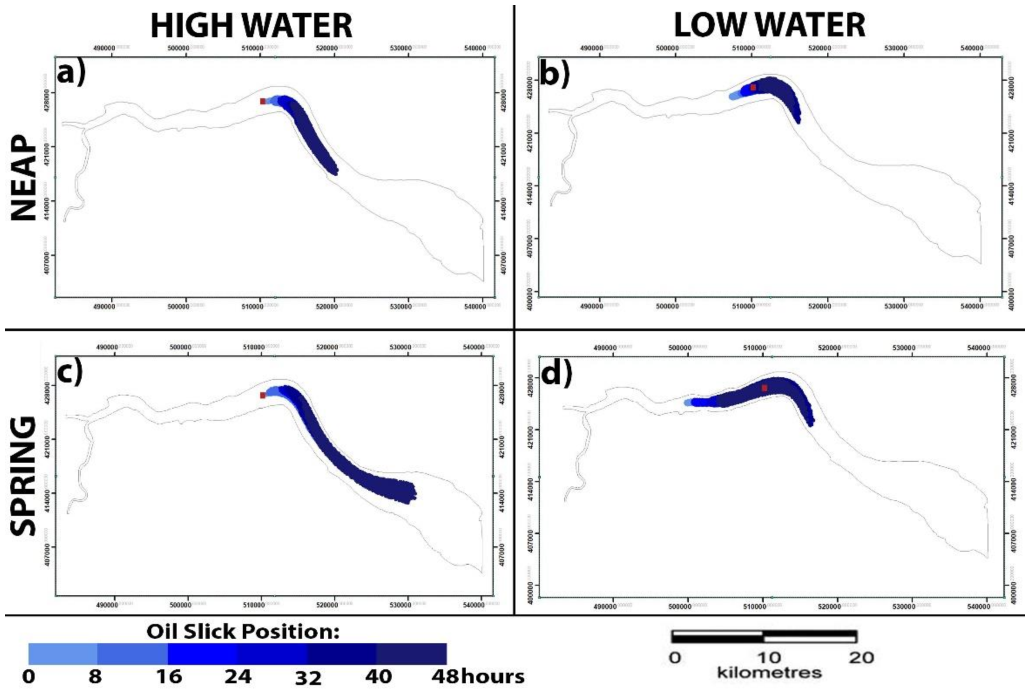

Figure 5: Simulated trajectories of oil released to the Humber Estuary at: a) high water neap tide; b) low water neap tide; c) high water spring tide; and d) low water spring tide. Point of oil release are indicated by red dot.

Table 3: Simulated oil slick area, A (sq. km).

Scenarios	0 - 8h	8 - 16h	16 - 24h	24 - 32h	32 - 40h	40 - 48h
	A	A	A	A	A	A
High water neap	5.04	6.92	10.23	16.50	17.47	20.82
Low water neap	2.20	6.32	7.30	9.18	15.25	16.90
High water spring	14.03	21.88	29.70	37.56	38.96	48.03
Low water spring	6.95	15.07	19.48	23.35	30.34	31.39

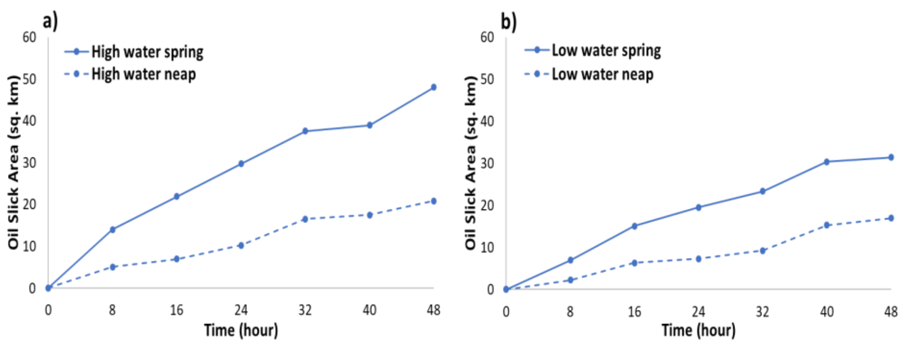

Figure 6: Area covered by simulated oil slick over time for a spill at: a) high water; and b) low water.

Table 4: Summary of maximum oil slick displacement (km) from point of release.

	upstream displacement	**downstream displacement**	**Overall distance**
High water neap	0	15.05	15.05
Low water neap	3.46	8.44	11.90
High water Spring	0	25.67	25.67
Low water Spring	10.96	9.45	20.41

Results also suggest that the time of oil release within a tidal cycle influences oil slick transport. After 48 hours, the oil slick impacted area was between 23% and 53% larger when released at high water than at low water (Table 3; Figure 6). There was no upstream displacement observed for oil slicks released at high water. While oil slicks released at low water were displaced upstream. This is possibly due to the initial direction of displacement at the time of oil release or entry in the estuarine waters. The total distance travelled by oil slicks released at high water was on average 26% greater than at low water (Table 4).

Findings indicate that oil slicks released under spring tide have greater slick impacted area on water surface and distance travelled.. Compared to oil spills released at low water, oil spills released at high water present greater oil slick size (impacted area on the water surface) and overall distance travelled. Findings suggest that to efficiently deal with oil spill in tide-dominated estuaries, oil spill responders will need to be aware of the prevailing conditions as well as the time of oil release within a tidal cycle.

6. Conclusion

Oil spill dynamics in estuarine environment presents a gap in academic knowledge and literature. To address this gap, we developed a model for understanding tidal influence on oil spills in a tide-dominated estuary. We now know that for this large tide-dominated estuary:

(a) the tidal range significantly influences oil slick impacted area and overall distance travelled as oil slicks released under spring tide was on average 109% larger than spills under neap tide and travelled on average 71% farther;

(b) oil spills released at high water present present greater oil slick impacted area and overall distance travelled; and

(c) the time of release in a tidal cycle significantly influences upstream and downstream displacement.

The implications of these findings for operational oil spill response are: (a) the need to understand how the interaction of river discharge and tidal range influences oil slick transport; and (b) the need to be aware of the time of release within a tidal cycle, to efficiently deal with oil spills.

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