OIL SPILL TRAJECTORY MODELLING

TTR mining barge, New Zealand

Prepared for Trans-Tasman Resources

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EXECUTIVE SUMMARY

An 11-year database containing all the likely trajectories for an oil spill from the mining barge located in the centre of the permit area has been produced. Oil spills have been tracked continuously from 1999 to 2009 until they beach or leave the modelled region. This technique provides a robust statistical basis to quantify the most likely pathways for oil in the unlikely event of a spill from the mining barge, and from this knowledge an assessment of the coastal areas that are most likely to be affected can be reliably determined. Results from the trajectory database have been examined for the seasonal conditions, showing the relative probabilities for beaching and statistics for beaching times.

The hydrocarbon used for this study is a 380 Heavy Fuel Oil (HFO). Weathering of this oil is expected to result in around 20% of the released volume evaporating or being dispersed 120 hour from initial release (Table E.1). Wind speed has a significant effect on the amount of dispersion, evaporation and mechanical weathering experienced by the oil. Accordingly, while the stronger wind conditions may lead to shorter beaching times, it may be the more moderate winds that result in the highest volumes of oil reaching the shore.

Analysis of the trajectory database shows that some 92.4 – 97.8% of spill events are predicted to result in a beaching outcome. The spring season has the highest probability of beaching (97.8%) while autumn has the lowest (92.4% - Table E.2). The minimum time between a spill and beaching varies throughout the seasons; from 12.5 hours in summer to 16.6 hours in spring and autumn (Table E.2).

A series of coastal beaching probability maps have been produced, and maps of beaching probabilities are provided for each season. The region of coast most likely to be affected from a spill is located in the South Taranaki Bight in the vicinity of the Rangitikei River Mouth (e.g. Figs. E.1 - E.4).

The worst-case outcome of an accidental release of 100 mT of 380 Heavy Fuel Oil has been investigated. The release date in the 11-year trajectory database that produces the maximum beaching outcome has been identified, and the coastal impacts associated with that scenario are quantified. The area with the highest impact is in the South Taranaki Bight near Wanganui, where oil concentrations of 4.79 m^3 per kilometre of coastline are predicted (Fig. E.5).

Table E.1 Volume percentage of oil remaining on surface after a 2-hour release of 100 mT of 380 Heavy Fuel Oil as a function of wind speed and exposure time, calculated using ADIOS2. The model considers evaporation and dispersion in the water column under the action of wind and waves. Calculations were run for water temperatures of 13°C and 17°C, providing an interval of percentage indicated in each table cell. A table cell containing a single value indicates no difference in results between 13°C and 17°C.

Wind speed ($m.s^{-1}$)	**Hours into spill**															
	2	**4**	**6**	**8**	**10**	**12**	**18**	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
1	100	99-100	98-99	96-98	93-96	91-95	86-91	83-88	81-84	80-82	80-81	80-81	80	80	80	80
2	100	98-99	96-98	92-96	89-94	87-92	82-87	81-84	80-82	80-81	80	80	80	80	80	80
3	100	98-99	94-97	90-94	87-92	85-90	81-85	80-83	80-81	80-81	80	80	80	80	80	80
4	99-100	97-98	92-96	88-93	85-90	83-88	81-84	80-82	80-81	80	80	80	80	80	80	80
5	99-100	97-98	92-95	88-91	85-88	83-86	81-83	80-82	80	80	80	80	80	80	80	80
10	98-99	91-94	86-90	83-87	82-85	81-84	80-81	80	79-80	79-80	79-80	79-80	79-80	79-80	79-80	79
15	95-96	88-90	83-86	81-83	80-81	79-80	78-79	78-79	77-79	77-79	77-79	77-79	77-79	77-79	77-79	77-79
20	90-92	84	79-80	77-78	75-78	75-78	74-78	73-77	73-77	73-77	73-77	73-77	73-77	73-77	73-77	73-77
25	84-88	78-81	74-77	72-76	71-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-75
30	79-85	72-78	69-75	67-75	67-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74

Table E.2 Percentage of events that resulted in beaching within the 11-year database and minimum time (in hours) for released oil to beach per season from the approximate centre of the TTR permit area.

	Season			
	Spring	**Summer**	**Autumn**	**Winter**
Total % beaching	97.8	94.9	92.4	95.0
Min beaching time (hours)	16.6	12.5	16.6	12.7

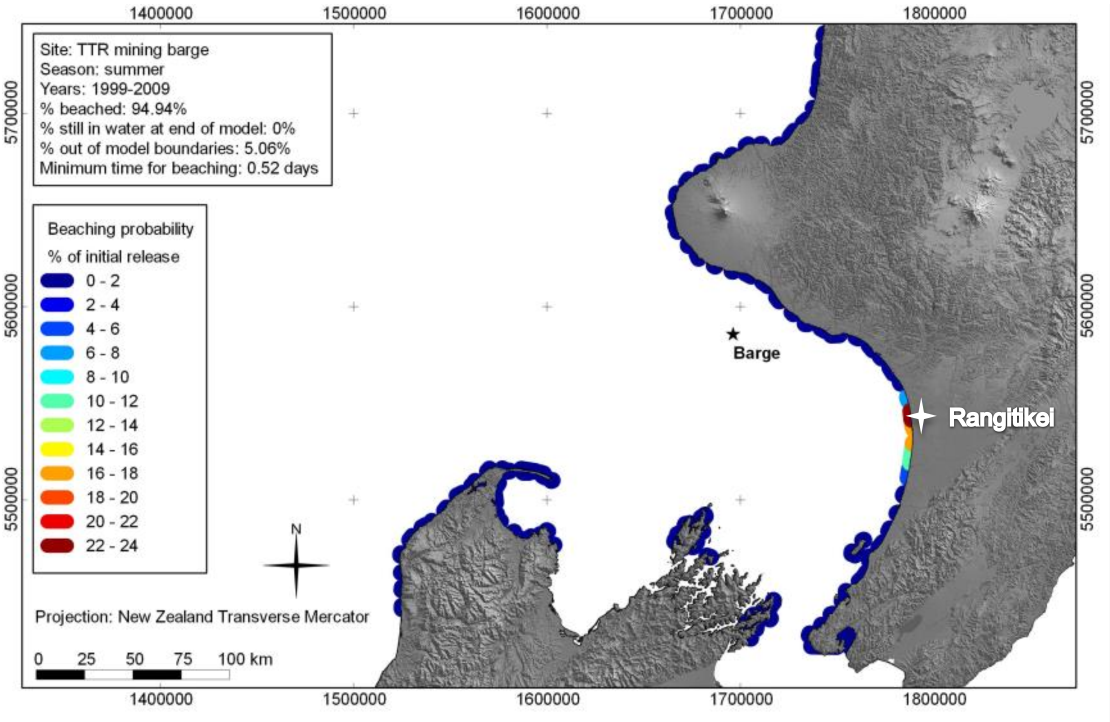

Figure E.1 Summer season beaching probability based on an 11-year trajectory database.

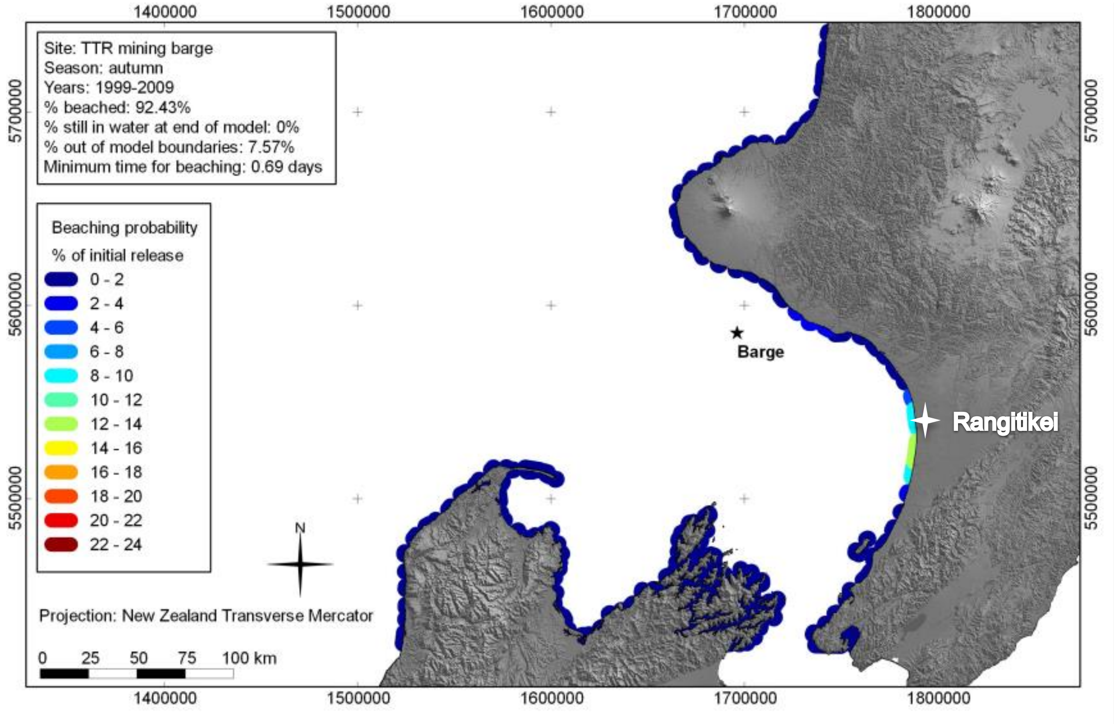

Figure E.2 Autumn season beaching probability based on an 11-year trajectory database.

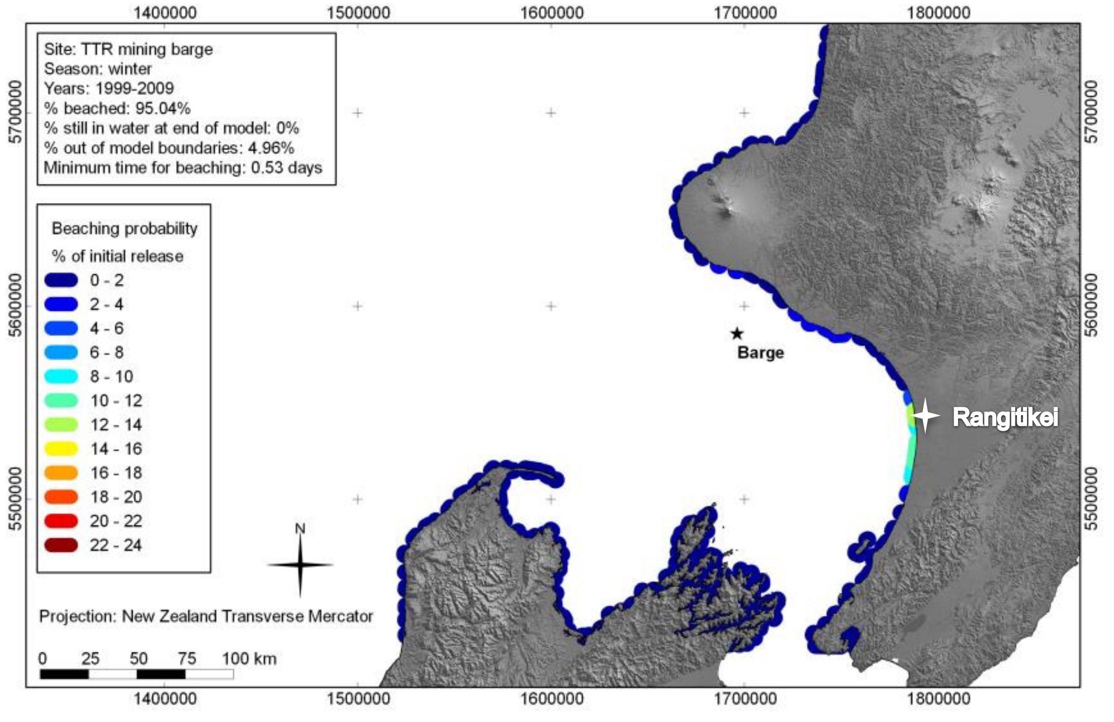

Figure E.3 Winter season beaching probability based on an 11-year trajectory database.

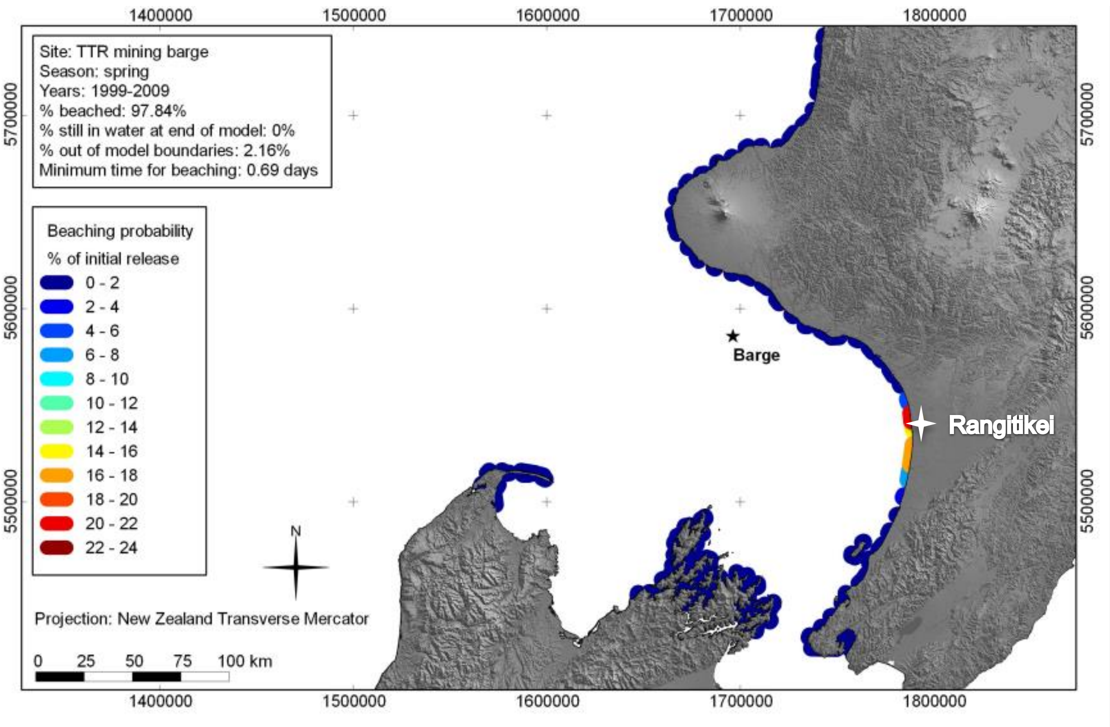

Figure E.4 Spring season beaching probability based on an 11-year trajectory database.

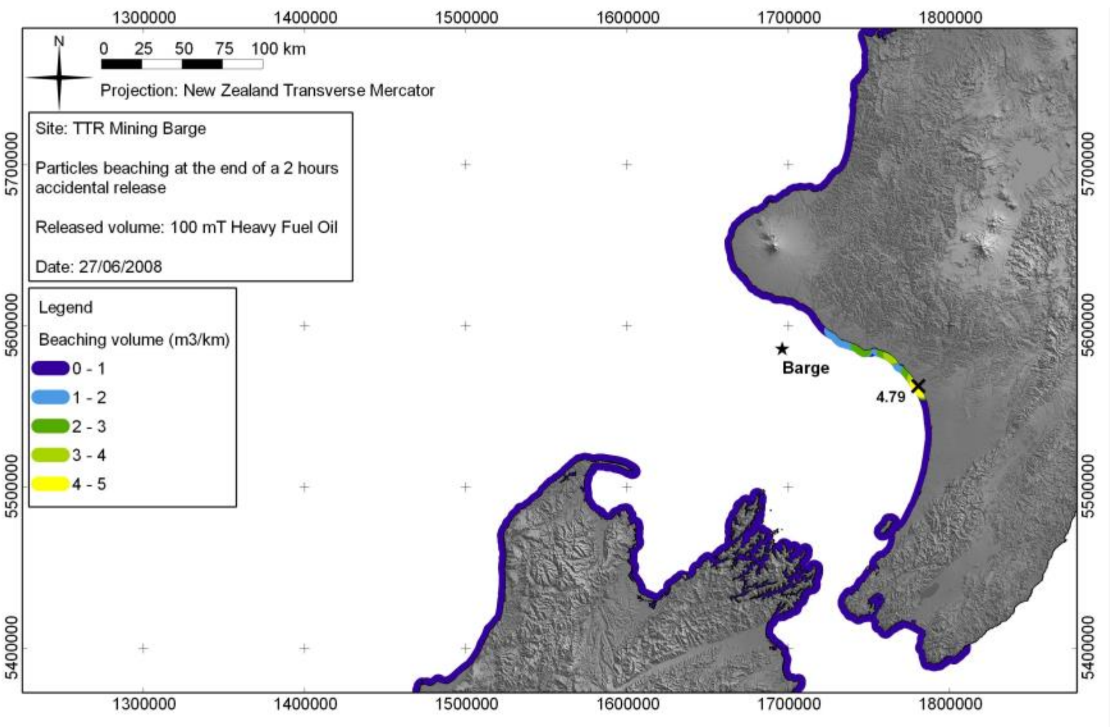

Figure E.5 Predicted beached percentages from a 2 hour accidental release of 100 mT of Heavy Fuel Oil from the mining barge. This figure represents the worst coastal beaching outcome within the 11-year trajectory database.

1. INTRODUCTION

Trans-Tasman Resources (TTR) has commissioned MetOcean Solutions Ltd (MSL) to undertake an oil spill trajectory model study to assess the potential coastal beaching from a release at the TTR mining barge site. The chosen location, in the centre of the permit area, is located at 39.873614°S / 174.125229°E (5585664.423 E / 1696227.169 N NZTM) in an estimated depth of 37.7 m in the offshore Taranaki Basin (Fig. 1.1).

Oil spill trajectory modelling involves simulating the release of hydrocarbon products from a given offshore location and tracking the “fate” (where it goes) and “persistence” (how long it remains in the system) of the release under the influence of ocean conditions, until beaching occurs or the contaminants are advected beyond the model boundaries. By running spill simulations over multi-year periods using the actual historical conditions (recreated using numerical models of the atmospheric and oceanographic processes) it is possible to produce statistical probability maps of the trajectory patterns, beaching locations and predictions of the likely times for spilled oil to reach the shore. In this study, a proprietary release trajectory model (EROil) has been used to simulate the dispersal of spilled hydrocarbons from the mining barge location.

Evaporation, dissolution and other weathering processes gradually reduce the volume of hydrocarbons at the sea surface over time. These processes were not simulated in the EROil trajectory model (i.e. the released product was completely conserved from release until beaching) because they do not materially change the contaminant trajectory, beaching times or the relative coastal beaching. Non-weathering simulations therefore allow the physical transport pathways to be clearly identified. Weathering of the surface hydrocarbons is considered by the ADIOS2 model from the National Oceanic and Atmospheric Administration Hazardous Materials Response Division (NOAA/HAZMAT). ADIOS2 estimates the volume of hydrocarbon remaining over time as a function of wind and oceanic conditions, using the physical and chemical properties of the released hydrocarbons.

This report is structured as follows; Section 2 describes the various metocean data sources that have been used as input to the oil spill model. Section 3 provides technical details of the oil trajectory model. The simulations carried out and the post-processing and analysis are described in Section 4. The study results are provided in Section 5 and a summary of the work is provided in Section 6. The references cited are listed in the final Section 7.

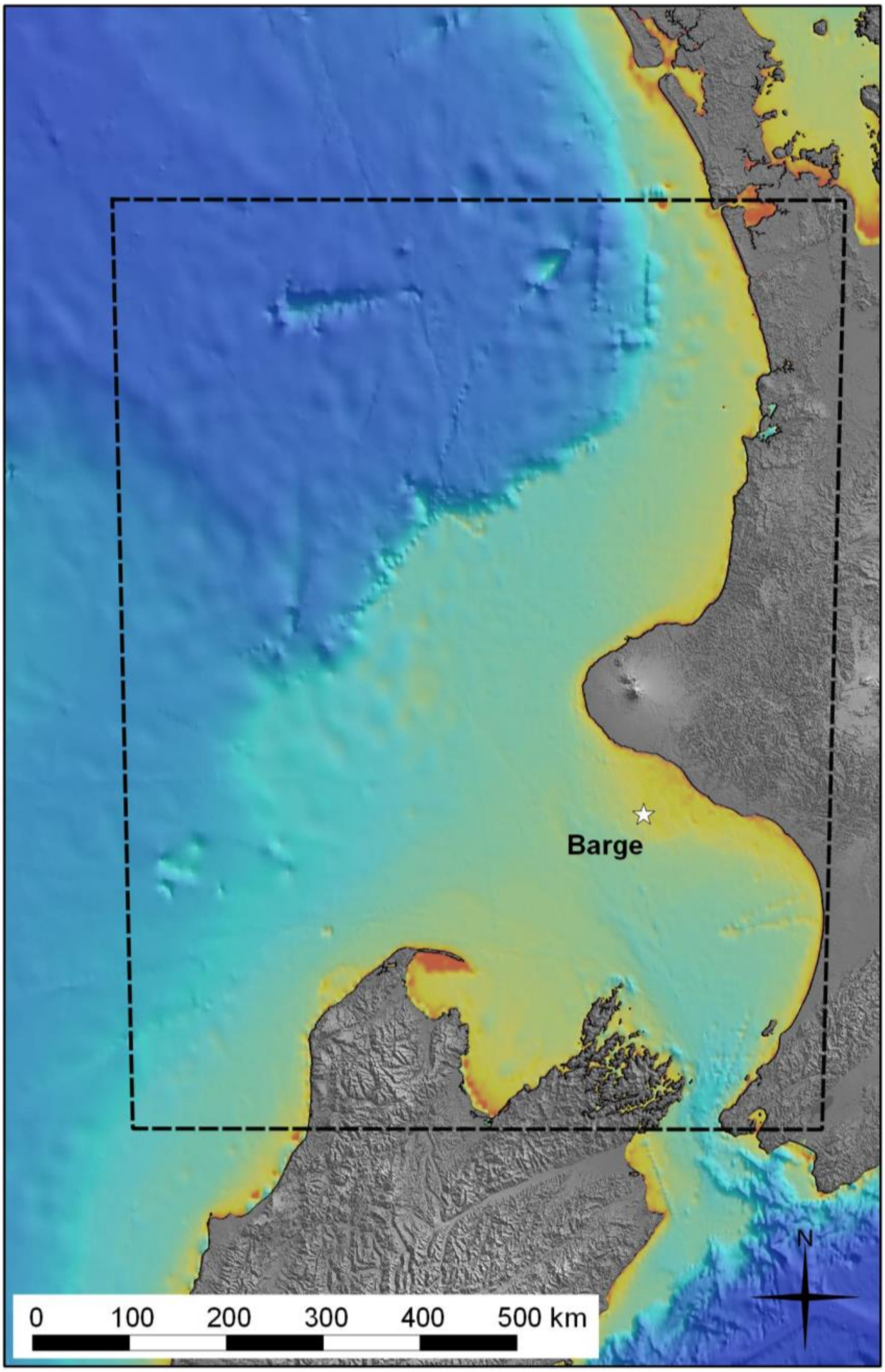

Figure 1.1 Location of the TTR mining barge (39.873614°S / 174.125229°E or 5585664.423 E / 1696227.169 N NZTM). The dashed black box represents the boundaries of the models: 171ºE to the West, 175.25ºE to the East, 41.32ºS to the South and 37ºS to the North.

2. METOCEAN DATA

2.1. Winds

The spatially varying wind field used in this study is an extract of a 33-year regional atmospheric hindcast produced by MetOcean Solutions Ltd. The hindcast was obtained by running the Weather Research and Forecasting model (WRF) nested within the Climate Forecast System Reanalysis (CFSR) data set from NOAA. The result is a nationwide 12 km resolution hindcast of full 3-dimensional atmospheric variables for each hour since January 1979, with a 4 km nested region through central New Zealand. The variables include the surface wind field (i.e. 10-minute mean at 10 m elevation) along with air temperature, humidity, solar radiation and precipitation.

The wind speed from this hindcast has been validated at numerous sites around New Zealand; shown in Figure 2.1 are time series data from Auckland Airport in January 2007 and a quantile-quantile plot from a full year (2007) at Brother's Island in the Cook Strait.

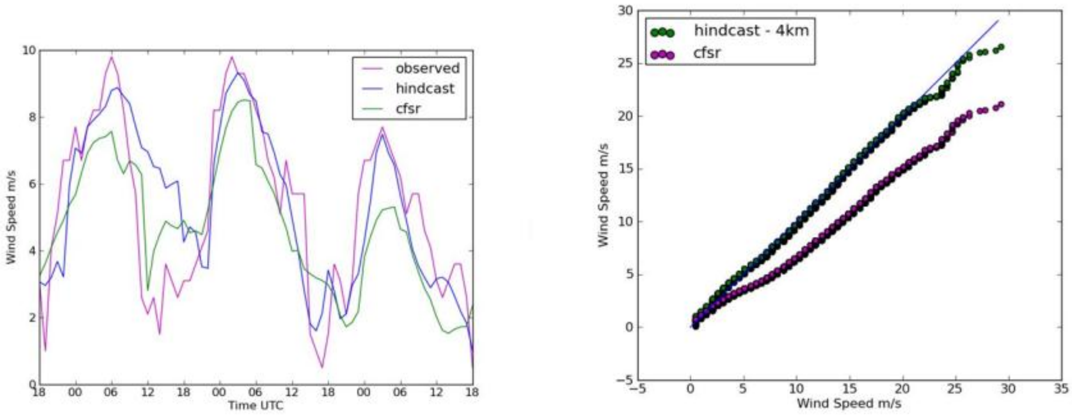

Figure 2.1 Comparison of both CFSR data and a high-resolution WRF hindcast for Auckland Airport during a few days in January 2007 (left) and quantile-quantile plot of both CFSR (magenta) and the WRF hindcast (green) against the observations from Brother's Island in the Cook Strait during 2007.

2.2. Currents

Surface non-tidal currents were defined from a fully nested high-resolution 28-year ROMS model hindcast that includes the barge location. The ROMS model is a three dimensional ocean model nested within the CFSR ocean hindcast. By using the CFSR boundary, a realistic time-varying deep-water boundary can be prescribed for ROMS. The hindcast is forced with the NZ atmospheric hindcast described in Section 2.1. The long duration of the hindcast provides a good statistical basis for estimating and characterising inter-annual variability. Tidal currents were obtained from the MSL NZ tidal solution and were added to the oceanic currents to provide combined residual and tidal current fields at an hourly interval.

2.3. Sea surface temperatures

Monthly average sea surface water temperatures at the approximate centre of the permit area were extracted from the satellite records (1999-2009, Table 2.1). Note that sea surface temperature does not influence the surface oil trajectory, but it does affect the weathering process.

Table 2.1 Mean monthly sea surface temperatures (SST) at 39.873614°S / 174.125229°E from satellite data (1999-2009).

Season	Month	Sea surface temperature (°C)	
		Monthly average	**Seasonal average**
Summer	December	16.47	17.68
	January	18.11	
	February	18.44	
Autumn	March	18.15	17.24
	April	17.37	
	May	16.21	
Winter	June	14.69	13.75
	July	13.31	
	August	13.23	
Spring	September	13.65	14.32
	October	14.20	
	November	15.09	
Annual		15.75	

3. OIL SPILL MODEL DESCRIPTION

3.1. Overview

EROil is a Lagrangian model for simulating the transport and fate of hydrocarbon liquids and gases, both on the surface as a slick, and in its subsurface phases such as following a deep water loss of well control. The model has been developed by MSL using well established methodologies and techniques described in the scientific literature. The main model simulates the trajectories of particles advected by currents, and when on the surface, blown by the wind. There is parameterisation for turbulent mixing. A plume module simulates the initial stages of a deep water loss of well control, during which the initial momentum of the hydrocarbon jet is important.

3.2. Lagrangian particle model

EROil simulates hydrocarbon dispersion with Lagrangian particles that move within a continuous Eulerian environment. The spreading and dispersion of the particles is based on a Fickian random walk. The motion of each particle is governed by the equation:

$$\frac{d\vec{X}}{dt} = \vec{U} + \vec{D} + C_w\overrightarrow{W_{10}} + \overrightarrow{w_b} \tag{3.1}$$

where $\vec{X}$ is the particle position, $\vec{U}$ is the current speed, $\vec{D}$ is a random diffusion component and w_b is the buoyant rise velocity of the hydrocarbon liquid or gas. The particle motion is integrated using a 4th order Runge-Kutta method for the current component and a 1st order forward time method for the wind and diffusion components.

When a liquid particle reaches or is on the surface, it is also influenced by a wind term where $\overrightarrow{W_{10}}$ is the wind vector at 10-metres above the surface and C_w is the windage factor. The windage factor can be given a range of values, from which a random value is chosen at each time step to allow for uncertainty in its value. Gas particles that reach the surface are assumed to disperse in the air above, however their location is recorded so that near surface concentrations can be calculated.

The diffusion component is a random vector defined as:

$$D_i = \frac{1}{\Delta t}\sqrt{6K_i\Delta t}\; U_i(-1,1) \tag{3.2}$$

where K_i is the diffusion coefficient in each direction and $U_i(-1,1)$ is a random number drawn from a uniform distribution between -1 and 1.

The buoyant velocity of oil drops or gas bubbles is calculated following Zheng and Yapa, (2000). The model currently uses a single representative size for both oil droplets and gas bubbles, usually taken to be the median value. When a particle hits a shoreline it can either be held in place (sticky shoreline) or is allowed to move again after a re-float half-life timescale.

EROil has been verified by undertaking an extensive range of tests for surface slicks and ensuring that the trajectories obtained from EROil were similar to those obtained in GNOME, the NOAA oil response model (Beegle-Krause, 2001, 1999).

4. NUMERICAL SIMULATIONS

4.1. Release scenarios

In the present work, EROil was used to consider the fate of all possible spill trajectories that would have occurred within an historical 11-year period (1st of January 1999 to 31st of December 2009). Simulation of the trajectories over many years provides a robust statistical basis to identify the most probable pathways in the unlikely event of a spill, and also to identify the coastal regions most likely to be affected by beaching of a spill. Multi-year simulations do not imply that a spill of this duration is anticipated; rather it is a modelling technique used to provide information from many seasons and years with a range of realistic weather patterns.

The simulated discharge rate was 10,000 barrels per day of 380 Heavy Fuel Oil with a 30% gas/oil ratio (at depth). The models were run with a time-step of 15 minutes for the particle component, which is short enough to capture the movement of tidally induced currents. The results were output every 24 hours for visual checks, display and data processing. The diffusion coefficient was 10 in both horizontal axes. The windage factor C_W in Equation 3.1 was set to the range 0.01 to 0.04 (1% to 4%).

In the present work, if a particle reaches the shore during the simulation it is immobilized for all subsequent time-steps until the end of the model simulation (i.e. “sticky coast”). The time elapsed since release and the time elapsed since beaching are both recorded, thereby allowing the age of the particle when beaching occurred to be determined. The western, eastern, southern and northern model boundaries were respectively 171°E, 175.5°E, 41.32°S and 37°S (see Fig. 1.1).

4.2. Seasonal results

The final state of the model outputs (particles final position, time since release, beaching state and time since beaching, if applicable) were combined for all years to produce seasonal results. Quantitative information was then extracted from these results, including:

- The percentage of the total release that beached,
- The percentage of the total release that was still in the water at the end of the model simulation,
- The percentage of the total release that left the model domain, and
- The minimum beaching age in days (minimum difference between time elapsed since release and time elapsed since beaching), and the beaching location of the associated particle.

4.3. Beaching concentration and age analysis

4.3.1. Beaching concentration calculation

Maps of the relative concentration of spill products along the coastline can be produced from the distribution of beached particles in the seasonal results. In the present work, a kernel method with variable bandwidth was used to reconstruct the concentration calculated at the location of *receptors* defined at 10 km intervals along the coastline while a 1 km bandwidth was used to calculate the median and minimum beaching times. The use of a variable bandwidth (kernel size) attempts to represent true variability of spatial concentration, while minimising statistical variability that inevitably occurs away from the source due to a necessarily finite number of particles. A small kernel is used in regions gathering a high number of particles, where it is statistically appropriate to infer relatively small scale changes in concentration. Conversely, a larger kernel is used in regions presenting a low number of particles, so as to prevent unrealistically high concentrations around the precise (but partially random) locations of a few isolated particles.

In practice, the concentration C at a receptor location (x,y) on the coastline is computed as:

$$C(x,y)=\sum_{i=1}^{n}\frac{m_i}{\lambda_x(x,y)\lambda_y(x,y)}K\left(\left|\frac{x_i-x}{\lambda_x}\right|\right)K\left(\left|\frac{y_i-y}{\lambda_y}\right|\right) \tag{4.1}$$

where (x_i,y_i) is the location of each particle i, n is the total number of particles, m_i is the loading for each particle, λ_x and λ_y, are the kernel bandwidth in the x and y directions for location (x,y) and K is the kernel function.

The loading m_i for each particle depends on the quantity being calculated and may represent, in the case of an oil spill (for example), the remaining amount of oil represented by a particle after weathering. Since weathering was not implemented in the present trajectory modelling, m_i was equal to 1 for all particles.

Following Vitali *et al*., (2006), an Epanechnikov kernel function was used:

$$K(q)=\begin{cases}0.75\left(1-q^2\right) & ,|q|\le 1\\ 0 & ,|q|>1\end{cases} \tag{4.2}$$

A receptors-based method (a modification of the RL3 in Vitali *et al*., 2006) was used to define the bandwidths λ_x and λ_y. For each receptor location (x,y), a neighbourhood was defined as the region enclosing the 1/20th closest particles. Then, for each direction x and y, the bandwidths λ_x and λ_y were defined as the minimum value between the maximum projected distance of the particles within the neighbourhood and twice the standard deviation of the projected distances within the neighbourhood. Finally, in order to prevent unrealistically elongated kernels, the aspect ratio λ_x/λ_y was limited to be no greater than 5:1, with the smaller value increased.

4.3.2. Beaching age analysis

The beaching concentration calculation algorithm described above includes a step to record, for each receptor location (x,y) along the coastline, the minimum and median beaching age (time difference between particle release and beaching) of all beached particles within the bandwidths λ_x and λ_y, thereby allowing maps of minimum and median beaching ages to be produced.

4.4. Short-term probability distributions

The relative probabilities of wind direction and wind speed at the spill location provide “best-guess” information as to the short-term direction and extent of the surface expression of a release. However, this information does not take into account the short-term variation in wind direction and speed, nor the influence of the other environmental movers (currents and diffusion).

In order to provide a more precise assessment of the probabilities of short-term trajectory patterns, the 11-year trajectory database was used to estimate probability distributions at 24, 48 and 72 hours after release. First, the location of all particles aged between 21 and 27 hours (24±3 hours) were recorded for each season and combined over each of the years, thus producing the seasonal distributions of particles with age of 24 hours. Then, the concentration calculation algorithm described in Section 4.3.1 was applied to these seasonal distributions over a grid of oceanic receptors (instead of coastline-based) set at a 500 m resolution, thus producing seasonal relative concentrations at 24 hours after release. Besides the offshore location of receptors, the only difference to the coastal concentration algorithm is that the neighbourhood for each grid point (x,y) was defined as the region enclosing the 1/10th closest particles (instead of 1/20th for the coastal algorithm).

Finally, the concentration was blanked out, outside the 99th percentile convex-hull, thus producing the final seasonal maps displaying the probabilistic distribution of a 24-hours-old spill. The process was repeated for particles aged between 45 and 51 hours to produce seasonal 48-hours-old release probability distribution maps and for particles aged between 69 and 75 hours to produce seasonal 72-hour-old release probability distribution maps.

4.5. Weathering model

The ADIOS2 model is used to simulate and estimate the gradual weathering of the released products as a function of oil type, physical and chemical properties, wind speed and water temperature.

Since weathering is highly dependent on the type of oil, ADIOS2 contains a detailed library of oils compiled from a number of sources (including Environment Canada, the U.S. Department of Energy, the International Oil Companies’ European Organization for Environmental and Health Protections, and other industry groups). For each oil product, information about the location, density, viscosity, flash point, pour point, hydrocarbon group analysis, and distillation data is included in the library. MSL has added several Taranaki crudes to this database, including Maari crude, Tui crude, Amokura crude, Kupe crude and Pohokura crude. For the presented study, hydrocarbon weathering has been estimated using the chemical composition of 380 Heavy Fuel Oil.

The ADIOS2 model computes the remaining volume percentage of oil products at given time intervals after a release of user-input parameters, including release timing and amount, by considering the processes of oil evaporation, emulsification, dispersion and spreading, based on user-input environmental parameters, including water temperature, water sediment load, water salinity, and wind speed (Jones, 1997; Lehr *et al.*, 2000). ADIOS2 uses the wind speed information to estimate wave height – a required parameter for the calculation of the physical weathering of a hydrocarbon – by assuming a constant wind speed over the model duration.

In the present study, ADIOS2 was used to estimate the remaining oil volume percentage at time intervals ranging from 2 hours until 120 hours after the beginning of a 2 hour release of 100 mT of 380 Heavy Fuel Oil. Wind speeds ranging from 1 $m.s^{-1}$ and 30 $m.s^{-1}$ and water temperatures ranging between 13°C and 17°C have been considered in these estimates.

4.6. Uncontrolled release scenario

The worst-case outcome of an accidental spill from the mining barge has been investigated. To consider the worst case outcome for coastal impacts in that situation, the release date associated with the highest potential beaching was identified within the 11-year trajectory database. Assuming a total release of 100 mT of 380 Heavy Fuel Oil over this period, and using the method outlined in Section 4.3, the worst-case shoreline concentrations have been derived. Weathering is accounted for using ADIOS (Section 4.5) and assuming the released oil has an average resident time exceeding 120 hours before beaching and is subjected to an average wind speed of ~10 $m.s^{-1}$.

The relative costal impact and worst case scenarios were also investigated for representative sections of coastline for the same spill conditions. For each shoreline segment, the worst case outcome was identified within the 11-year trajectory database. The released volume and weathering were accounted for as described above. The maximum and average beaching concentrations, along with the beaching percentage of released volume were obtained for each segment.

5. RESULTS

5.1. Wind and current climate

Joint probability distributions of wind speed and direction at the approximate centre of the permit area are given in Table 5.1, while Figures 5.1 - 5.5 present the annual, summer, autumn, winter and spring wind compass rose plots. This data suggests a bimodal wind distribution, with the primary mode represented by winds from the NW sector, with a second smaller directional mode from the SE.

The joint probability distribution of the depth-averaged current speed and direction at the approximate centre of the permit area are provided in Table 5.2, while Figures 5.6 - 5.10 present the annual, summer, autumn, winter and spring current velocity compass rose plots. This data shows a clear bimodal current distribution with the dominant flows directed towards the E-SE. The dominant currents are due to a combination of local and regional wind-stresses on the ocean surface, as well as the tidal flows.

Table 5.1 Annual joint probability distribution (parts-per-thousand) of the wind speed and direction at 10 m above sea level at the approximate centre of the permit area.

Wind speed ($m.s^{-1}$)	Wind direction (coming from) (degT)								
	337.5 -22.5	22.5 -67.5	67.5 -112.5	112.5 -157.5	157.5 -202.5	202.5 -247.5	247.5 -292.5	292.5 -337.5	Total
> 0 <= 2	5	4.7	4	4.2	4.2	4.7	5.5	4.9	37.2
> 2 <= 4	14.9	13.8	12	11.7	12.5	11.9	18.8	16.3	111.9
> 4 <= 6	19.3	17.3	13.7	20.2	15	11.3	30.8	31	158.6
> 6 <= 8	18.8	15.3	11.6	27.1	13.8	9.3	42.8	49.6	188.3
> 8 <= 10	17.9	10.8	7.5	29.4	13.1	7.9	49	56.2	191.8
> 10 <= 12	14.7	6	4.5	27.4	11.8	4.7	41.2	41.2	151.5
> 12 <= 14	10.3	2.1	1.5	17.5	9.5	2.3	24.4	22.5	90.1
> 14 <= 16	4.9	0.7	0.4	7.3	7	1	10.8	11	43.1
> 16 <= 18	2.6	0.2	0.3	3.7	4	0.2	4	3.8	18.8
> 18 <= 20	0.8	0	0.1	1.2	1.9	0	0.9	1.2	6.1
> 20 <= 22	0.1	0	0	0.4	0.8	0	0.1	0.3	1.7
> 22 <= 24	0	0	0	0.1	0.2	0	0	0.1	0.4
Total	109.3	70.9	55.6	150.2	93.8	53.3	228.3	238.1	1000

Table 5.2 Joint probability distribution (parts-per-thousand) of the depth-averaged current speed and direction at the approximate centre of the permit area.

Current speed ($m.s^{-1}$)	**Current direction (going to) (degT)**								
	337.5 -22.5	**22.5 -67.5**	**67.5 -112.5**	**112.5 -157.5**	**157.5 -202.5**	**202.5 -247.5**	**247.5 -292.5**	**292.5 - 337.5**	**Total**
> 0 <= 0.05	18.5	20.7	20.9	18.9	18.1	16.7	18.1	18	149.9
> 0.05 <= 0.1	29.7	51.6	55.5	35.5	20.8	20.2	40.8	32.8	286.9
> 0.1 <= 0.15	18.5	49.9	68.3	33.1	10.2	10.7	42.5	25.5	258.7
> 0.15 <= 0.2	6.4	23.1	53.7	26	4.5	4.4	30	18.8	166.9
> 0.2 <= 0.25	1.6	6.4	28.7	16.6	1.8	1.5	16.6	11	84.2
> 0.25 <= 0.3	0.4	1.9	11.8	8.9	0.7	0.5	6.5	4.6	35.3
> 0.3 <= 0.35	0	0.1	4.1	3.4	0.2	0	3	1.4	12.2
> 0.35 <= 0.4	0	0	1.7	1	0.1	0	1.1	0.2	4.1
> 0.4 <= 0.45	0	0	0.5	0.5	0	0	0.5	0	1.5
> 0.45 <= 0.5	0	0	0.1	0	0	0	0.1	0	0.2
> 0.5 <= 0.55	0	0	0	0	0	0	0	0	0
> 0.55 <= 0.6	0	0	0	0	0	0	0.1	0	0.1
Total	75.1	153.7	245.3	143.9	56.4	54	159.3	112.3	1000

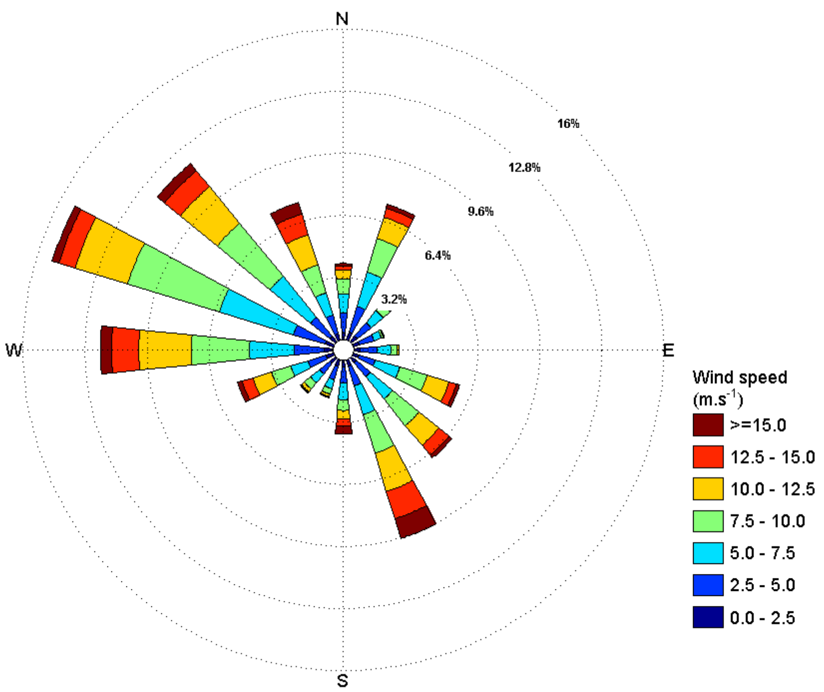

Figure 5.1 Annual wind rose for the approximate centre of the permit area. Sectors indicate the direction from which wind is coming.

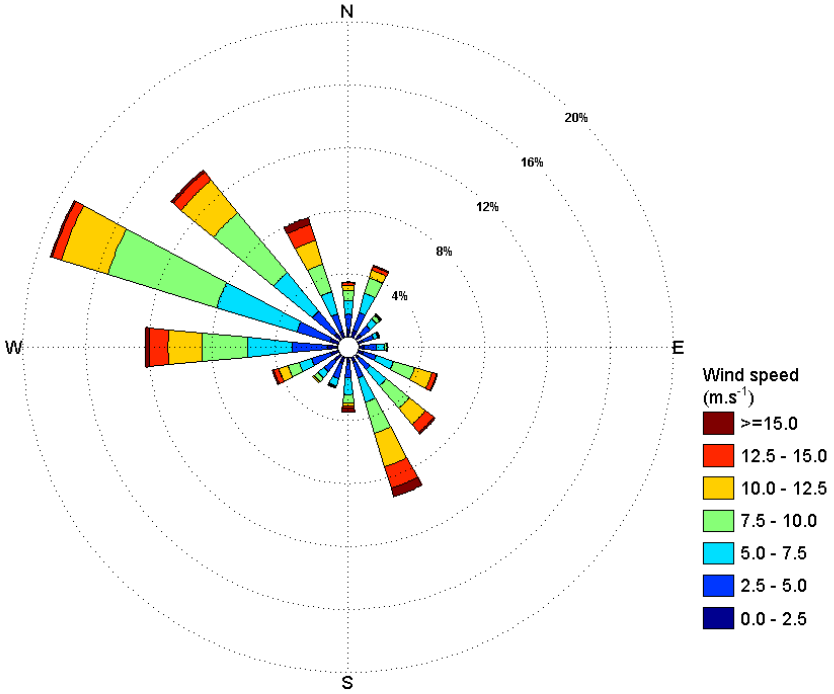

Figure 5.2 Summer wind rose for the approximate centre of the permit area. Sectors indicate the direction from which wind is coming.

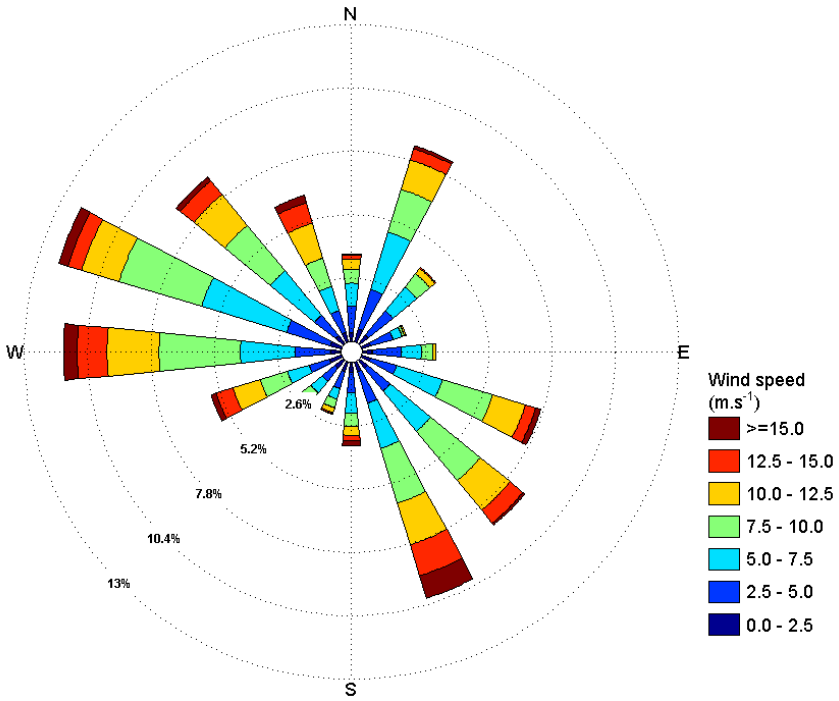

Figure 5.3 Autumn wind rose for the approximate centre of the permit area. Sectors indicate the direction from which wind is coming.

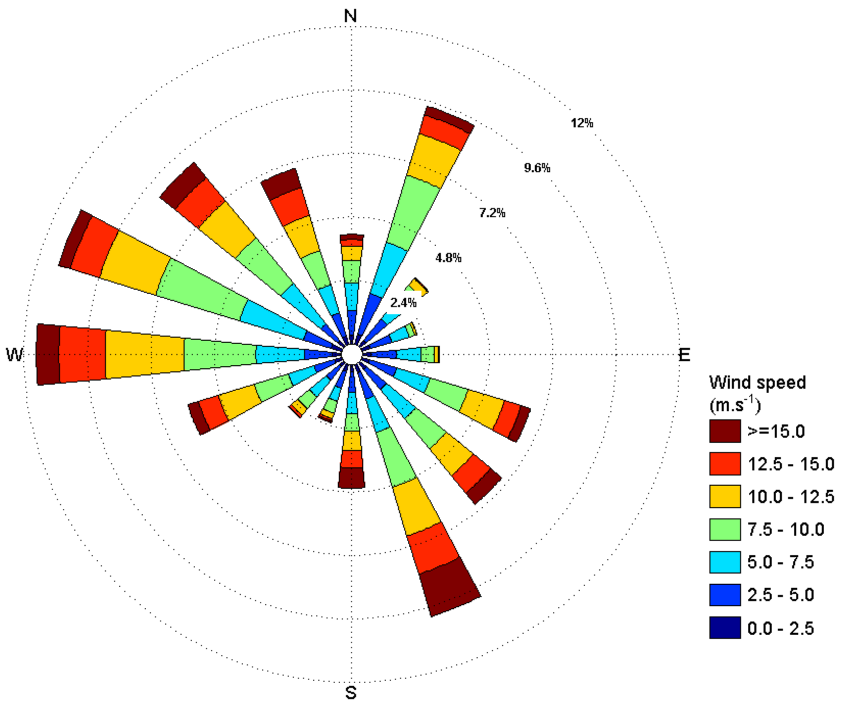

Figure 5.4 Winter wind rose for the approximate centre of the permit area. Sectors indicate the direction from which wind is coming.

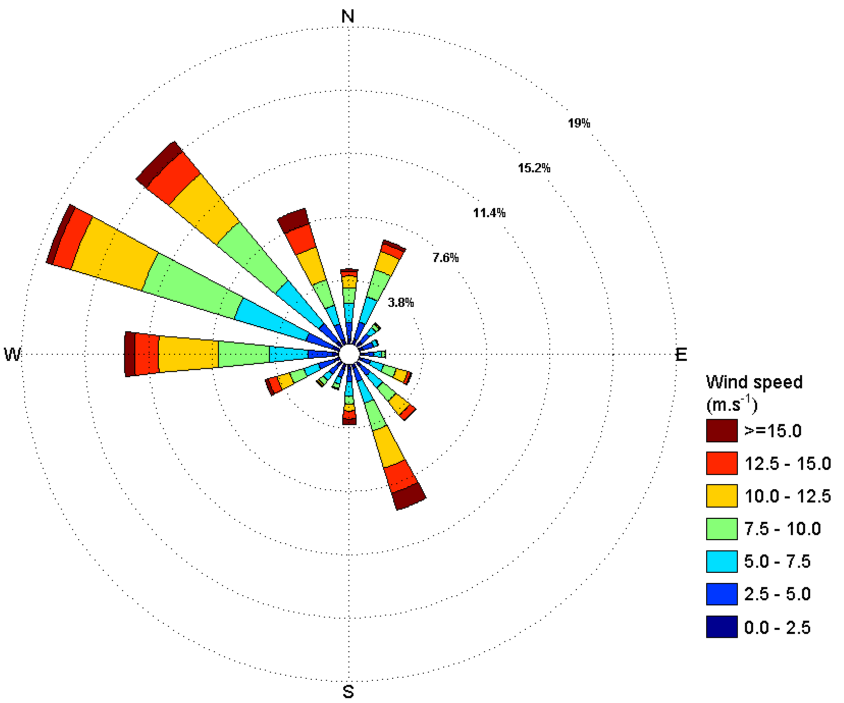

Figure 5.5 Spring wind rose for the approximate centre of the permit area. Sectors indicate the direction from which wind is coming.

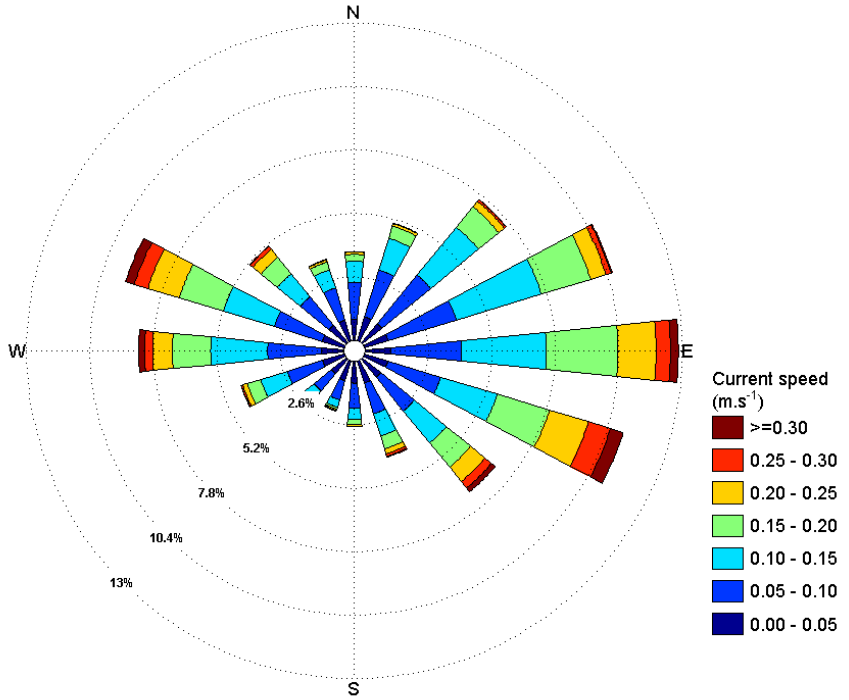

Figure 5.6 Annual regime of surface current at the approximate centre of the permit area. Note currents are shown in the 'going to' directional convention.

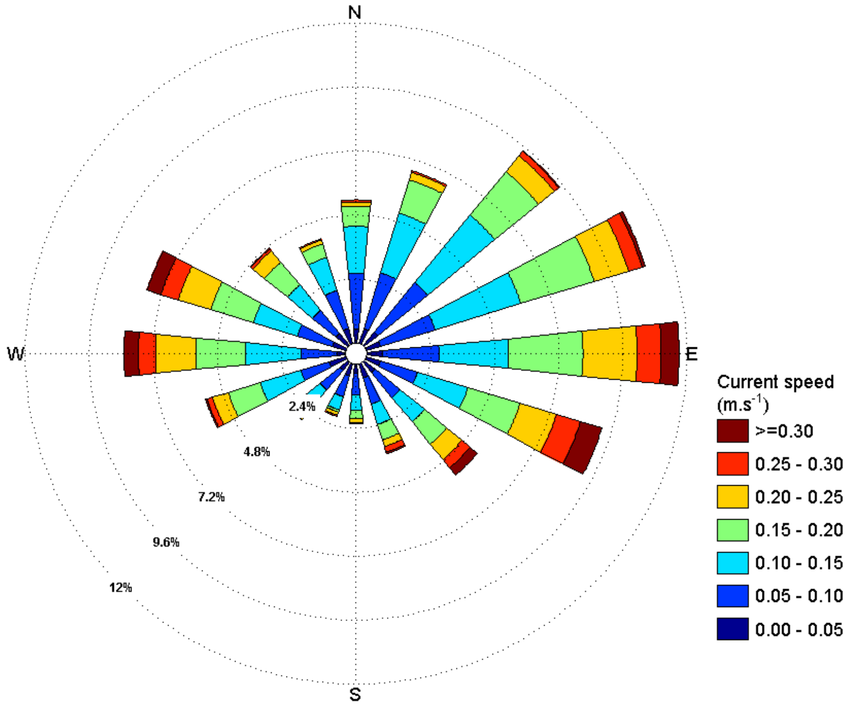

Figure 5.7 Summer regime of surface current at the approximate centre of the permit area. Note currents are shown in the 'going to' directional convention.

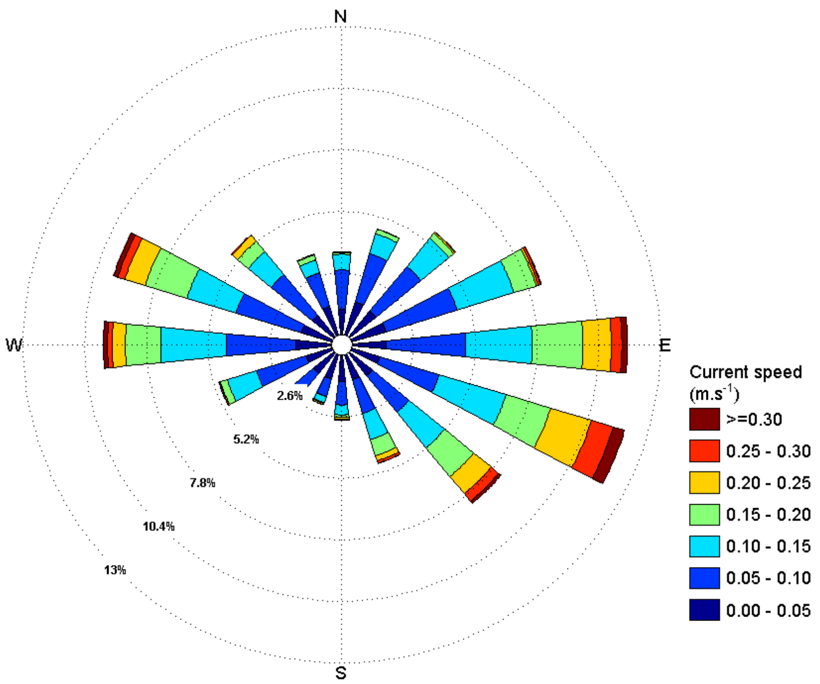

Figure 5.8 Autumn regime of surface current at the approximate centre of the permit area. Note currents are shown in the ‘going to’ directional convention.

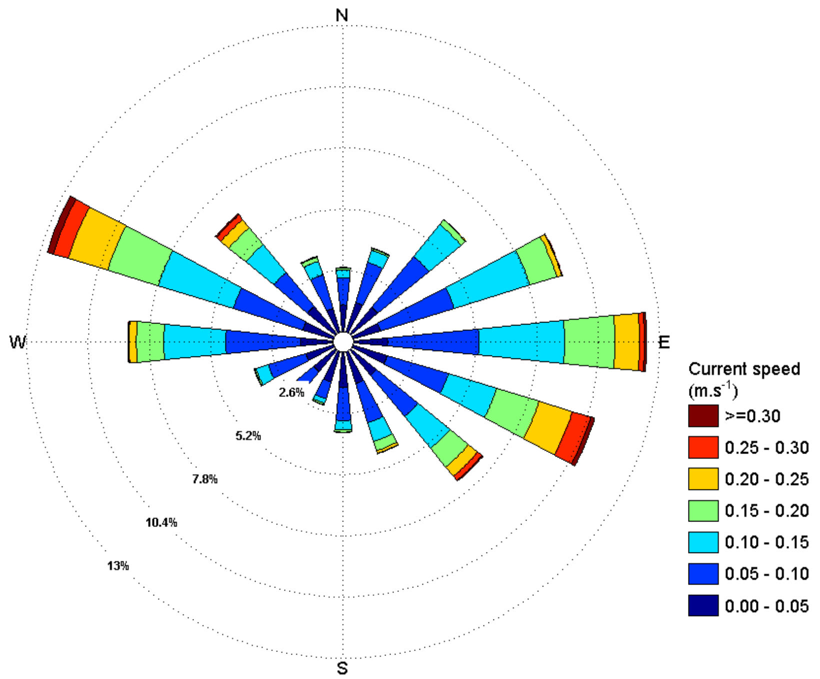

Figure 5.9 Winter regime of surface current at the approximate centre of the permit area. Note currents are shown in the ‘going to’ directional convention.

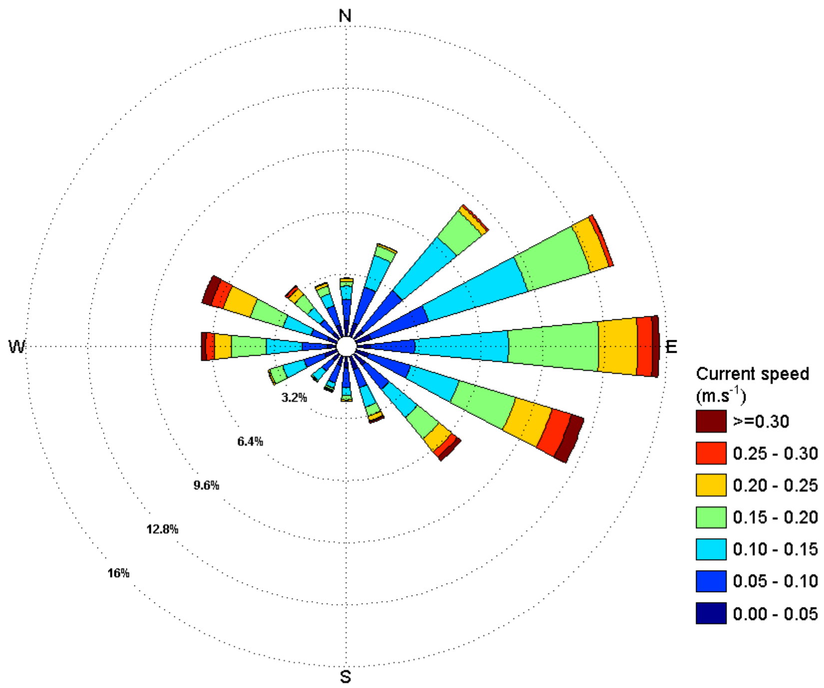

Figure 5.10 Spring regime of surface current at the approximate centre of the permit area. Note currents are shown in the 'going to' directional convention.

5.2. Short-term probability distributions

The seasonal results for probability distribution at 24, 48 and 72-hours after a spill are provided in Figures 5.11 – 5.22. The results are expressed as normalised probability densities, which represent the relative likelihood of oil visitation at the given time interval from release.

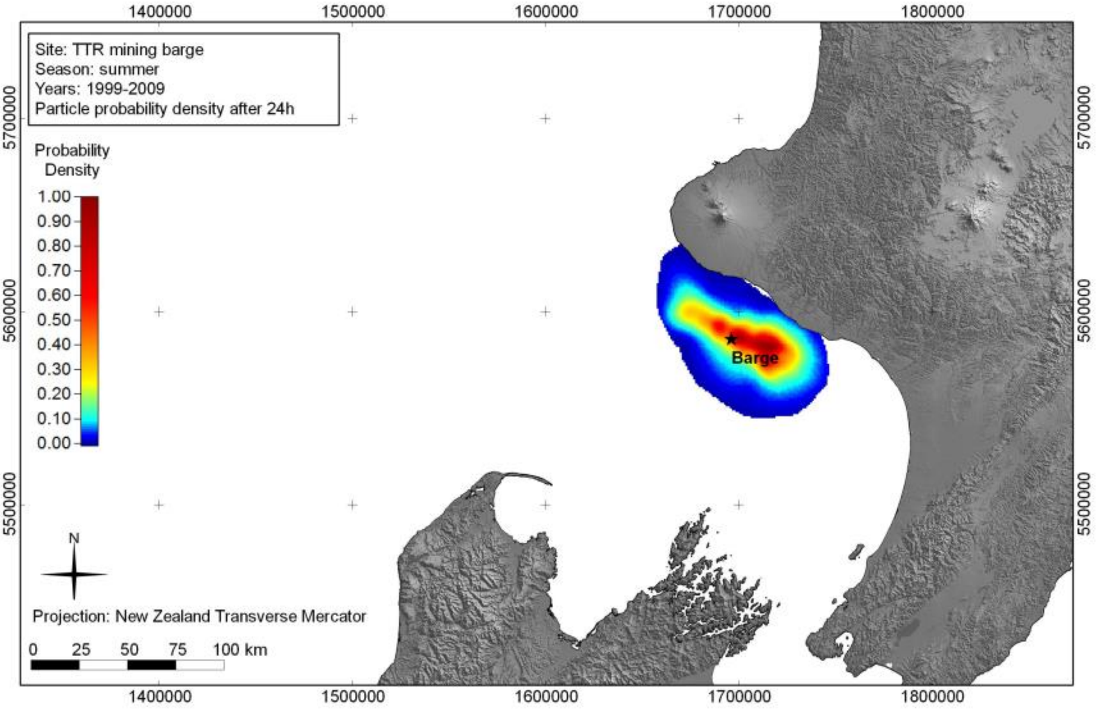

Figure 5.11 Summer season probability density distribution of non-weathered oil at 24 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

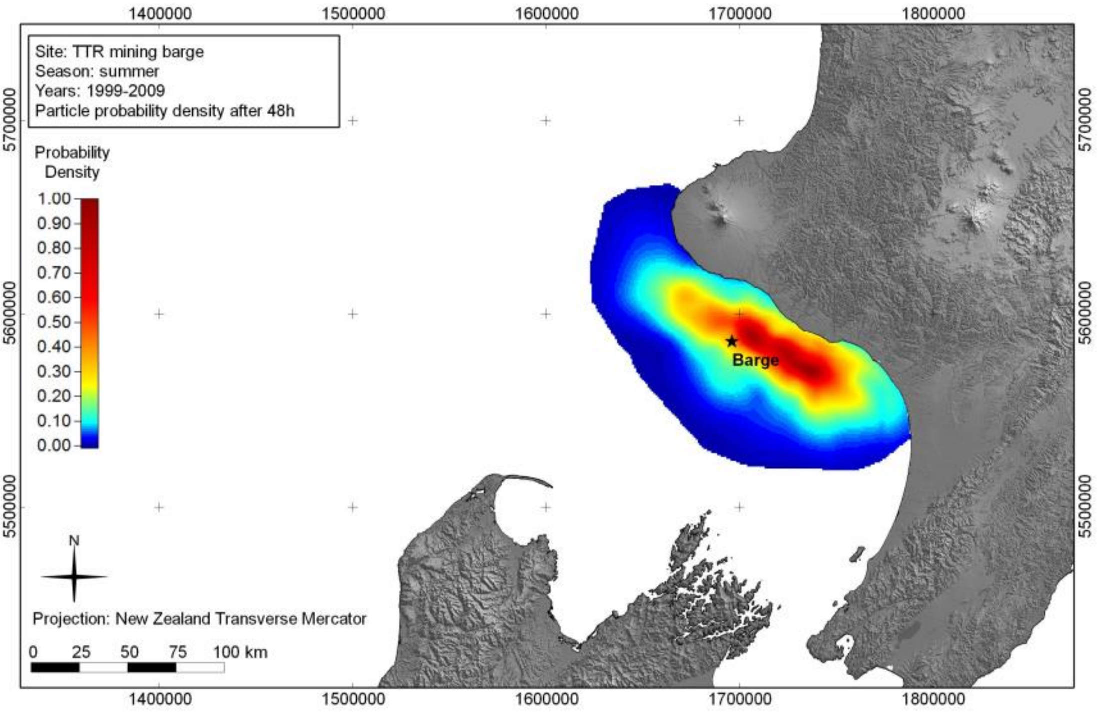

Figure 5.12 Summer season probability density distribution of non-weathered oil at 48 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

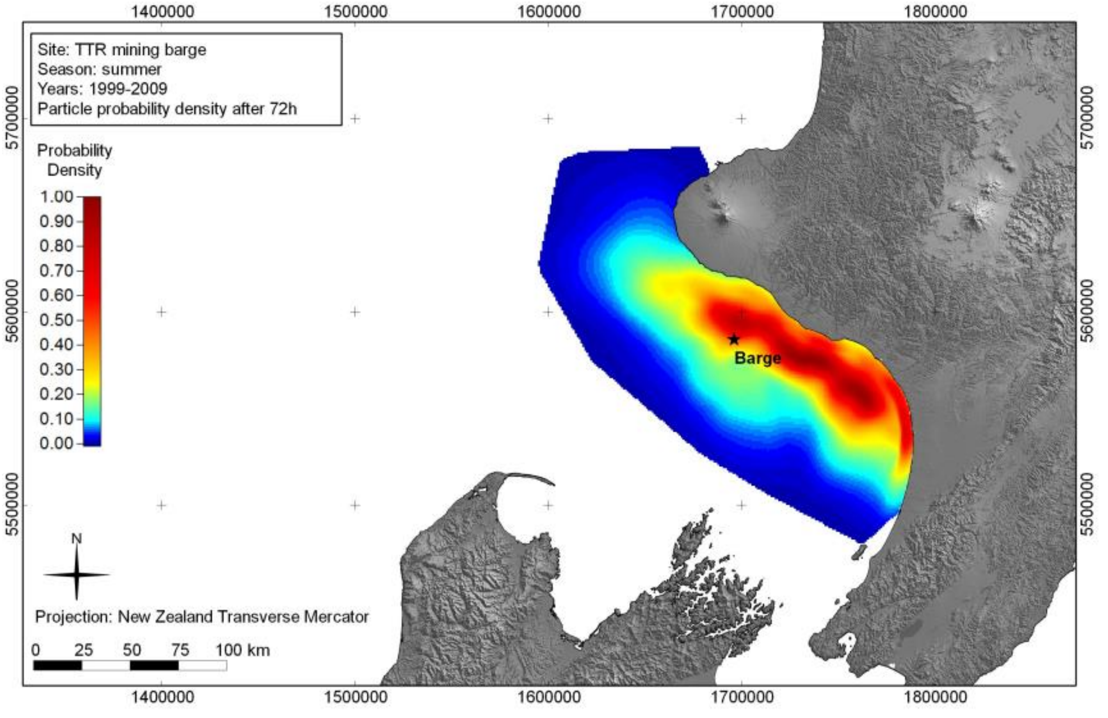

Figure 5.13 Summer season probability density distribution of non-weathered oil at 72 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

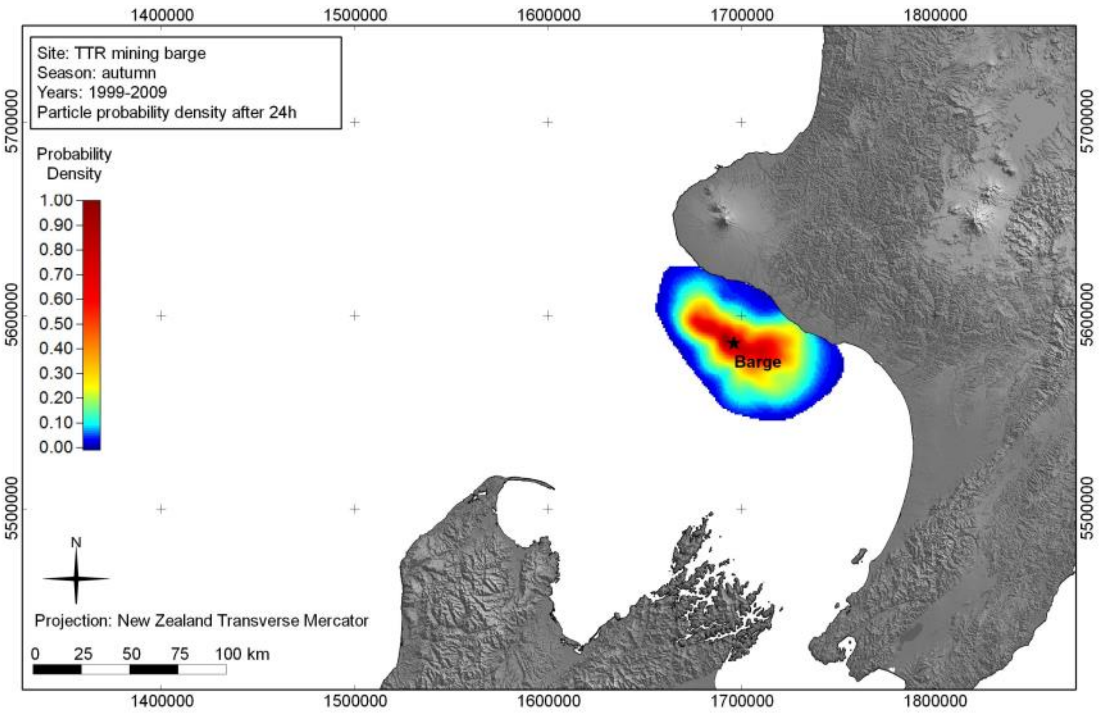

Figure 5.14 Autumn season probability density distribution of non-weathered oil at 24 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

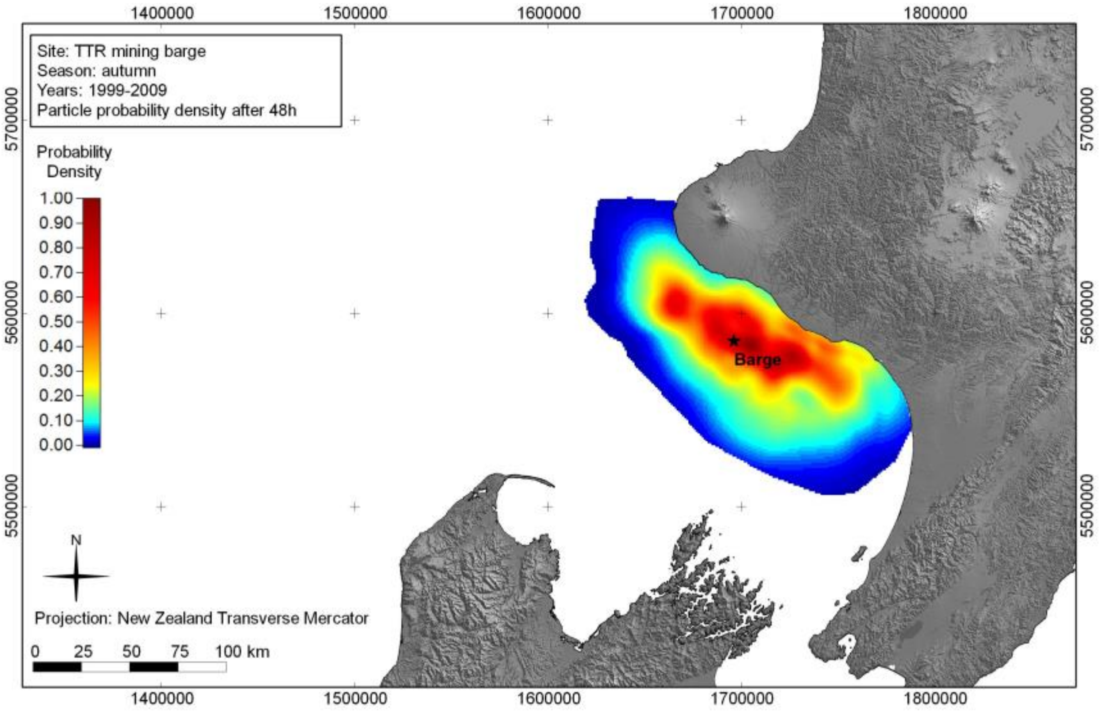

Figure 5.15 Autumn season probability density distribution of non-weathered oil at 48 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

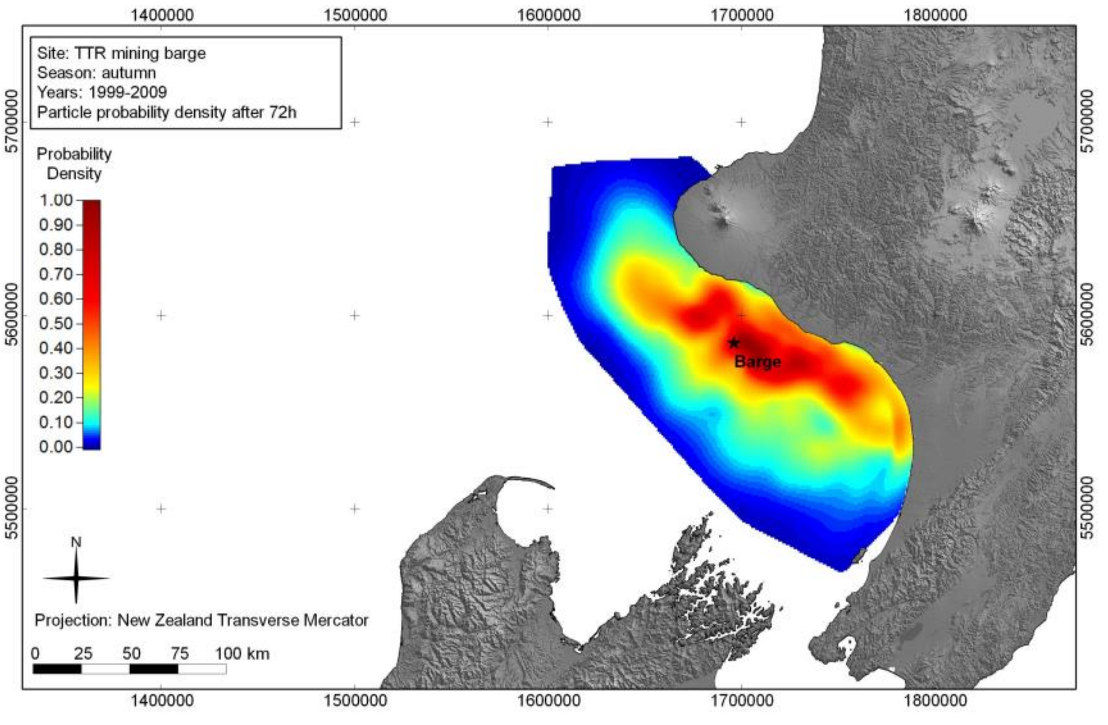

Figure 5.16 Autumn season probability density distribution of non-weathered oil at 72 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

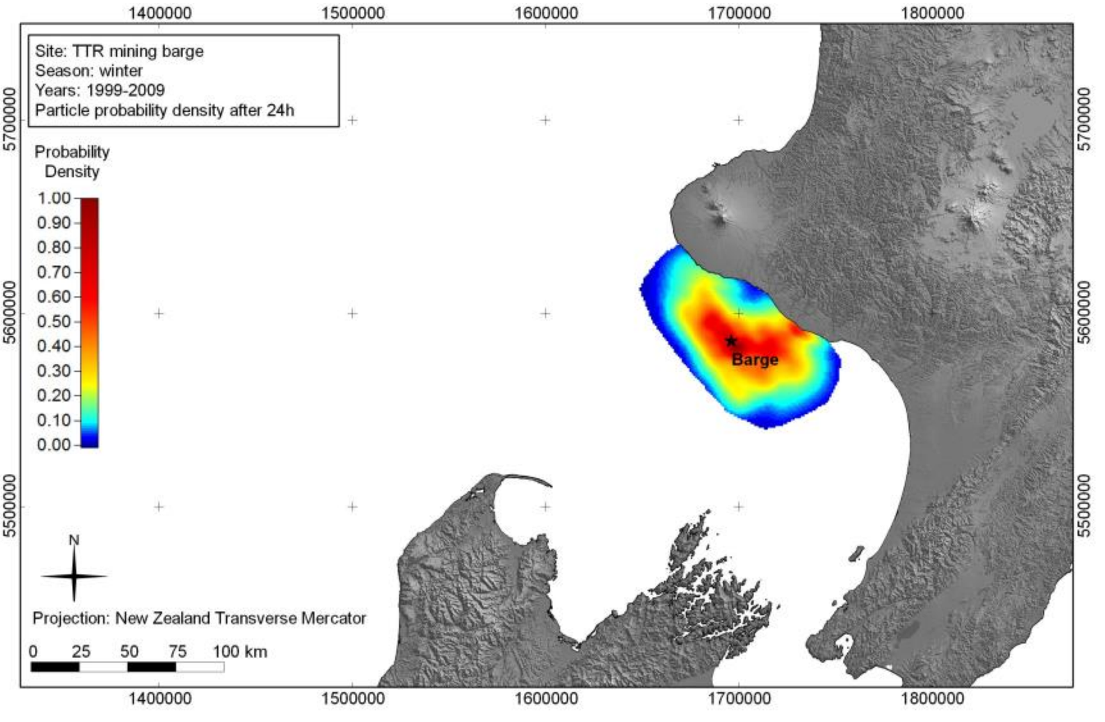

Figure 5.17 Winter season probability density distribution of non-weathered oil at 24 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

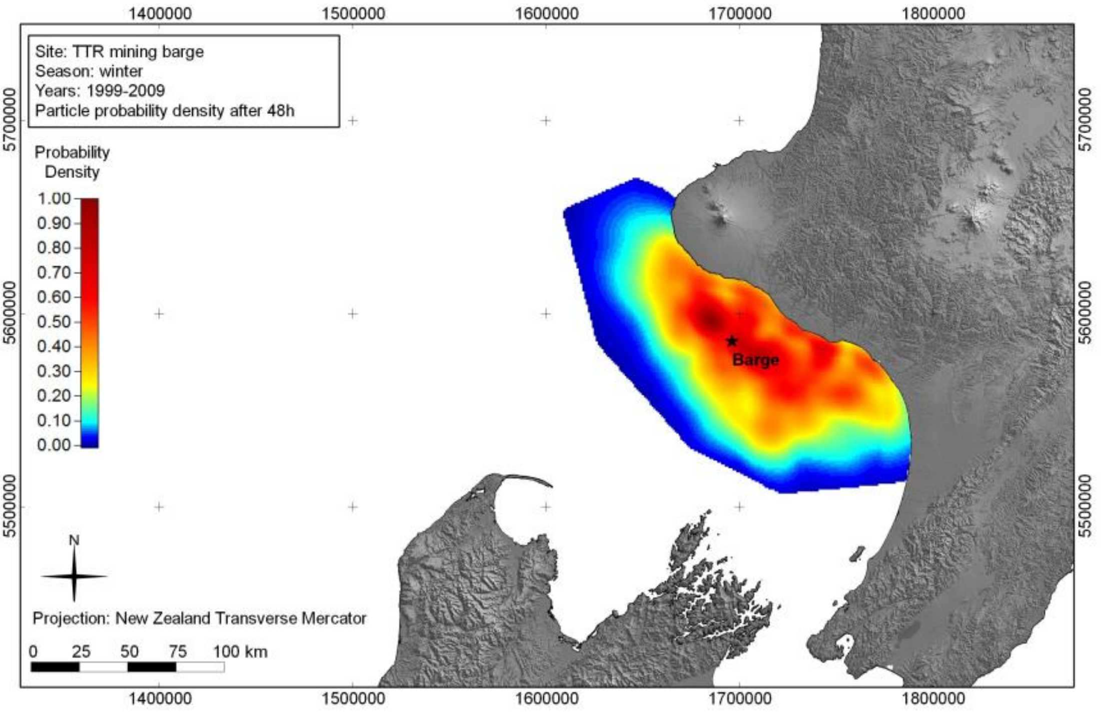

Figure 5.18 Winter season probability density distribution of non-weathered oil at 48 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

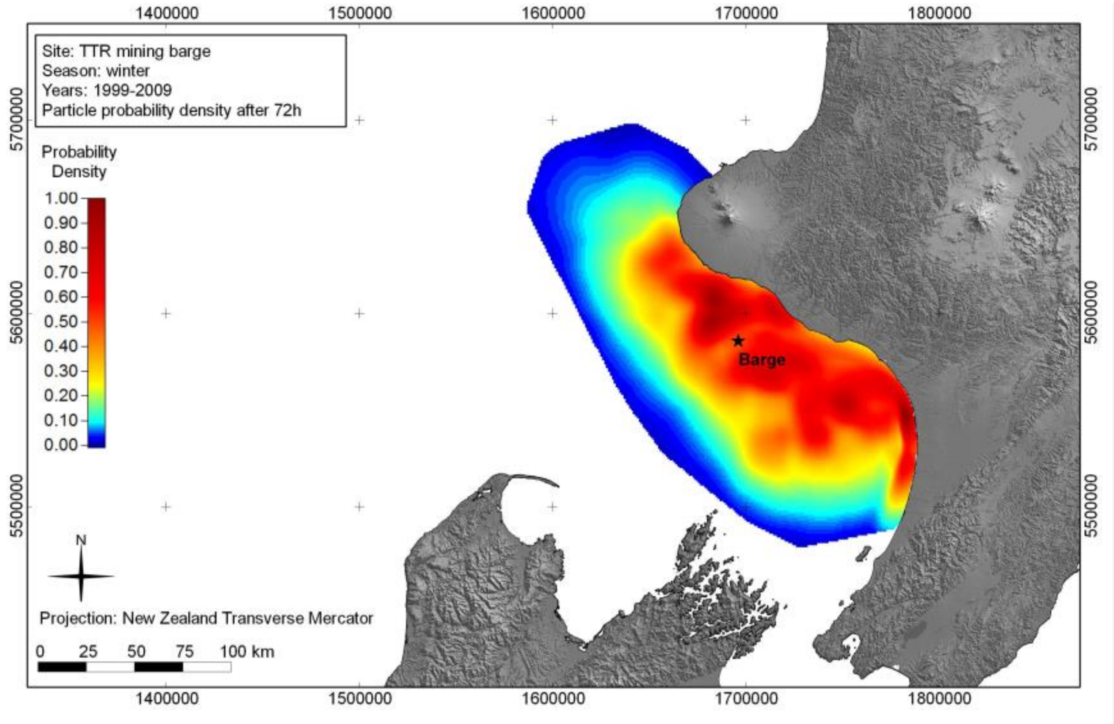

Figure 5.19 Winter season probability density distribution of non-weathered oil at 72 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

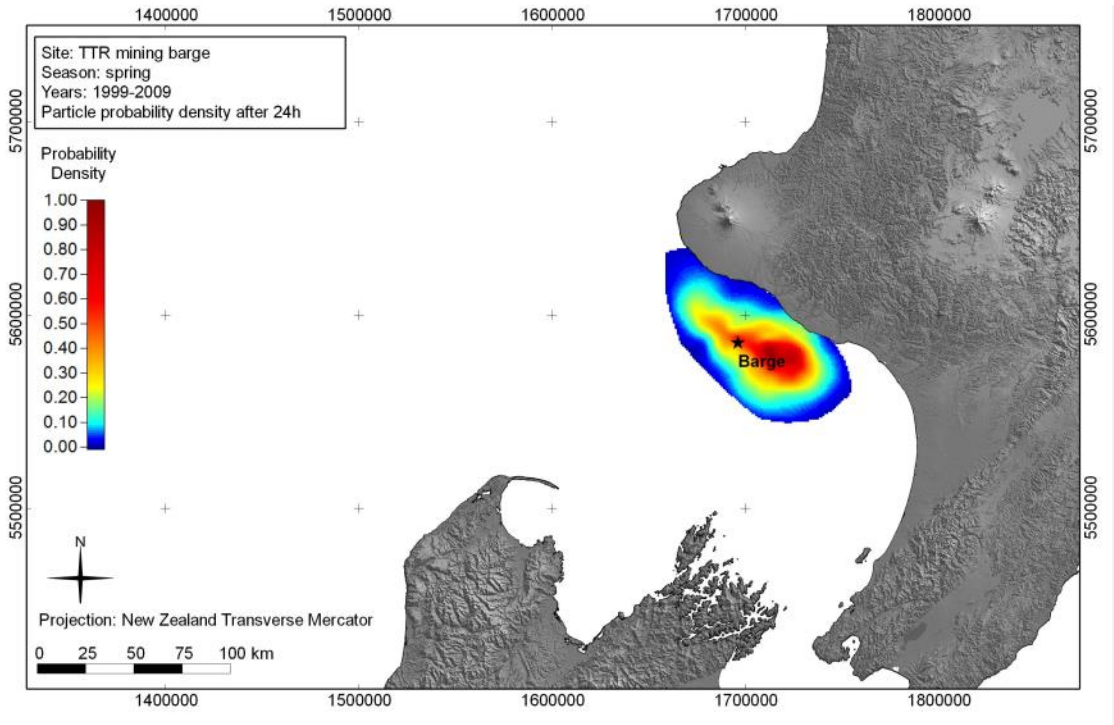

Figure 5.20 Spring season probability density distribution of non-weathered oil at 24 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

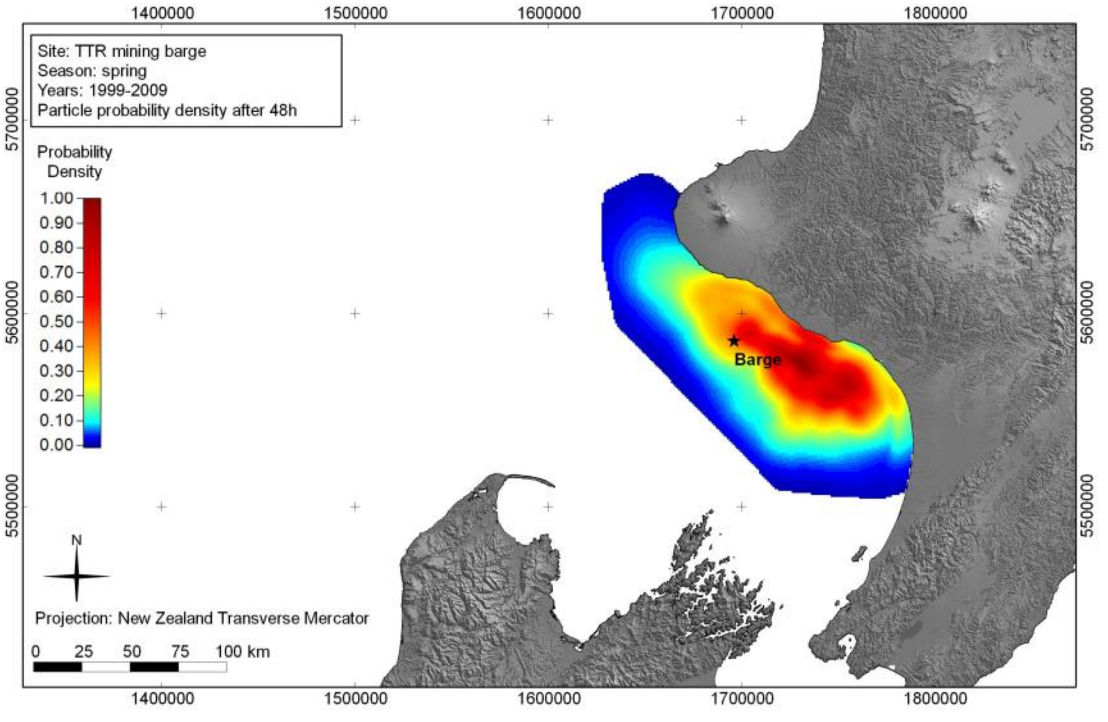

Figure 5.21 Spring season probability density distribution of non-weathered oil at 48 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

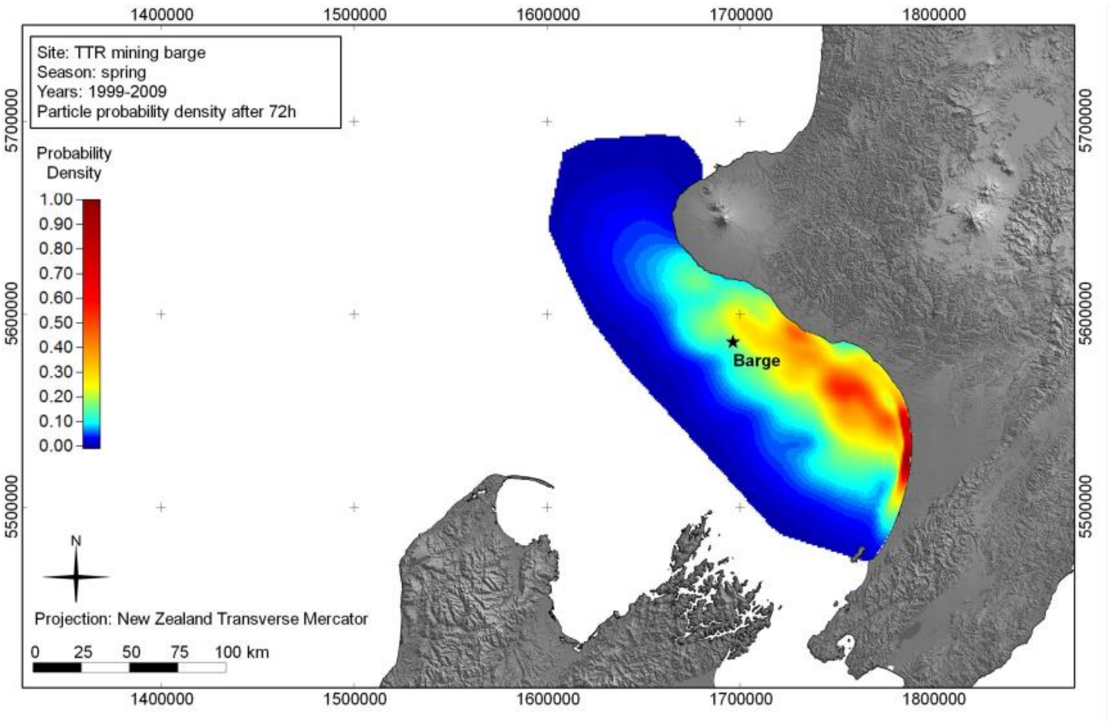

Figure 5.22 Spring season probability density distribution of non-weathered oil at 72 hours following release from the mining barge at the approximate centre of the permit area (based on an 11-year trajectory database).

5.3. Beaching probabilities

The seasonal results, showing the potential beaching outcomes identified by the 11-year trajectory database are provided in Figures 5.23– 5.34. Also shown on the maps are the minimum beaching times. These probability results represent the relative likelihood of a beaching outcome should a release occur in any given season. The percentage of trajectory outcomes that result in beaching and the minimum times for beaching from the 11-year database are summarised in Table 5.3.

Table 5.3 Percentage of events that result in beaching (determined from the 11-year trajectory database) and the minimum time (in hours) for beaching per season.

	Season			
	Spring	**Summer**	**Autumn**	**Winter**
Total % beaching	97.8	94.9	92.4	95.0
Min beaching time (hours)	16.6	12.5	16.6	12.7

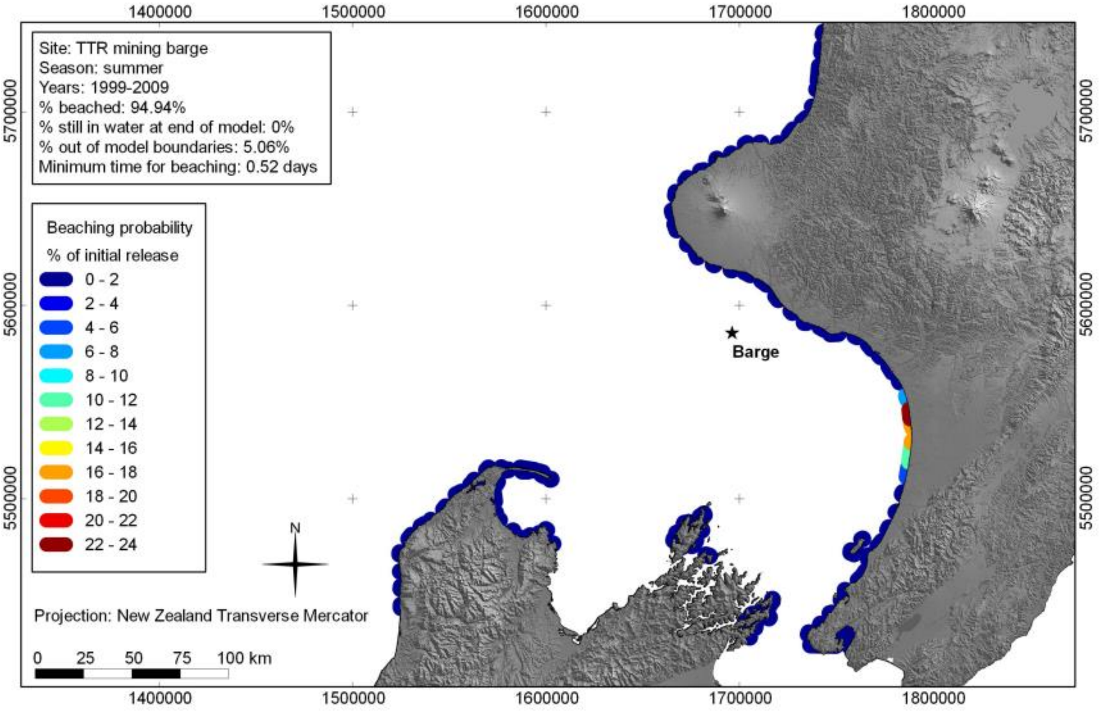

Figure 5.23 Summer season beaching probability based on an 11-year trajectory database.

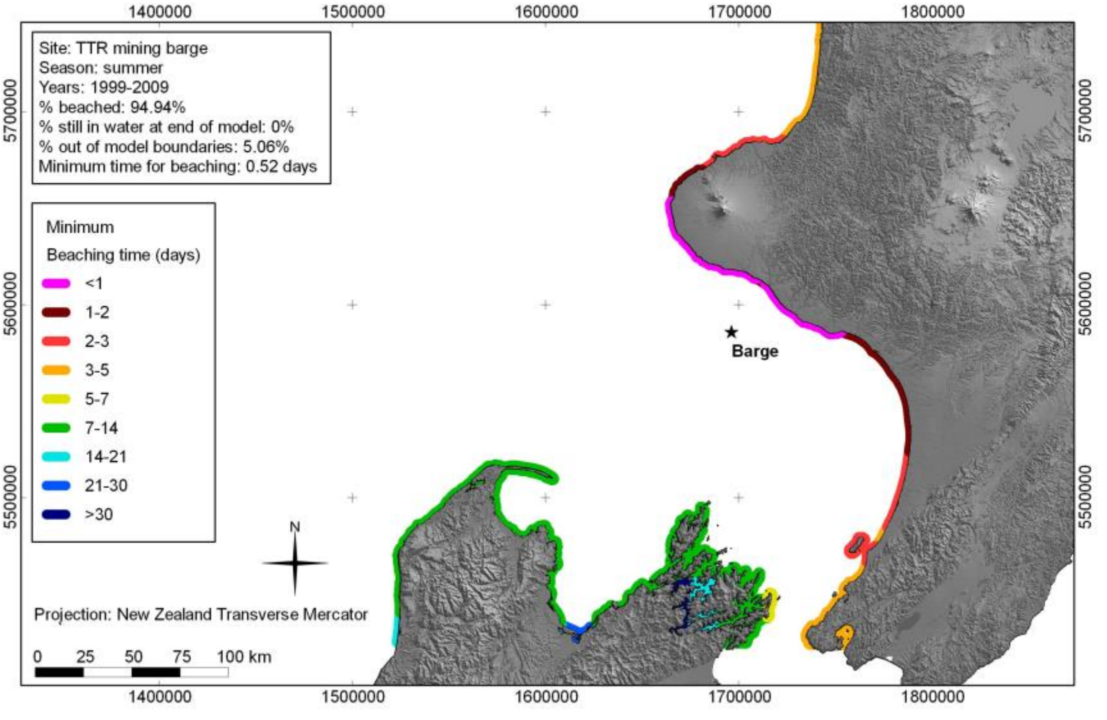

Figure 5.24 Summer season minimum beaching times.

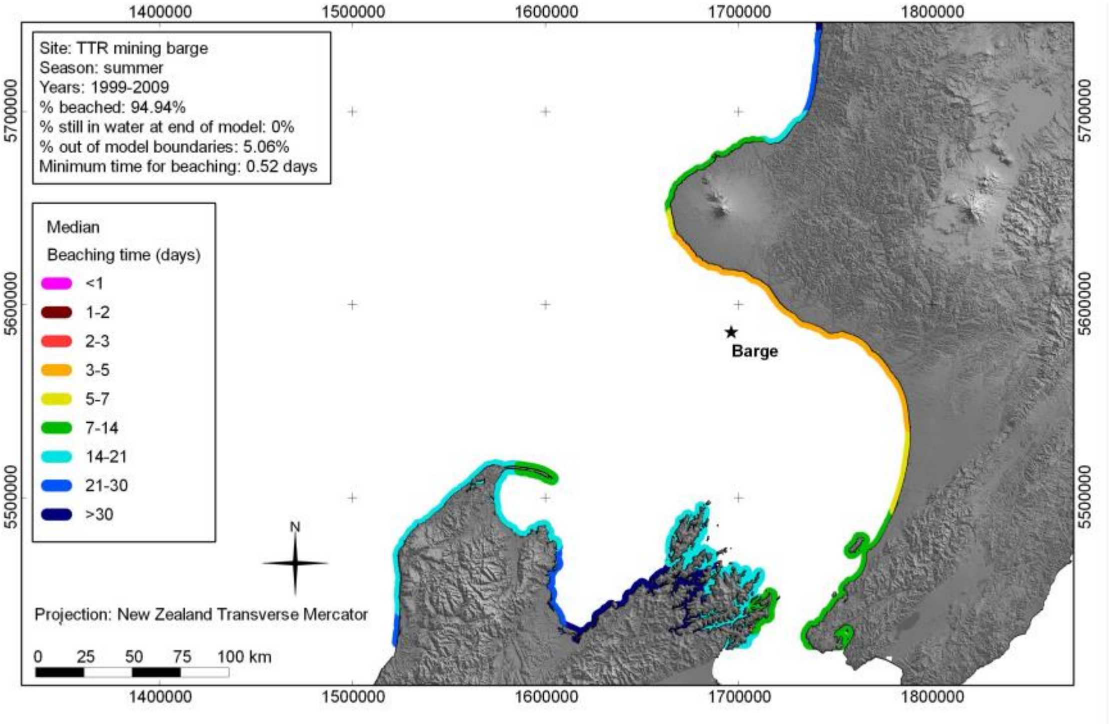

Figure 5.25 Summer season median beaching times.

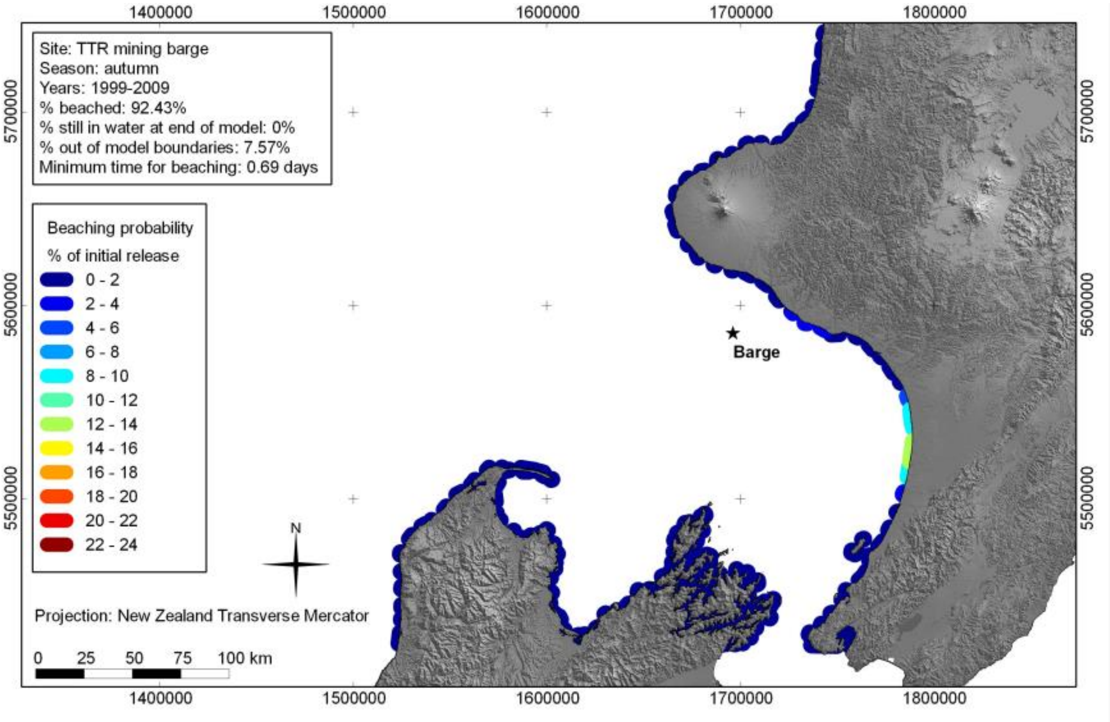

Figure 5.26 Autumn season beaching probability based on an 11-year trajectory database.

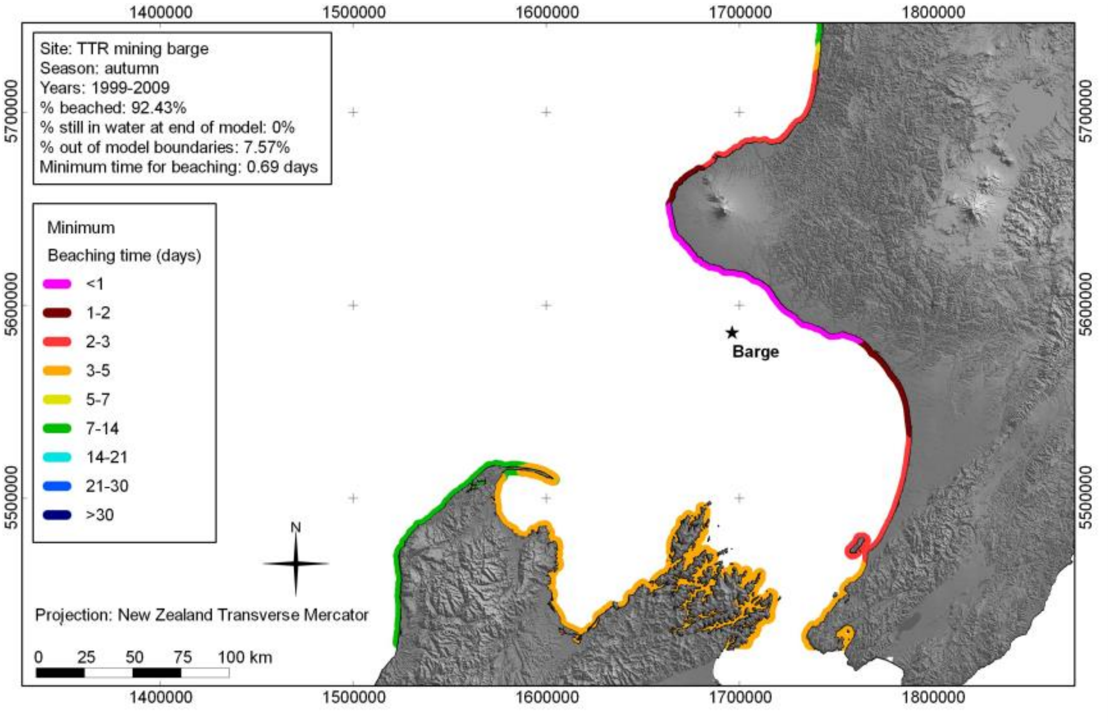

Figure 5.27 Autumn season minimum beaching times.

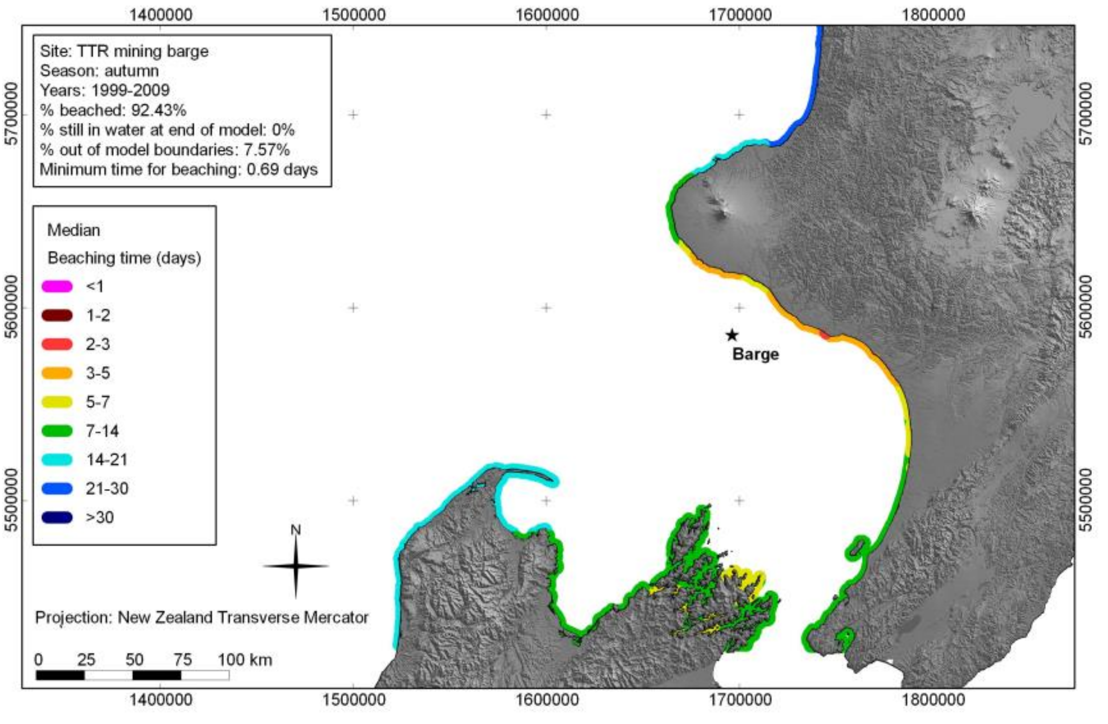

Figure 5.28 Autumn season median beaching times.

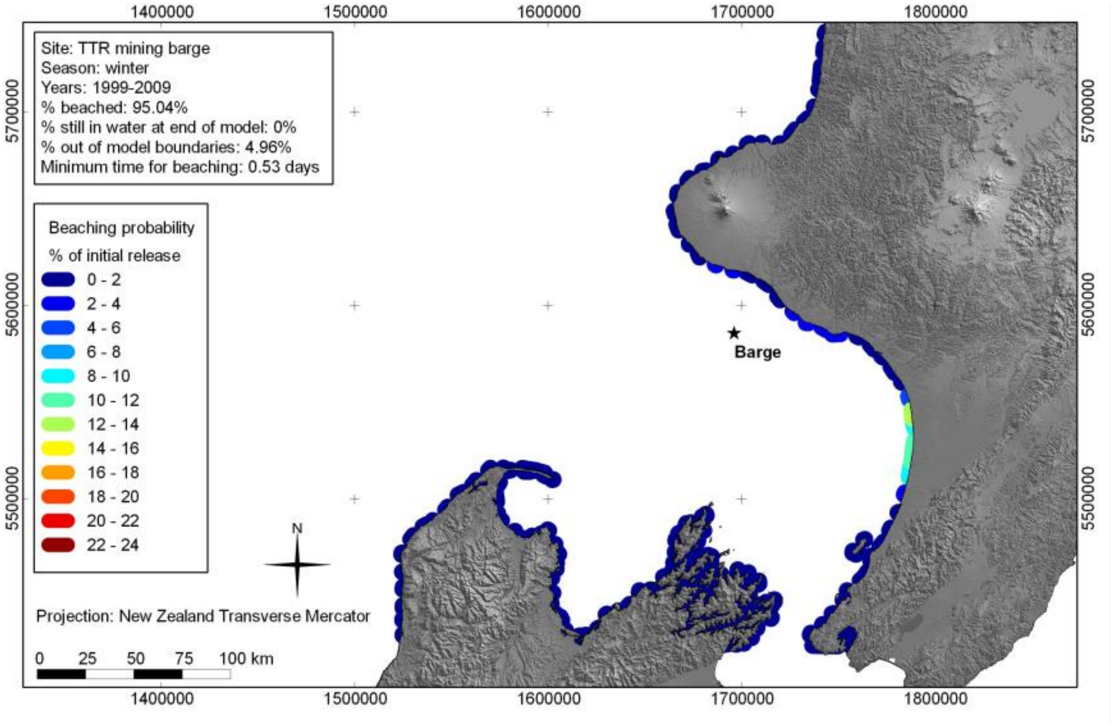

Figure 5.29 Winter season beaching probability based on an 11-year trajectory database.

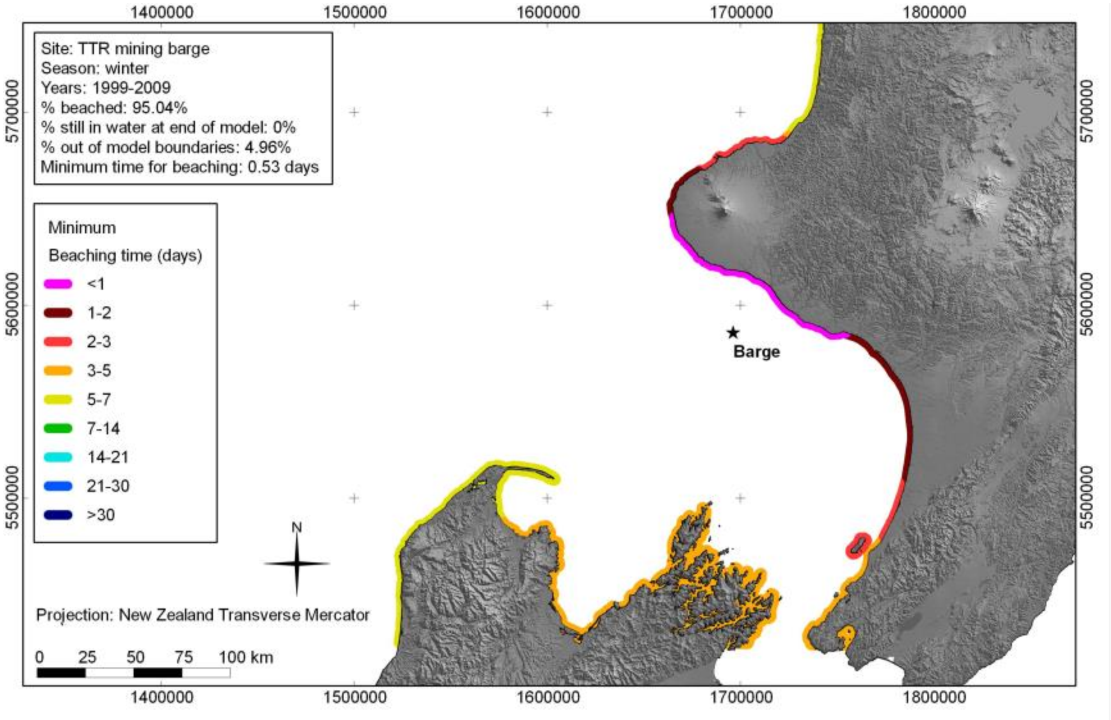

Figure 5.30 Winter season minimum beaching times.

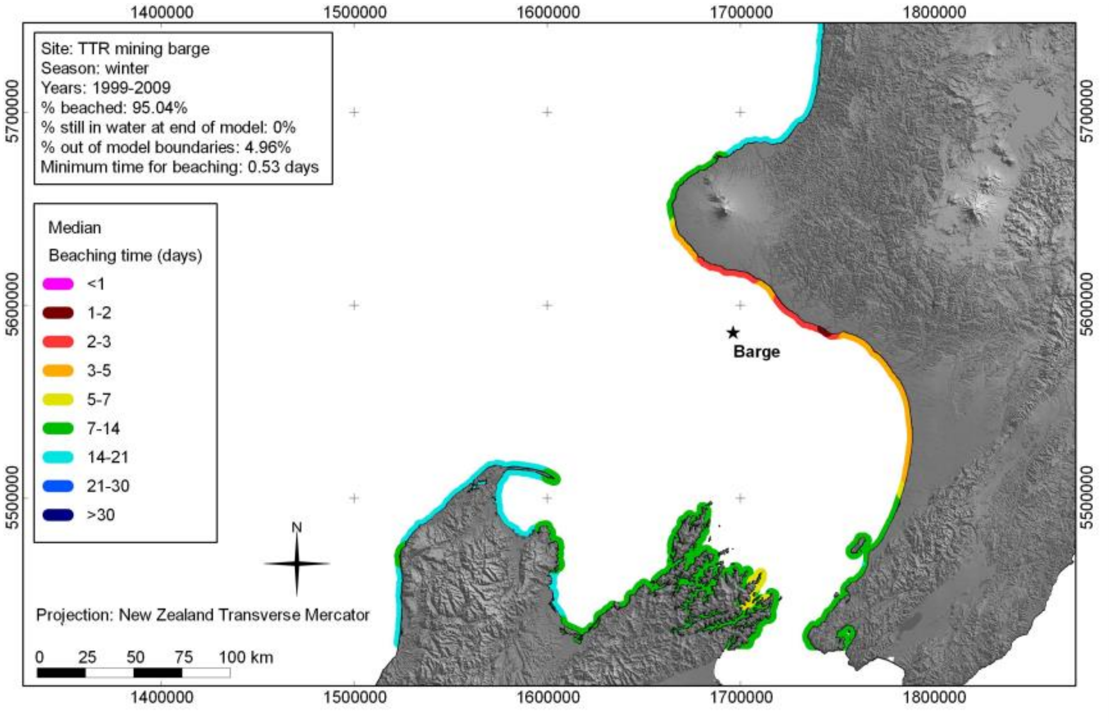

Figure 5.31 Winter season median beaching times.

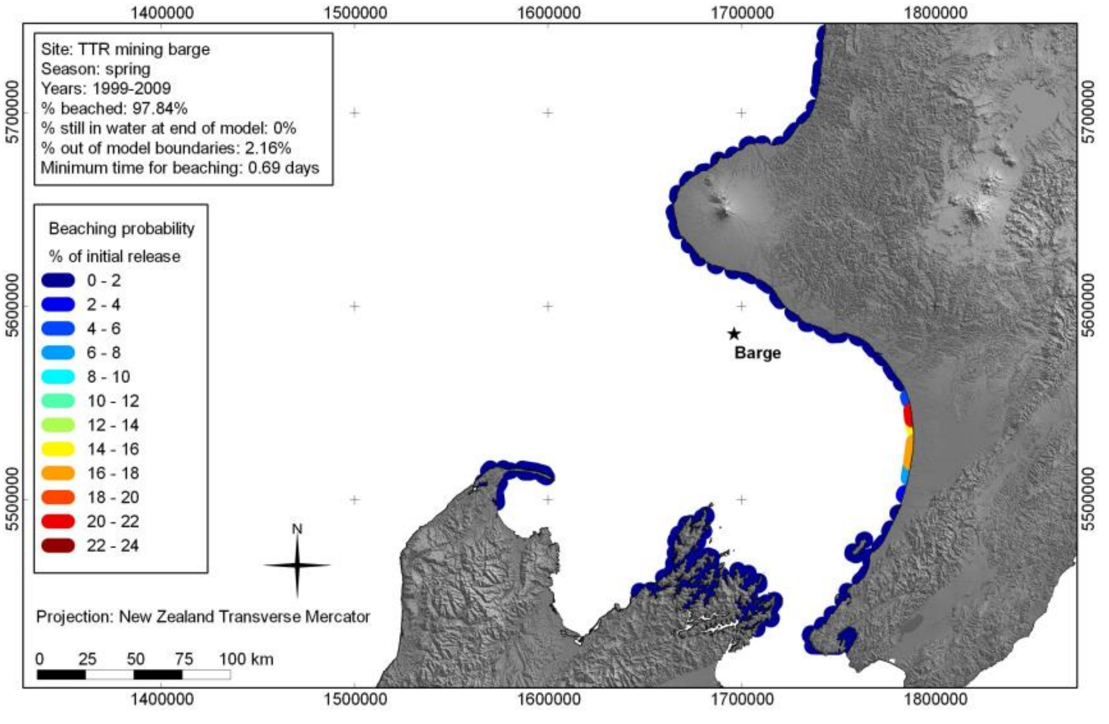

Figure 5.32 Spring season beaching probability based on an 11-year trajectory database.

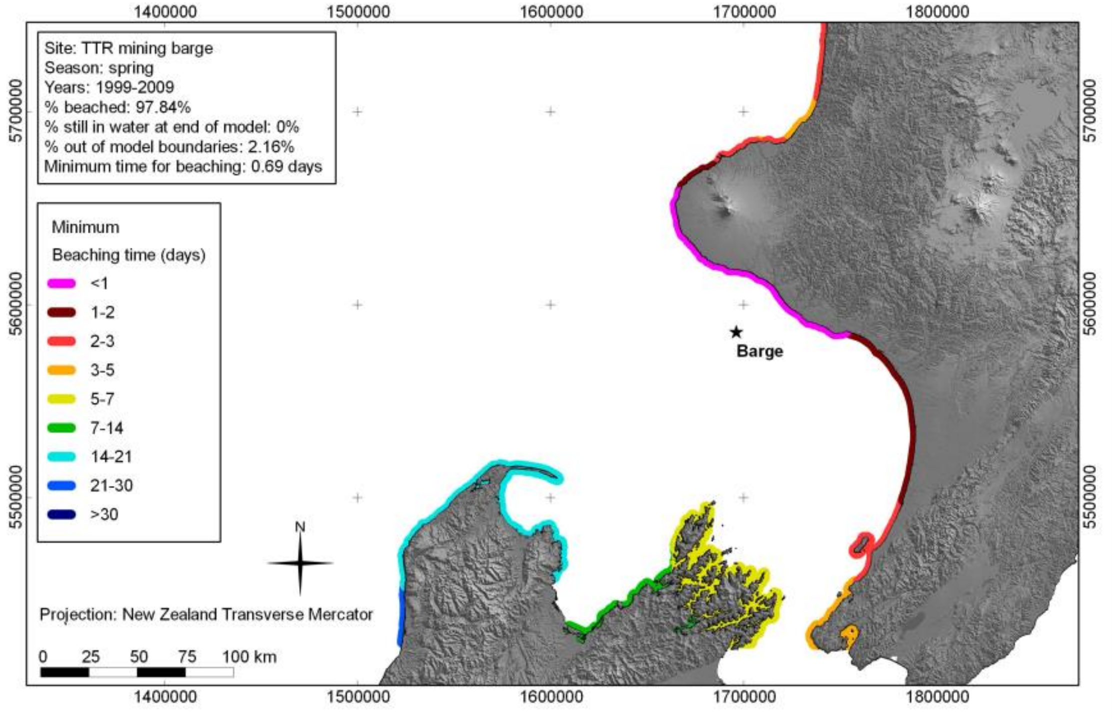

Figure 5.33 Spring season minimum beaching times.

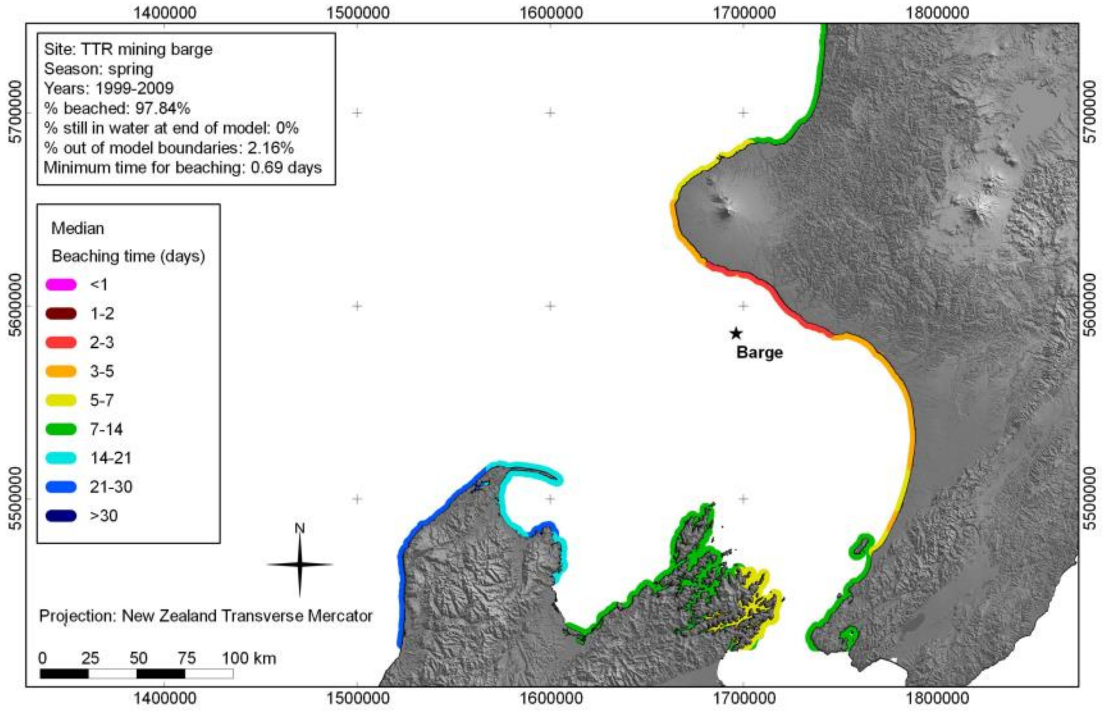

Figure 5.34 Spring season median beaching times.

5.4. Weathering budgets

A weathering table has been produced for 380 Heavy Fuel Oil (Table 5.4). This table expresses the volume percentage of spilled oil predicted to remain on the sea surface at time increments out to 120 hours after the release. The two key variables to weathering are water temperature and wind speed.

Table 5.4 Volume percentage of oil remaining on surface after a 2-hour release of 100 mT of 380 Heavy Fuel Oil as a function of wind speed and exposure time, calculated using ADIOS2. The model considers evaporation and dispersion in the water column under the action of wind and waves. Calculations were run for water temperatures of 13°C and 17°C, providing an interval of percentage indicated in each table cell. A table cell containing a single value indicates no difference in results between 13°C and 17°C.

Wind speed ($m.s^{-1}$)	**Hours into spill**															
	2	**4**	**6**	**8**	**10**	**12**	**18**	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
1	100	99-100	98-99	96-98	93-96	91-95	86-91	83-88	81-84	80-82	80-81	80-81	80	80	80	80
2	100	98-99	96-98	92-96	89-94	87-92	82-87	81-84	80-82	80-81	80	80	80	80	80	80
3	100	98-99	94-97	90-94	87-92	85-90	81-85	80-83	80-81	80-81	80	80	80	80	80	80
4	99-100	97-98	92-96	88-93	85-90	83-88	81-84	80-82	80-81	80	80	80	80	80	80	80
5	99-100	97-98	92-95	88-91	85-88	83-86	81-83	80-82	80	80	80	80	80	80	80	80
10	98-99	91-94	86-90	83-87	82-85	81-84	80-81	80	79-80	79-80	79-80	79-80	79-80	79-80	79-80	79
15	95-96	88-90	83-86	81-83	80-81	79-80	78-79	78-79	77-79	77-79	77-79	77-79	77-79	77-79	77-79	77-79
20	90-92	84	79-80	77-78	75-78	75-78	74-78	73-77	73-77	73-77	73-77	73-77	73-77	73-77	73-77	73-77
25	84-88	78-81	74-77	72-76	71-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-76	70-75
30	79-85	72-78	69-75	67-75	67-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74	66-74

5.5. Worst-case beaching predictions

The potential worst-case beaching arising from an accidental release of 100 mT of 380 Heavy Fuel Oil for 2 hours from the TTR mining barge is presented in Figure 5.35. The worst-case release date has been identified as the 27th of June 2008. During this period the highest beaching concentrations are predicted to occur in the South Taranaki Bight, with maximum concentrations of 4.79 m^3 per kilometre of coastline in the vicinity of Wanganui.

The results of the same uncontrolled release on the beaching at shoreline sections defined in Figure 5.36 are presented in Table 5.5.

Table 5.5 Beaching outcomes from the worst case 2 hours accidental spill scenario identified from the 11-year trajectory database for 12 shoreline segments (Fig. 5.36).

Shoreline Section	Release Duration (days)	Start Date	Maximum Concentration (m^3/km)	Beaching %	Average Concentration (m^3/km)
A	1	15-Mar-03	3.76	100.00	0.17
B	1	22-Aug-01	4.30	41.87	0.06
C	1	10-Aug-09	7.03	99.22	0.08
D	1	-	0.00	0.00	0.00
E	1	11-Jun-04	10.20	19.04	0.06
F	1	13-Sep-03	3.43	100.00	0.40
G	1	18-Feb-04	7.18	100.00	0.44
H	1	22-May-09	17.70	100.00	0.40
I	1	27-May-09	8.94	100.00	0.29
J	1	12-Jan-03	5.24	82.87	0.27
K	1	8-Sep-06	5.34	88.48	0.32
L	1	9-Nov-00	2.71	50.80	0.16
Complete coastline	1	27-Jun-08	4.79	100.00	0.04

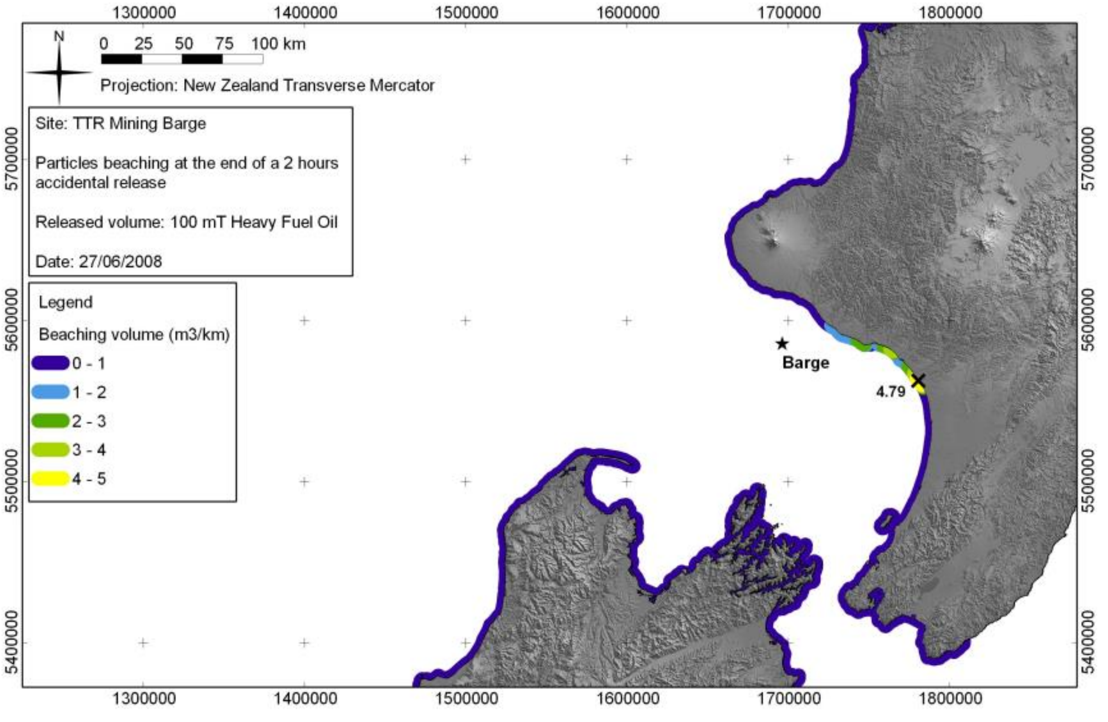

Figure 5.35 Predicted beached percentages from a 2 hours accidental release of 100 mT of Heavy Fuel Oil from the mining barge at the approximate centre of the permit area. This figure represents the worst coastal beaching outcome within the 11-year trajectory database.

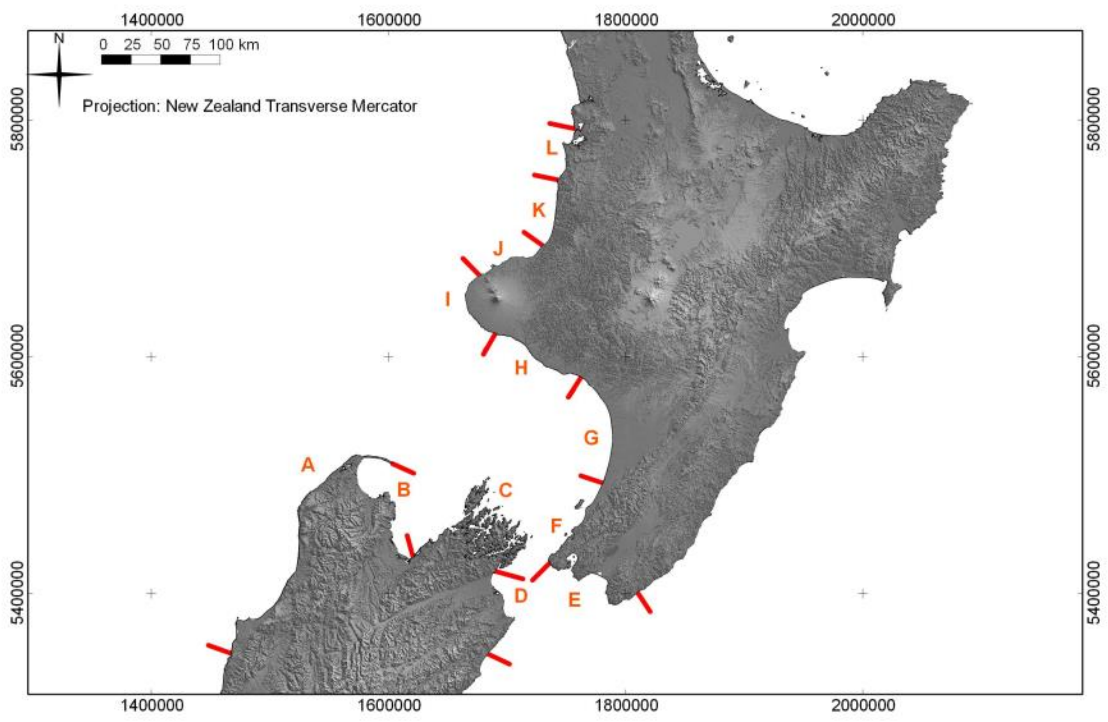

Figure 5.36 Shoreline sections used for the detailed beaching assessment and identification of the worst case scenario in the event of an accidental spill.

6. SUMMARY OF RESULTS

An 11-year database containing all the likely trajectories for an oil spill from a mining barge located at the centre of the permit area has been constructed. Oil spills have been tracked continuously from 1999 to 2009 until they beach or leave the modelled region. This technique provides a robust statistical basis to quantify the most likely pathways for oil in the unlikely event of a spill from the mining barge, and from this knowledge an assessment of the coastal areas that are most likely to be affected can be reliably determined.

Results from the trajectory database have been examined for the seasonal conditions, showing the relative probabilities for beaching and statistics for beaching times. The season with the highest probability of beaching is spring, while the season that exhibits the lowest beaching outcome is autumn. Taking a conservative approach without including the effects of weathering on spilled oil, beaching is a likely outcome from a spill for 92.4 – 97.8% of events, depending on the season. The minimum time for beaching of spilled oil ranges between 12.5 hours during summer to 16.6 hours during spring and autumn.

A series of coastal beaching probability maps have been produced, and maps of beaching probabilities are provided for each season. The region of coast most likely to be affected from a spill is in the South Taranaki Bight in the vicinity of the Rangitikei River Mouth.

Short-term probability density distributions have been calculated to show the likely spread of spilled oil from the mining barge at the approximate centre of the permit area, at the T+24, 48 and 72-hour time horizons. A hydrocarbon weathering model has been used to estimate the time-varying release budget for 380 Heavy Fuel Oil. A volumetric percentage remaining on the sea surface is provided for a range of probable water temperatures and wind speed scenarios.

The worst-case outcome of an accidental release of 100 mT of 380 Heavy Fuel Oil has been investigated. The release date in the 11-year trajectory database that produces the maximum beaching outcome has been identified, and oil concentrations of over 2 m^3 per kilometre of shore have been predicted in the South Taranaki Bight. A maximum concentration (4.79 $m^3.km^{-1}$) was found around Wanganui. The maximum and average concentrations of weathered oil, per linear kilometre of coast have been reported for representative sections of the coastline.

REFERENCES

Beegle-Krause, C.J., 1999. GNOME: NOAA's next-generation spill trajectory model. Presented at the Oceans '99 MTS/IEEE Proceedings, MTS/IEEE Conference Committee, Escondido, CA, pp. 1262–1266.

Beegle-Krause, C.J., 2001. General NOAA Oil Modeling Environment (GNOME): a new spill trajectory model., in: IOSC 2001. Proceedings. St. Louis, MO: Mira Digital Publishing, Inc., Tampa, FL, pp. 865–871.

Jones, R.K., 1997. A simplified pseudo-component oil evaporation model, in: Proceedings of the Twentieth Arctic Marine Oil Spill Program Technical Seminar, Environment Canada. Ottawa, Ontario, pp. 43–61.

Lehr, W., Wesley, D., Simecek-Beatty, D., Jones, R., Kachook, G., Lankford, J., 2000. Algorithm and interface modifications of the NOAA oil spill behavior model, in: Proceedings of the Twenty-Third Arctic and Marine Oilspill Program (AMOP) Technical Seminar, June 14-16, 2000. Environment Canada, Vancouver, British Columbia, Canada.

Vitali, L., Monforti, F., Bellasio, R., Bianconi, R., Sachero, V., Mosca, S., Zanini, G., 2006. Validation of a Lagrangian dispersion model implementing different kernel methods for density reconstruction. Atmos. Environ. 40, 8020–8033.

Zheng, L., Yapa, P.D., 2000. Buoyant velocity of spherical and non-spherical bubbles/ droplets. J. Hydraul. Eng. Asce 852–855.