FSO SAFER

Oil Spill Trajectory Modelling

16 July 2021

EXECUTIVE SUMMARY

Oil spill modelling was carried for the FSO SAFER, located off the western coast of Yemen (Figure 1), to support oil spill contingency planning. Four hypothetical scenarios were modelled, three scenarios were based on an assessment of possible causes of an oil spill and one was a worst case scenario resulting in the total loss of oil on board the FSO:

Scenario 1: Release of 3 tanks due to fire/explosion or cracking of hull resulting in an oil spill of 47,694 m^3 over 2 days.

Scenario 2: Release of 50% of 1 tank, due to corrosion of bottom steel resulting in an oil spill of 7,900 m^3 over 21 days.

Scenario 3: Release caused by damages to the PLEM structure and pipeline resulting in an oil spill of 2,500 m^3 over 60 days.

Scenario 4: Worst case scenario, resulting in an oil spill of approximately 180,000 m^3 (1,140,000 bbls) over 7.5 days.

Stochastic modelling techniques were used for this study. Scenarios 1 - 3 were modelled using year round conditions. Scenario 4 was modelled over the following seasons:

- January – March
- April – June
- July – September
- October – December

For each scenario, a series of identical oil spill simulations were modelled, each simulation was subject to different metocean (wind and currents) conditions from a historical dataset. The results were then combined and processed to create the stochastic modelling results presented in this report. The seasonal results aid in the understanding of the variation due to prevailing winds and currents experienced at different points during the year.

The stochastic approach therefore provides a wide range of possible spill trajectories which can be used to indicate probability of exposure to oil of areas of sea surface or coastline and therefore inform response planning.

It should be noted that the modelling is based on several assumptions and estimates where more accurate information may be lacking. For example, the degree of weathering of the oil on board the FSO is currently unknown. The model uses oil properties similar to those of a fresh Marib light crude. Without sampling the oil currently in the tanks, it is not possible to determine the degree to which these properties may have changed and how these changes might impact the modelled fate and behaviour of the oil. Evaporation of the oil's lighter factions and an increase in its viscosity would be expected over time.

Detailed information on the assumptions and estimates used in this modelling can be found in the Appendices to this report.

The results of the various spill scenarios are summarized below, but in general the model demonstrates that across all scenarios for a spill at any time of year, heavy shoreline oiling will be concentrated along the western coast of Yemen and its islands, particularly the Governorate of Al Hudaydah, with oil reaching the coast within 3 hours of a spill. The probability of oil reaching the coastline of the Kingdom of Saudi Arabia is highest for a spill occurring between October to March, where depending on the volumes spilled there is potential coastline impact to coastline of Jizan and the Islands of the Farasan Island Marine Sanctuary. The probability of impacts of the coastlines of Eritrea, Djibouti and Somalia are low, where any oiling observed is likely to be light.

Scenario 1 summary: Release of 3 tanks due to fire/ explosion

Spilled oil has a low probability of impacting any sea area of Djibouti (10%), Eritrea (13%), Kingdom of Saudi Arabia (15%) and Somalia (2%). Modelling predicts the spilled oil will spread predominantly within Yemeni waters in the Red Sea and move southwards towards the Bab al-Mandab Strait and into the Gulf of Aden.

Shoreline oiling along the Yemeni coastline could occur in as little as 3 hours.

Scenario 2 summary: Release of 50% of 1 tank, due to corrosion of bottom steel

Spilled oil has a low probability of impacting the sea area of Djibouti (3%), Eritrea (9%) and Kingdom of Saudi Arabia (10%), but will impact the Yemeni coastline (100%). Modelling predicts oil will spread predominantly within Yemeni waters of the Red Sea and move southwards towards the Bab al-Mandab Strait and into the Gulf of Aden. Sheen and rainbow sheen can be expected up to ~700 km away.

Shoreline oiling of Yemeni coastline could occur in as little as 3 hours.

Scenario 3 summary: Release caused by damages to the PLEM structure and pipeline.

Spilled oil is likely to remain within Yemeni waters with a low probability of impact to other countries. Heavy oiling along the coastline of Al Hudaydah is highly likely. Light oiling can be expected up to 127 km from source. Oil impact of the coastline is predicted within 4 hours of release.

Scenario 4 summary: Worst case scenario

A worst-case scenario oil spill during any time of the year is likely to impact Eritrea and Saudi Arabia, albeit to a much lesser extent than Yemen which will receive the vast majority of any oil spilled. Djibouti and Somalia are likely to be impacted by a worst-case scenario spill occurring from April December .

Heavy and moderate shoreline oiling is expected in the immediate vicinity of the FSO and up to ~300 km away. Light oiling may be found as far as Aden, ~500 km from the source.

DISCLAIMERS

- Modelling results are to be used for guidance purposes only and response strategies should not be based on these results alone.
- The resolution / quality of wind and current data vary between regions and models. As with any model, the quality and reliability of the results are dependent on the quality of the input data.

Giving consideration to the above, all advice, modelling, and other information provided for illustrative purposes and not intended to be relied upon in any specific instance. The recipient of any advice, modelling or other information from, or on behalf of, any number of variables may impact on an oil spill and, as such, should be addressed on an individual basis. .

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Background

Oil spill modelling was carried for the FSO SAFER[1], located off the western coast of Yemen (Figure 1), to support oil spill preparedness in Yemen. A total of four scenarios were modelled as summarised below, and detailed in Table 1.

Scenario 1 Release of 3 tanks due to fire/explosion or cracking of Hull resulting in a release of 47,694 m^3 over 2 days.

Scenario 2 Release of 50% of 1 tank, due to Corrosion of Bottom Steel resulting in a release of 7,900 m^3 over 21 days.

Scenario 3 Release caused by damages to the PLEM structure and pipeline resulting in a release of 2,500 m^3 over 60 days.

Scenario 4 Worst case scenario resulting in a release of approx. 180,000 m^3 (1,140,000 bbls) over 7.5 days.

The modelling was carried out using SINTEF's Oil Spill Contingency and Response (OSCAR) model. OSCAR is a 3D modelling tool used to predict the movement and fate of oil on the sea surface and throughout the water column (see APPENDIX E for further details).

[1] Oil spill modelling was carried for IMO by Oil Spill Response Ltd. (OSRL) using SINTEF's OSCAR oil spill model.

1.2 Aims

The aim of this report is to present the risk to the sea surface and the shoreline by creating spatial maps of:

1. Probability - to estimate how likely an area is to be impacted.
2. Arrival time - to estimate how quickly an area could be impacted; and
3. Emulsion thickness - to estimate how severely an area could be impacted.

The data behind these maps will help answer the following questions:

1. How quickly could oil reach nearby shorelines and what volume?
2. Which countries are more likely to be affected by an oil spill from the FSO SAFER?
3. Which environmental sensitivities could be affected by an oil spill from the FSO SAFER?

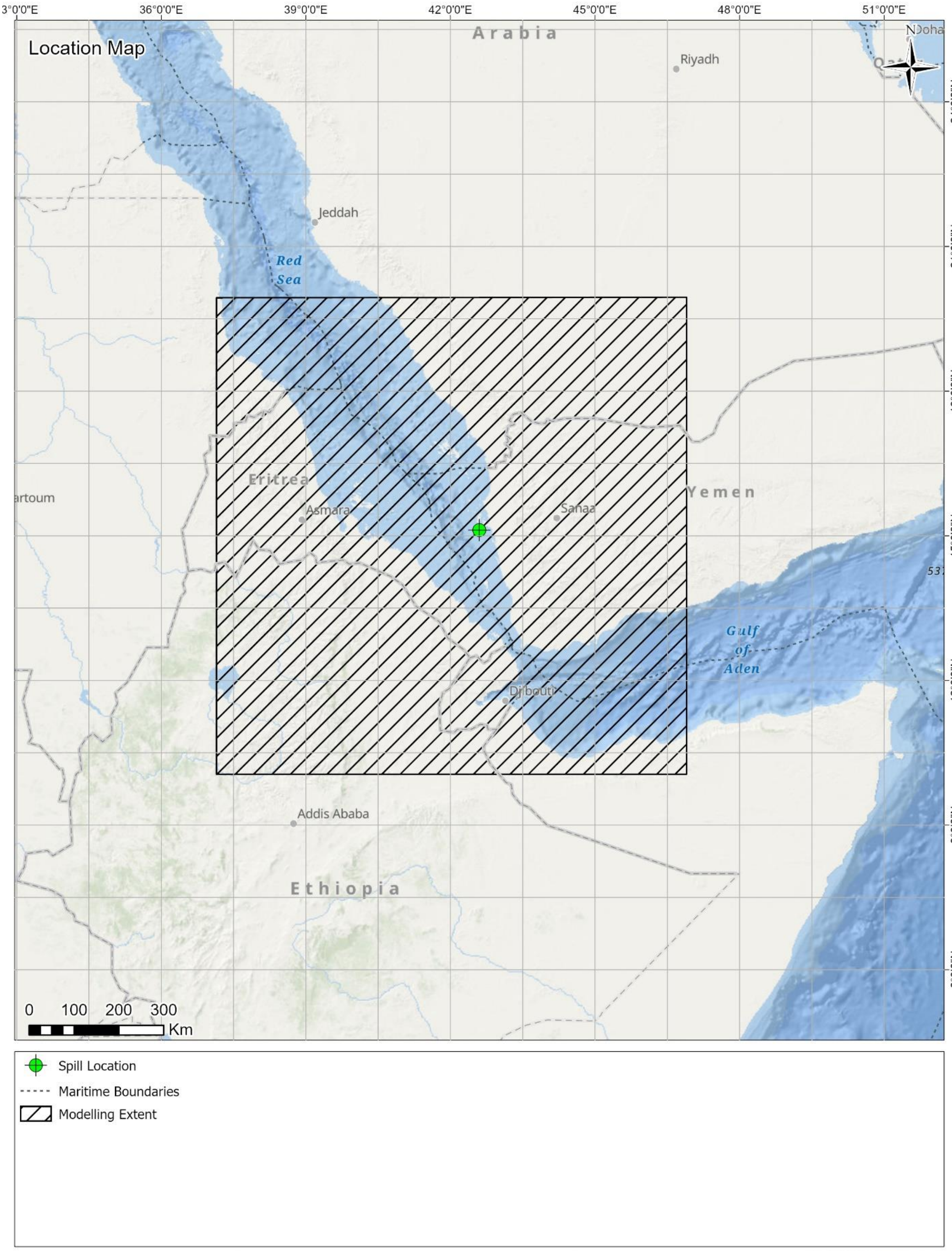


Figure 1: Map showing the release location and model area

1.3 Key Sensitivities

The statistical analysis of modelling results presented for each scenario includes a calculation of the impact to key sensitivities. These are areas included in the World Database of Key Biodiversity Areas (KBA)[2]. The below map shows the location of each KBA.

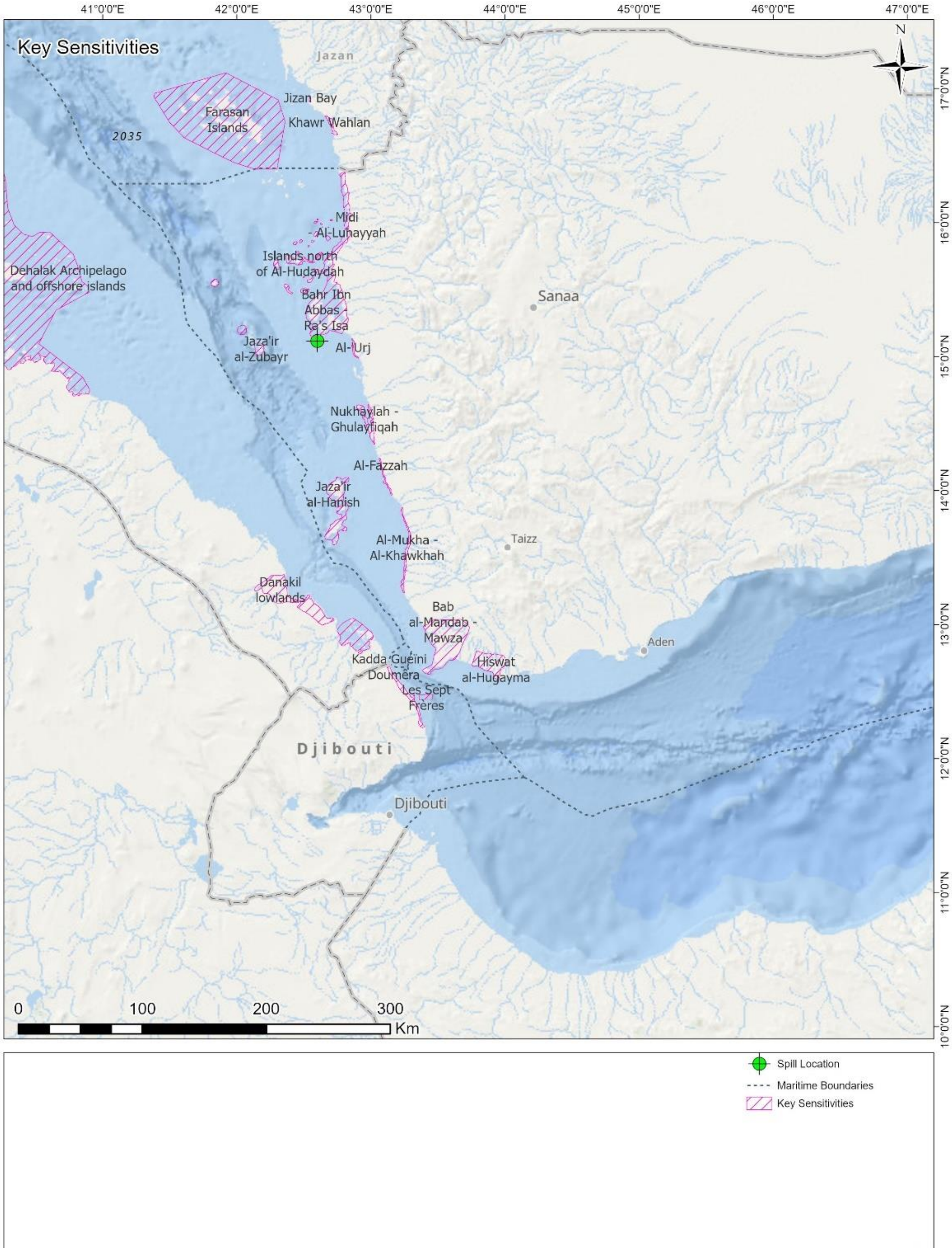


Figure 2: Key Biodiversity Areas

[2] http://www.keybiodiversityareas.org/, Data accessed through https://www.ibat-alliance.org/

2 SCENARIO SETUP

2.1 Modelling Setup

Seven stochastic simulations were run for the 4 scenarios (Table 1), with 150 individual trajectories post-processed for each scenario to create the stochastic results. Each trajectory began on a different start date, so that each oil spill was simulated using a range of wind and current conditions.

Three years of hydrodynamic data were used as model inputs. See APPENDIX A to APPENDIX E for more information on the model setup.

Table 1: Summary of stochastic setup for spill scenarios

Scenario Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Description	Release of 3 tanks due to fire/explosion or cracking of hull	Release of 50% of 1 tank, due to corrosion of bottom steel	Release caused by damage to the PLEM structure and pipeline	Worst case scenario
Season/Period	All year	All year	All year	January to March April to June July to September October to December
Location	15° 07'0" N 042° 36'0" E	15° 07'0" N 042° 36'0" E	15° 07'0" N 042° 36'0" E	15° 07'0" N 042° 36'0" E
Release Rate	23,847 m^3/day	376 m^3/day	43.6 m^3/day	24,000 m^3/day
Total Volume Released	47,694 m^3	7,900 m^3	2,500 m^3	Approx. 180,000m^3 (1,140,000 bbls)
Duration of Release	2 days	21 days	60 days	7.55 days
Total Run Duration	32 days	51 days	90 days	38 days
Depth of Release	Surface	Surface	35m	Surface
Nearest Shoreline	Al Jazirah, Yemen	Al Jazirah, Yemen	Al Jazirah, Yemen	Al Jazirah, Yemen
Total Number of Trajectories	150	150	150	150
Time Between Trajectories	7 days, 7 hours	7 days, 7 hours	7 days, 7 hours	1 days, 20 hours

2.2 Thresholds

Thresholds define the point below which data are no longer informative. For example, when surface emulsion thickness is less than 0.04 µm, the oil is no longer visible to the naked eye so may be considered insignificant to a response. The thresholds applied to this study are detailed in Table 2.

Table 2: Thresholds used in the post-processing stage of the modelling

Threshold	Value	Description
Surface	0.04 µm	The Bonn Agreement Oil Appearance Code (BAOAC) defines five oil layer thicknesses based on their optic effects and true colours. 0.04 µm is the minimum thickness that can be seen with the naked eye.
Shoreline	0.1 litres/m^2	Lower threshold for light oiling from the ITOPF document "Recognition of oil on shorelines".

The key used in the surface oil emulsion thickness maps throughout this document is derived from the Bonn Agreement Oil Appearance Code (Table 3).

Table 3: Key used for sea surface emulsion thickness outputs.

Appearance	Layer Thickness Interval	Colour
Sheen	0.04 µm - 0.3 µm	
Rainbow	0.3 µm -5 µm	
Metallic	5 µm - 50 µm	
Discontinuous True Colour	50 µm - 200 µm	
Continuous True Colour	>200 µm	

The key used in the shoreline maps throughout this document is derived from the ITOPF Technical Information Paper (TIP) No. 6 "Recognition of oil on shorelines" (ITOPF, 2011b). In many cases, no physical response is required for a very lightly oiled shoreline, apart from monitoring natural recovery.

Table 4: Key used for shoreline emulsion thickness outputs.

Shoreline Oiling Classification	Concentration	Thickness	Colour
Light Oiling	0.1 – 1 litres/m^2	0.1 mm – 1.0 mm	
Moderate Oiling	1 – 10 litres/m^2	1 mm – 10 mm	
Heavy Oiling	> 10 litres/m^2	> 10 mm	

3 RESULTS

3.1 Scenario 1 - Release of 3 tanks due to Fire/Explosion or Cracking of Hull

3.1.1 Stochastic Maps

The stochastic results for scenario 1 were calculated using 150 individual trajectories, equally distributed over a period of three years. Each trajectory involved the release of 23,847m^3 of oil per day, for 2 days which is then tracked for a further 30 days.

The following results are presented:

Sea Surface

Figure 3: Probability that a surface cell could be impacted.

Figure 4: Minimum arrival time of surface oil.

Figure 5: Maximum emulsion thickness of surface oil.

Shoreline

Figure 6: Probability that a shoreline cell could be impacted.

Figure 7: Minimum arrival time of shoreline oil.

Figure 8: Shoreline contamination based on emulsion mass.

SURFACE MAPS

Release of 3 tanks due to
Fire/Explosion or Cracking of Hull

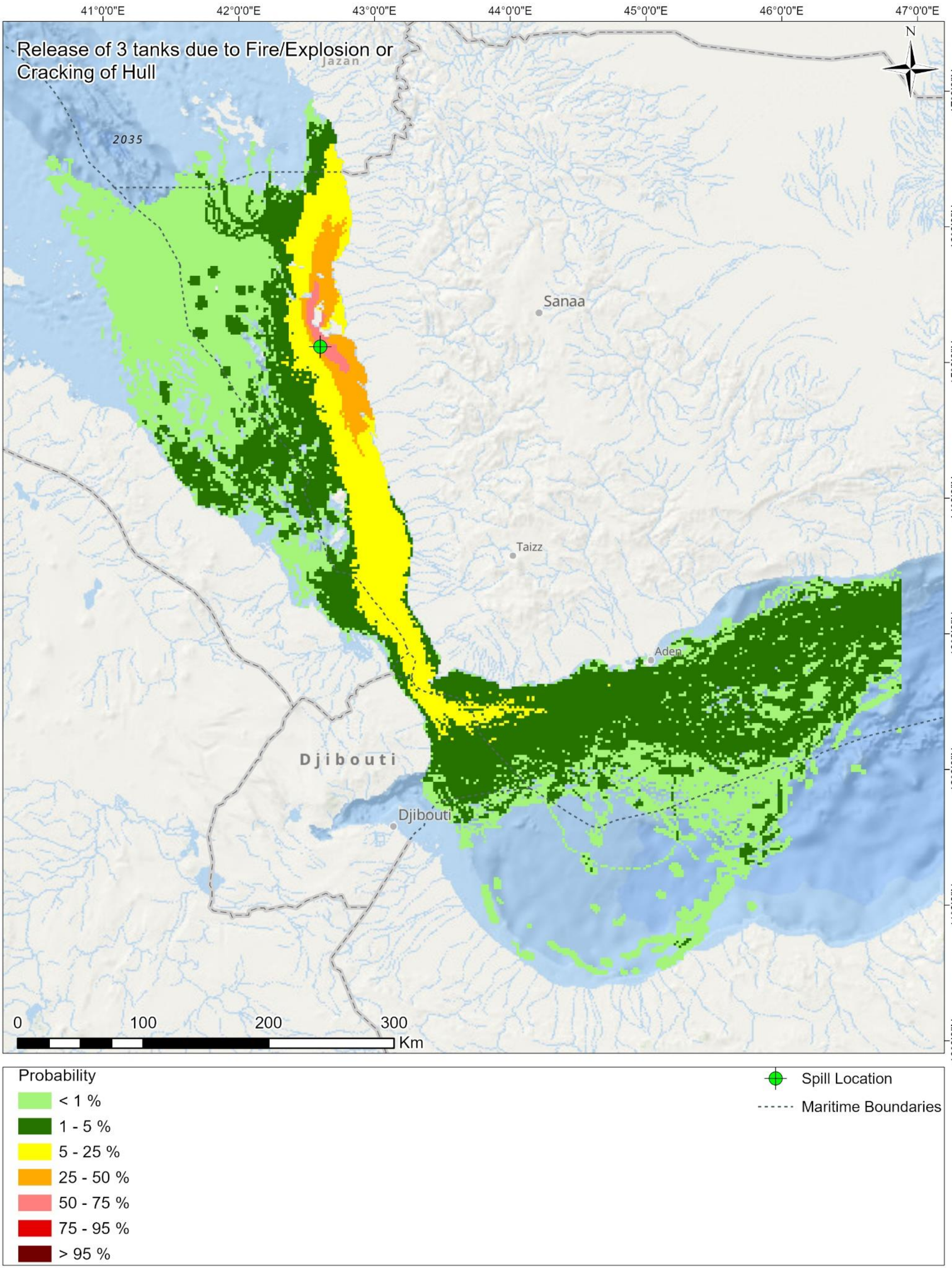


Figure 3: Probability that a surface cell could be impacted.

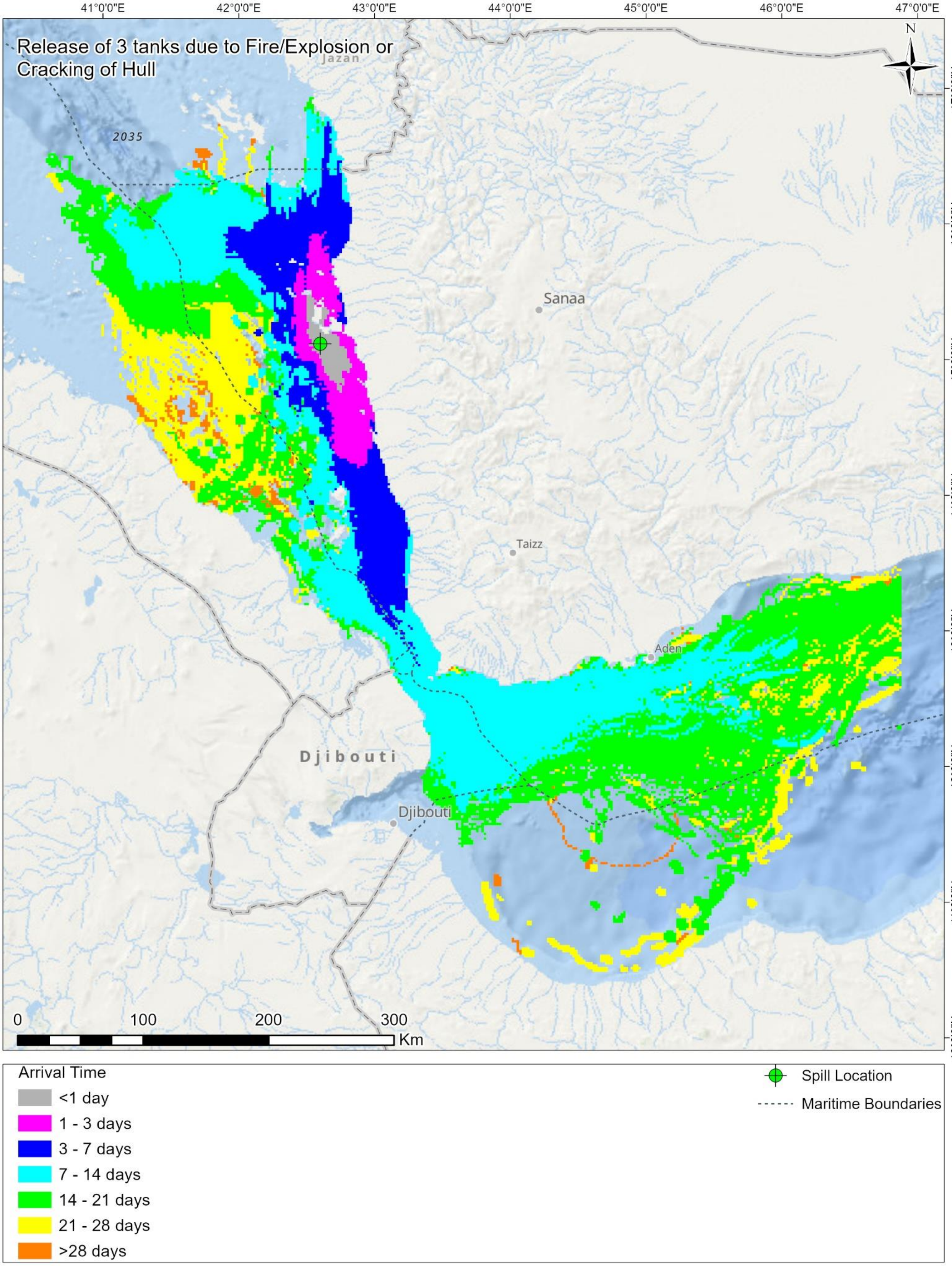


Figure 4: Minimum arrival time of surface oil.

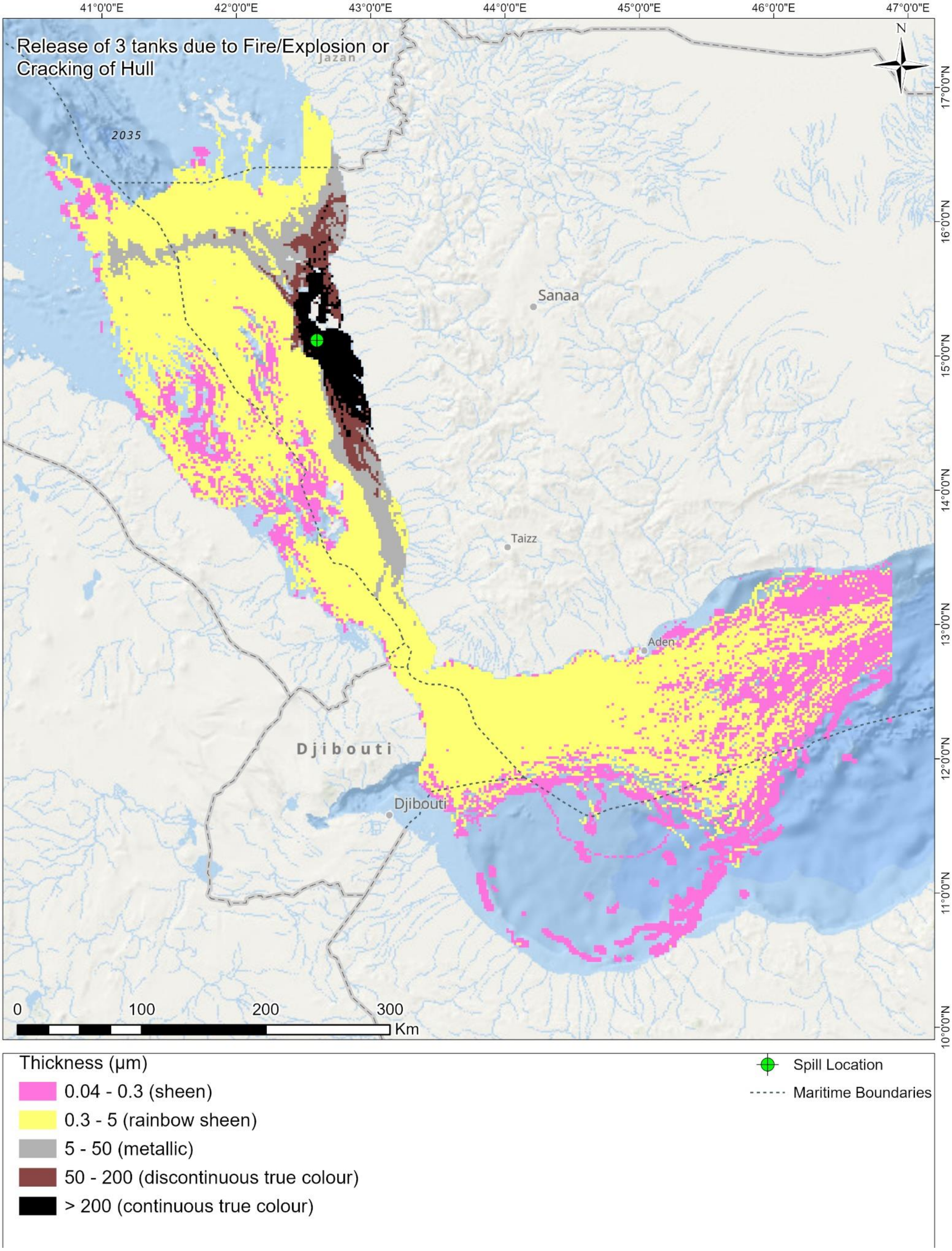


Figure 5: Maximum emulsion thickness of surface oil.

SHORELINE MAPS

Release of 3 tanks due to Fire/Explosion or Cracking of Hull

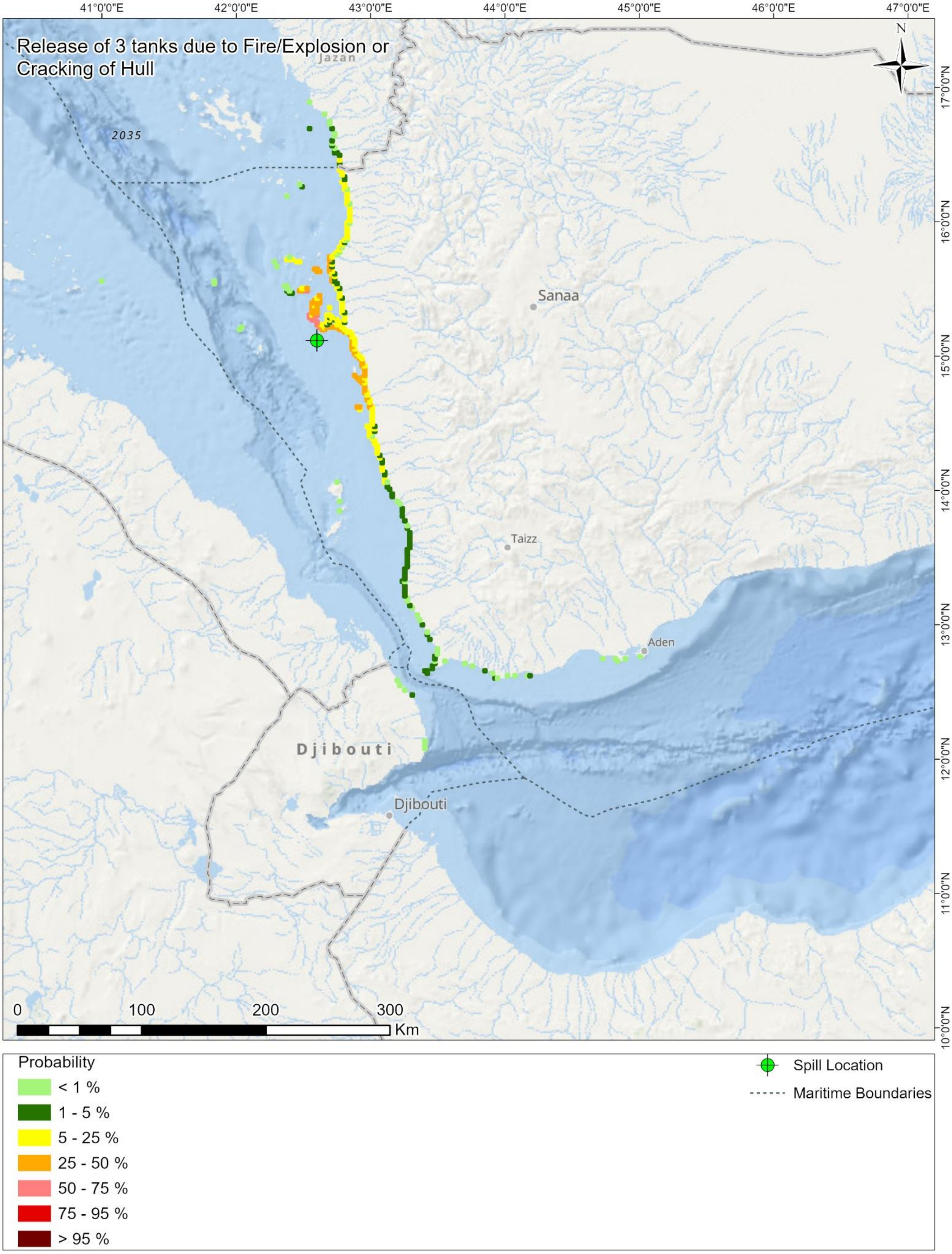


Figure 6: Probability that a shoreline cell could be impacted.

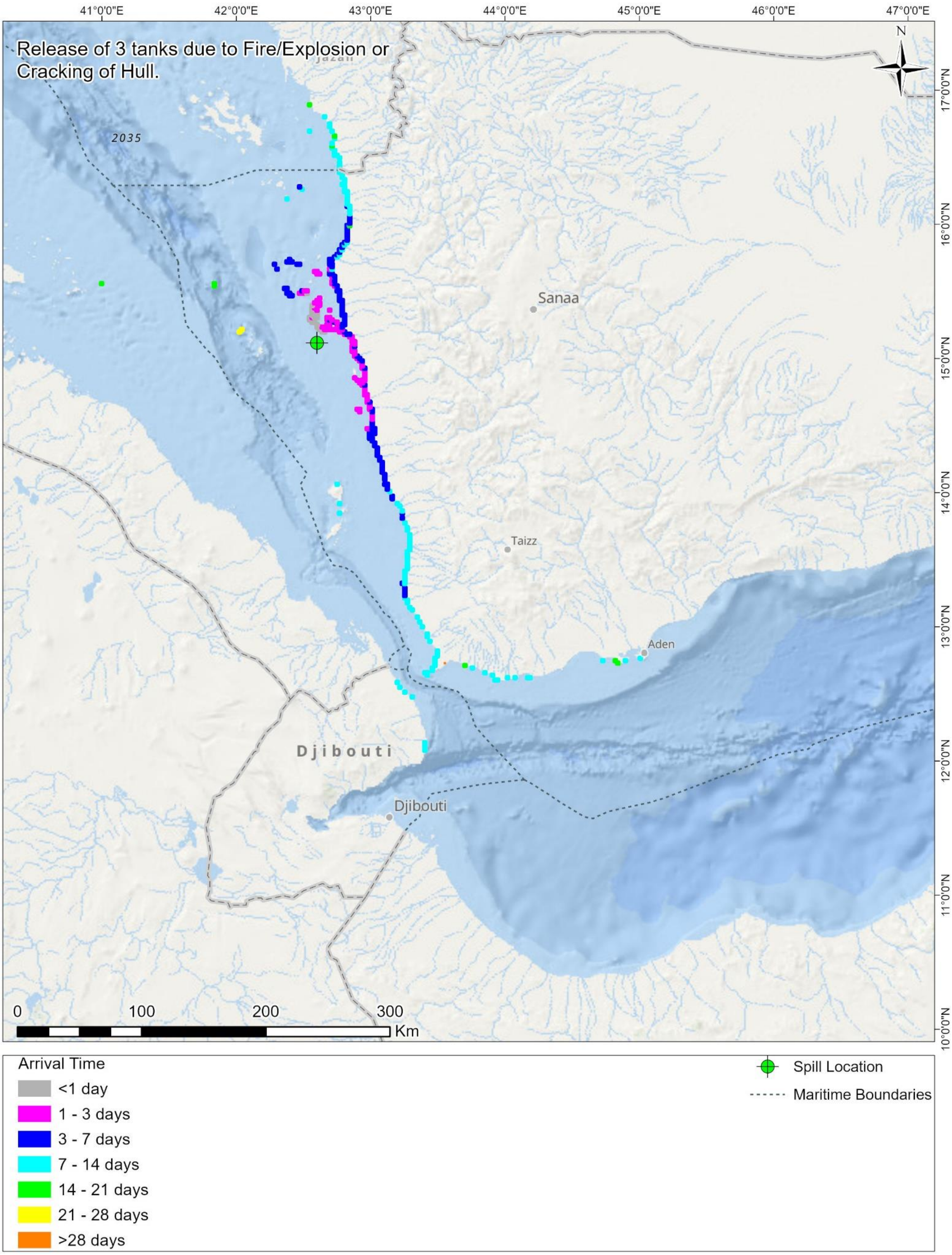


Figure 7: Minimum arrival time of shoreline oil.

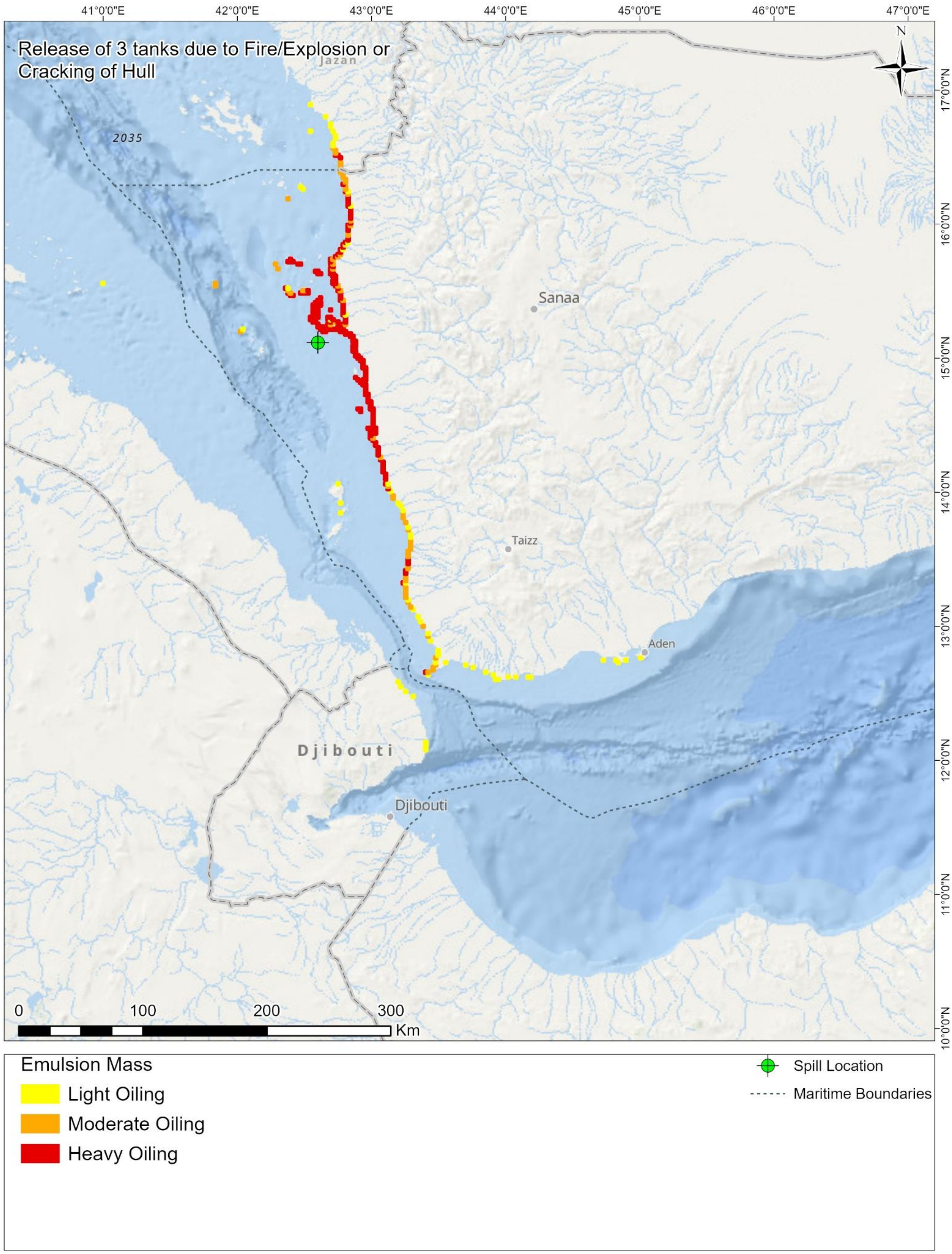


Figure 8: Shoreline contamination based on emulsion mass.

3.1.2 Statistical Analysis

Table 5: Statistical Analysis of Impact

Oil Spill Modelling Summary	
Spill Scenario/Description	Release of 3 tanks due to Fire/Explosion or Cracking of Hull
Median Line - Sea boundary crossing	
Identified Median Line – Sea boundary	Probability and shortest time to reach sea boundary; and maximum surface oil thickness
	All Year
Djibouti	13% 7 days, 5 hours Rainbow
Eritrea	24% 5 days, 23 hours Metallic
Saudi Arabia	15% 5 days, 5 hours Metallic
Somalia	5% 11 days, 11 hours Rainbow
Yemen	100% (Spill originates within country) Continuous True Colour
Landfall	
Identified Shoreline	Probability and shortest time to reach shoreline; and maximum possible degree of shoreline oiling
Djibouti	1% 8 days, 18 hours Light oiling
Eritrea	<1% 19 days, 23 hours Light oiling
Saudi Arabia	11% 7 days, 17 hours Heavy Oiling

Yemen	100% 0 days, 3 hours Heavy oiling
Maximum Volume Beached	
Mass of oil onshore	15,024 MT
Volume[3] of oil onshore	18,733 m^3
Water Content	85%
Volume of emulsion onshore	Up to 124,888 m^3

Table 6: Statistical Analysis Key Sensitivities

Key Sensitivities at Risk[4]	
Al-Fazzah	3% 5 days, 15 hours
Al-Mukha - Al-Khawkhah	7% 7 days, 0 hours
Bab al-Mandab - Mawza	7% 8 days, 1 hour
Bahr Ibn Abbas - Ra's Isa	80% 0 days, 2 hours
Dehalak Archipelago and offshore islands	4% 12 days, 10 hours
Farasan Islands	2% 8 days, 9 hours
Islands north of Al-Hudaydah	52% 1 day, 11 hours
Jaza'ir al-Hanish	19% 3 days, 21 hours
Jaza'ir al-Zubayr	1% 13 days, 22 hours
Kadda Guéïni - Doumêra	8% 8 days, 17 hours

[3] OSCAR does not provide the volume of oil onshore only the mass. To convert from mass to volume we assume that the density of the spilt oil is constant and the same as the source product (e.g., 0.843). In reality the density of the spill will be different over time and space, but the model is unable to capture this complex interaction. Therefore, the volume estimates presented in this report should be treated as approximate.

[4] A map showing the location of each sensitivity is presented in section 1.3

Les Sept Frères	9% 7 days, 20 hours
Midi - Al-Luhayyah	49% 2 days, 14 hours
Nukhaylah - Ghulayfiqah	34% 2 days, 4 hours

3.2 Scenario 2 - Release of 50% of 1 tank, due to corrosion of bottom steel

3.2.1 Stochastic Maps

The stochastic results for scenario 2 were calculated using 150 individual trajectories, equally distributed over a period of three years. Each trajectory involves the release of 7,900 m^3 of oil over a period of 21 days, which is then tracked for a further 30 days.

The following results are presented:

Sea Surface

Figure 9: Probability that a surface cell could be impacted.

Figure 10: Minimum arrival time of surface oil.

Figure 11: Maximum emulsion thickness of surface oil.

Shoreline

Figure 12: Probability that a shoreline cell could be impacted by oil.

Figure 13: Minimum arrival time of shoreline oil.

Figure 14: Shoreline contamination based on emulsion mass.

SURFACE MAPS

Release of 50% of 1 tank, due to Corrosion of Bottom Steel

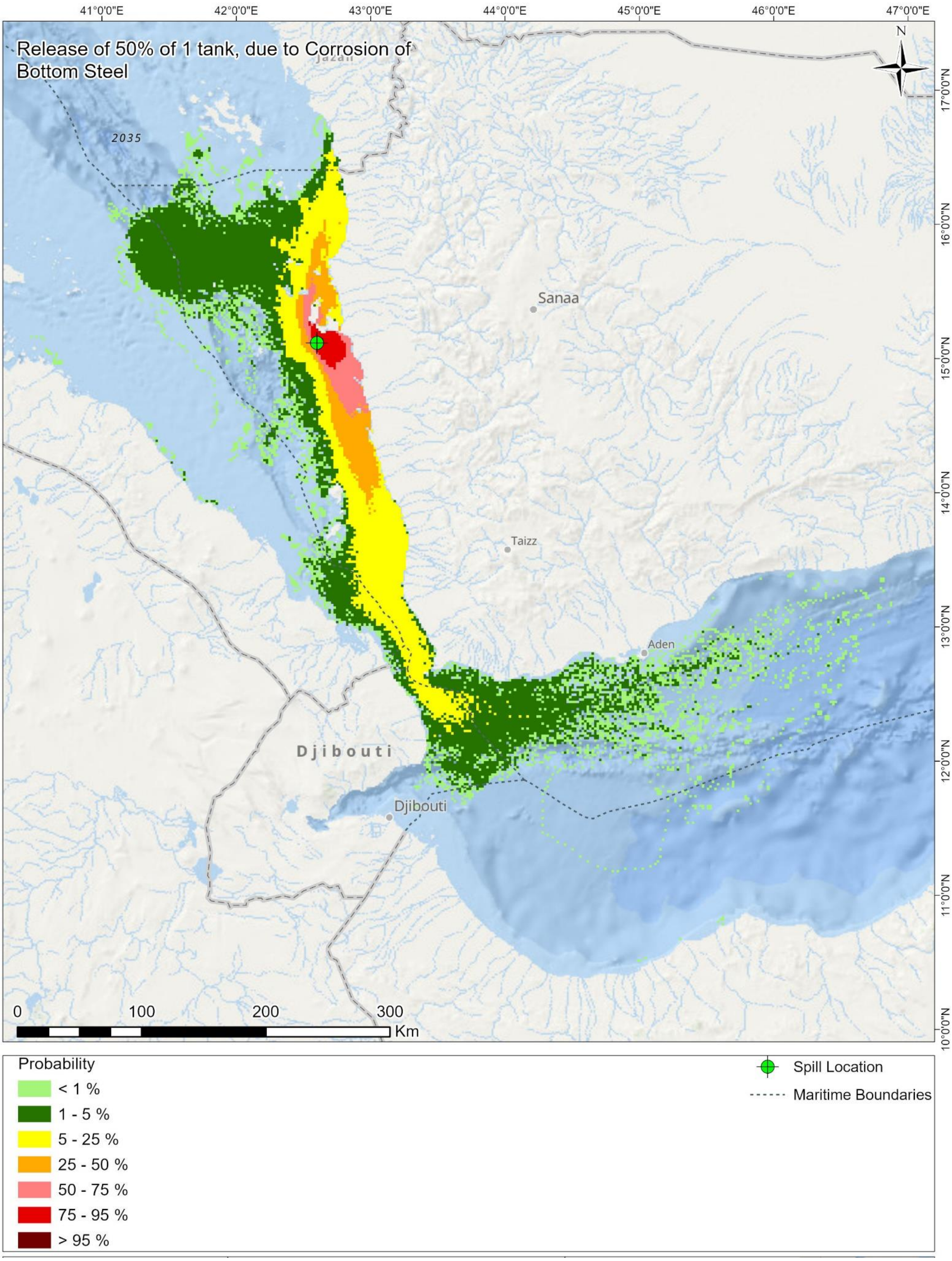


Figure 9: Probability that a surface cell could be impacted.

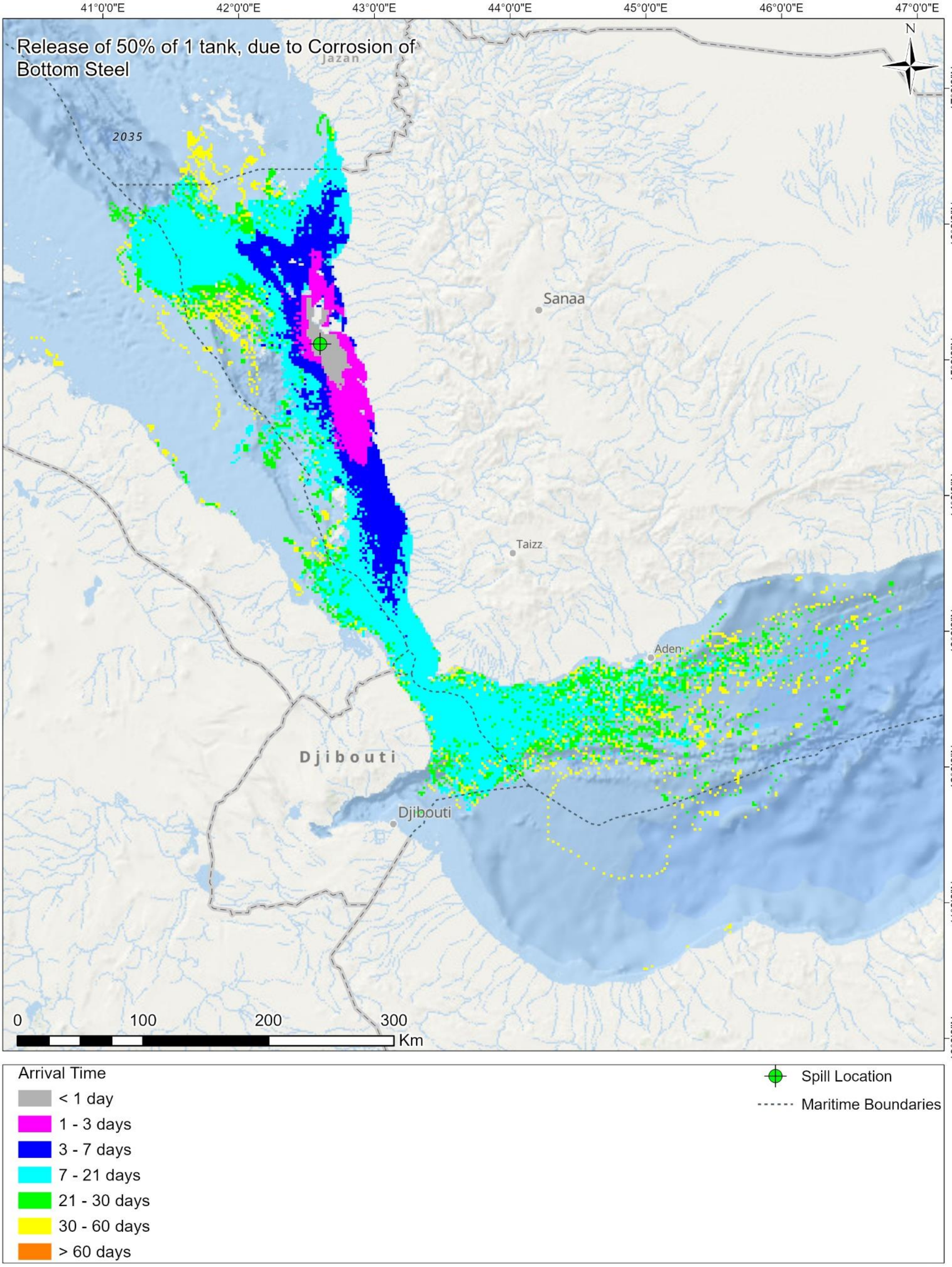


Figure 10: Minimum arrival time of surface oil.

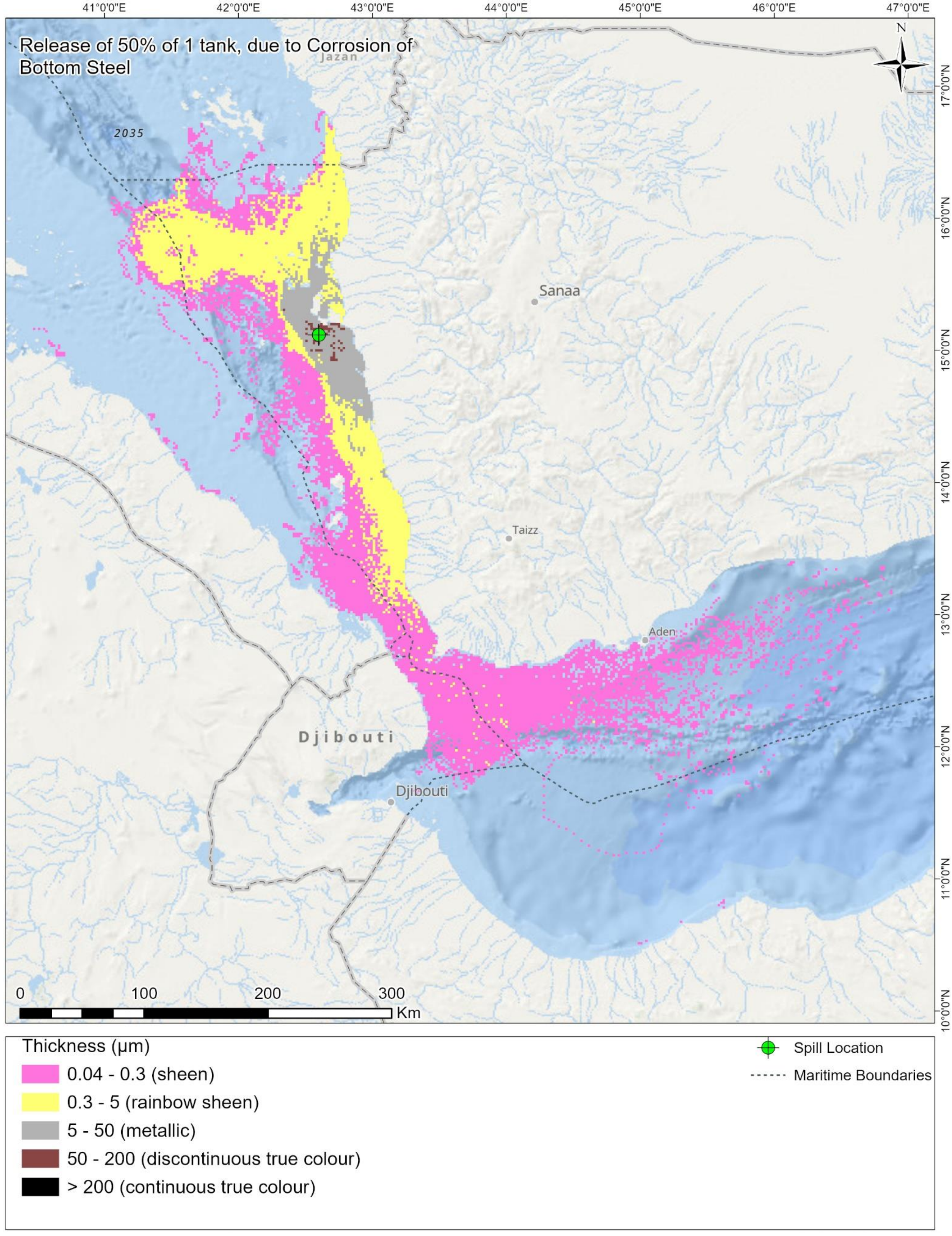


Figure 11: Maximum emulsion thickness of surface oil.

SHORELINE MAPS

Release of 50% of 1 tank, due to Corrosion of Bottom Steel

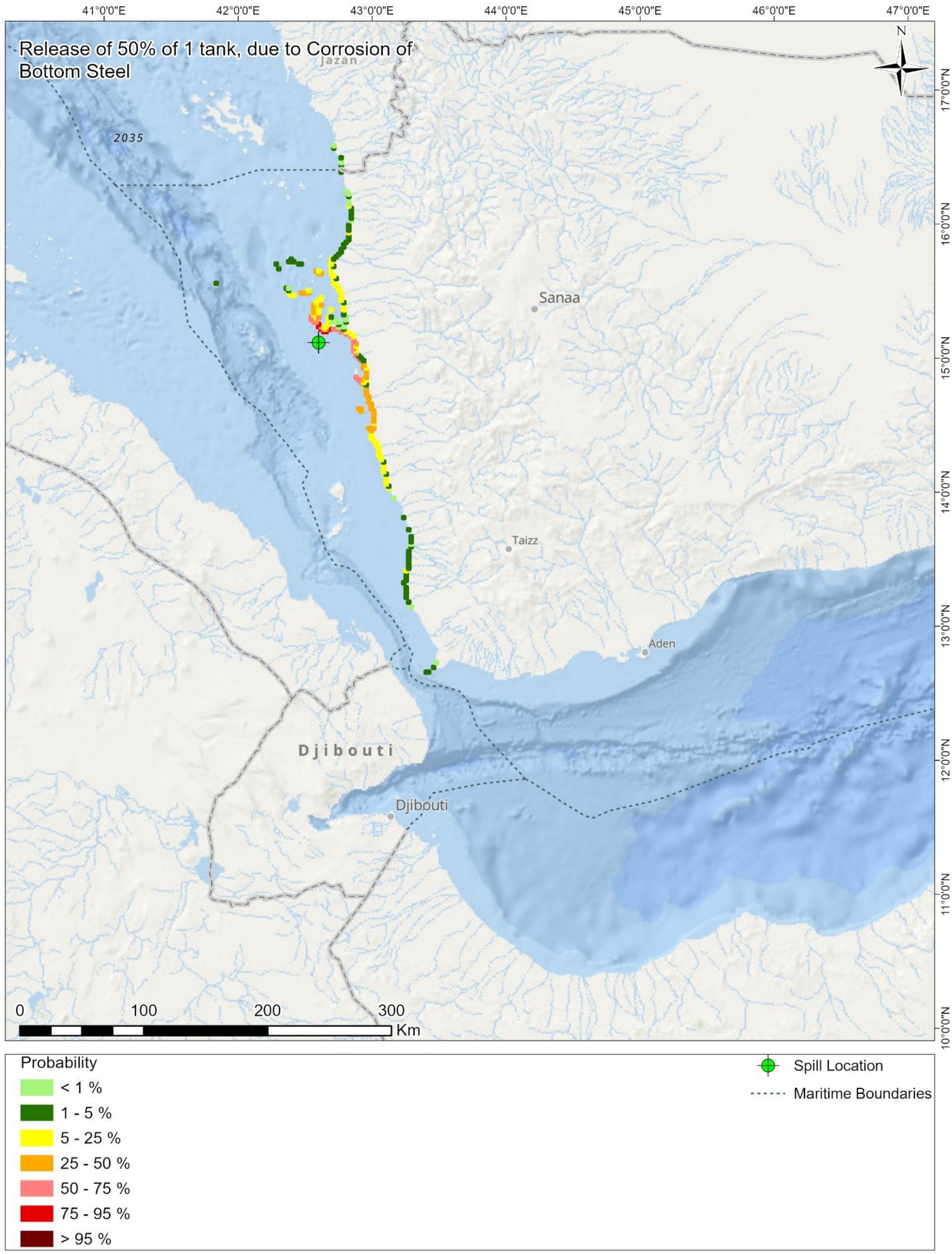


Figure 12: Probability that a shoreline cell could be impacted by oil.

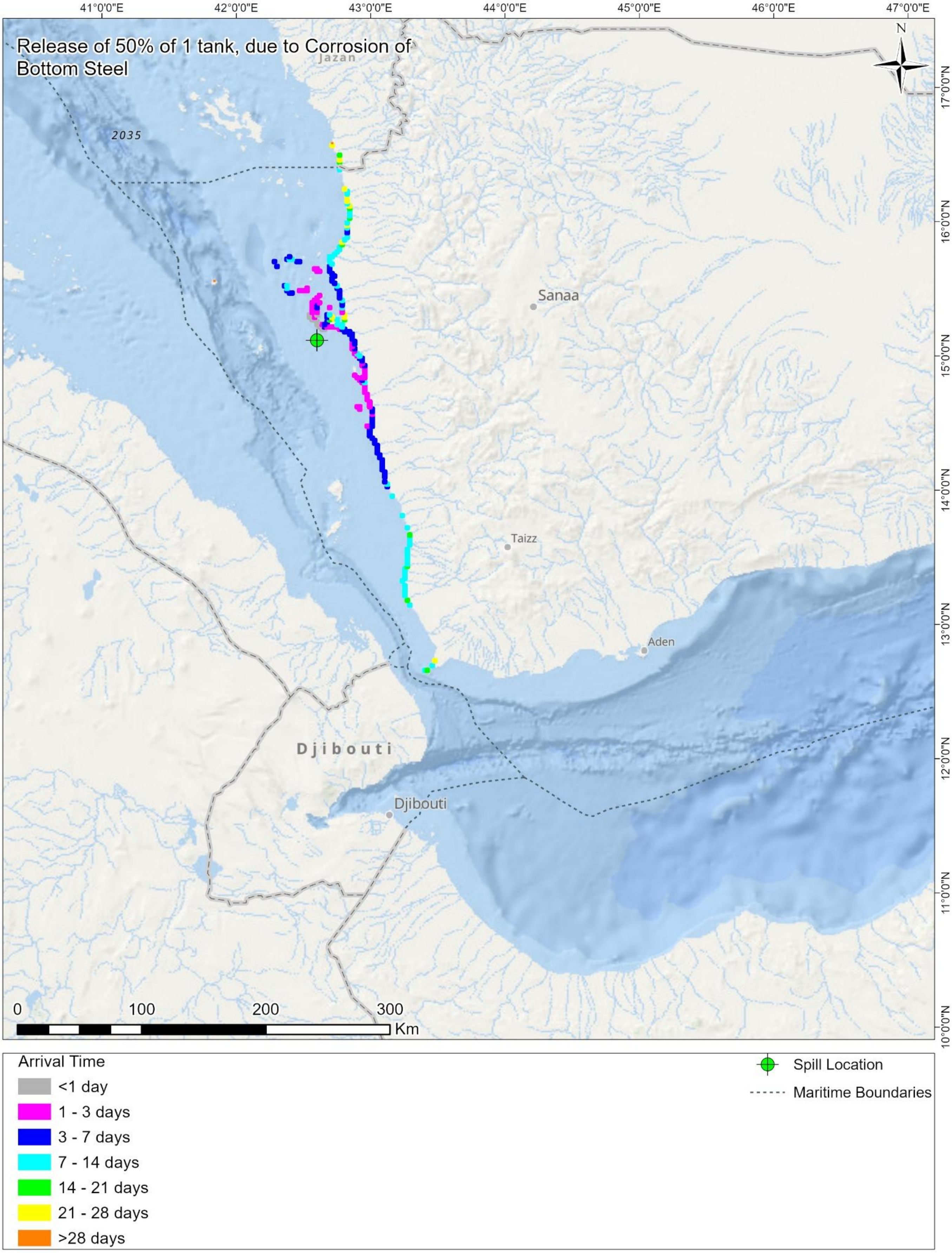


Figure 13: Minimum arrival time of shoreline oil.

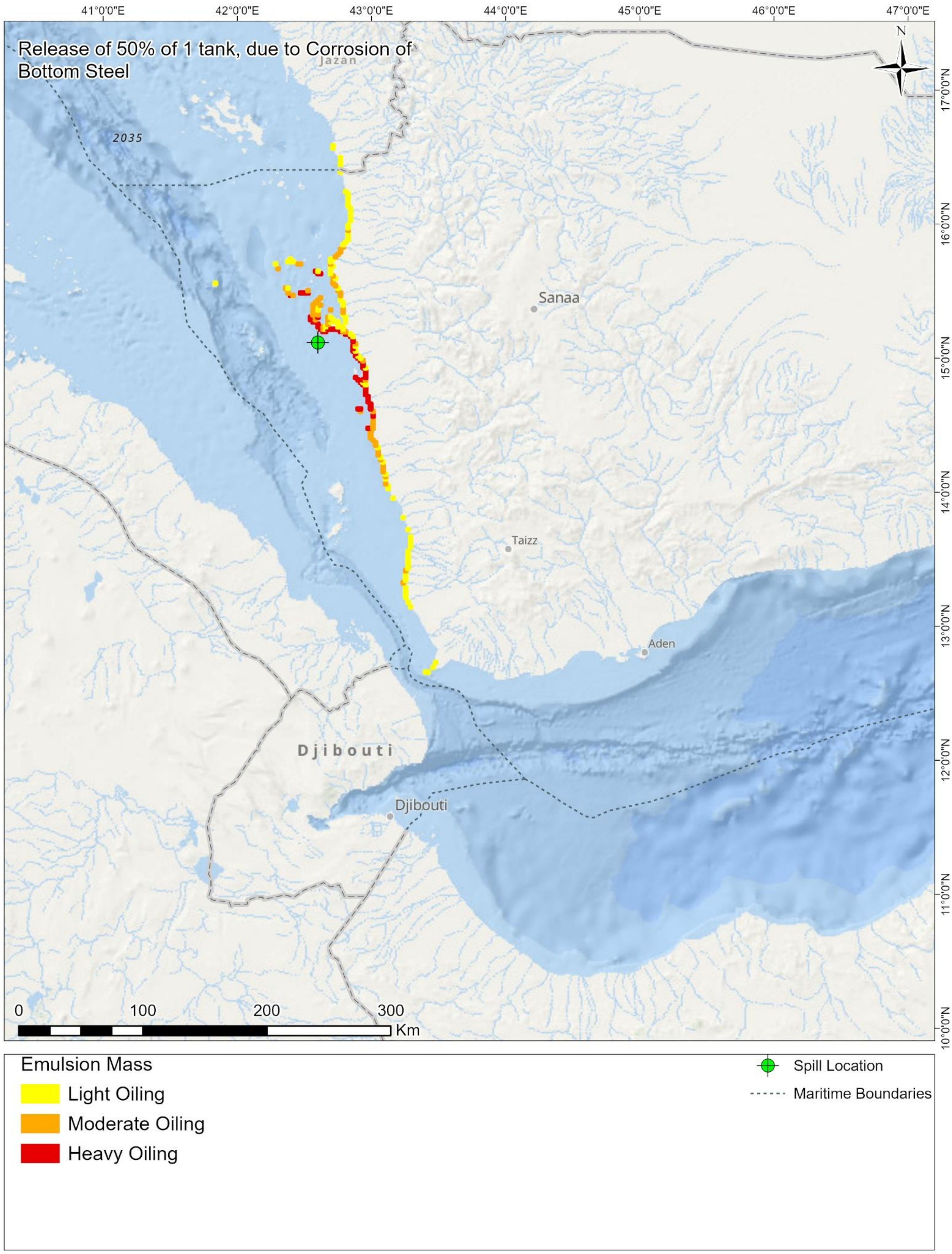


Figure 14: Shoreline contamination based on emulsion mass.

3.2.2 Statistical Analysis

Table 7: Statistical Analysis of Impact

Oil Spill Modelling Summary	
Spill Scenario/Description	Release of 50% of 1 tank, due to corrosion of bottom steel
Median – Sea boundary Crossing	
Identified Sea boundary - Median Line	**Probability and shortest time to reach sea boundary; and maximum surface oil thickness**
	All Year
Djibouti	22% 8 days, 12 hours Rainbow
Eritrea	31% 6 days, 12 hours Rainbow
Saudi Arabia	15% 8 days, 21 hours Rainbow
Yemen	100% (Spill originates within country) Discontinuous True Colour
Landfall	
Identified Shoreline	**Probability and shortest time to reach shoreline; and maximum possible degree of shoreline oiling**
	All Year
Saudi Arabia	5% 16 days, 3 hours Light oiling
Yemen	100% 3 hours Heavy oiling
Maximum Volume Beached	
Mass of oil onshore	3,355 MT
Volume[5] of oil onshore	4183 m^3
Water Content	85%

5 OSCAR does not provide the volume of oil onshore only the mass. To convert from mass to volume we assume that the density of the spilt oil is constant and the same as the source product (e.g., 0.843). In reality the density of the spill will be different over time and space, but the model is unable to capture this complex interaction. Therefore, the volume estimates presented in this report should be treated as approximate.

Volume of emulsion onshore	Up to 27,889 m^3

Table 8: Statistical Analysis of Key Sensitivities

Key Sensitivities at Risk[6]	
Al-Fazzah	16% 5 days, 18 hours
Al-Mukha - Al-Khawkhah	13% 6 days, 21 hours
Bab al-Mandab - Mawza	10% 8 days, 9 hours
Bahr Ibn Abbas - Ra's Isa	95% <1 hour
Dehalak Archipelago and Offshore islands	5% 16 days, 9 hours
Farasan Islands	2% 29 days, 0 hours
Islands north of Al-Hudaydah	54% 1 day, 21 hours
Jaza'ir al-Hanish	29% 4 days, 0 hours
Jaza'ir al-Zubayr	3% 6 days, 18 hours
Les Sept Frères	13% 9 days, 0 hours
Midi - Al-Luhayyah	47% 3 days, 21 hours
Nukhaylah - Ghulayfiqah	52% 2 days, 3 hours

[6] A map showing the location of each sensitivity is presented in section 1.3

3.3 Scenario 3 - Release caused by damages to the PLEM structure and pipeline

3.3.1 Stochastic Maps

The stochastic results for scenario 3 were calculated using 150 individual trajectories, equally distributed over a period of three years. Each trajectory involves the release of 2,500 m^3 of oil over a period of 60 days, which is then tracked for a further 30 days.

The following results are presented:

Sea Surface

Figure 15: Probability that a surface cell could be impacted.

Figure 16: Minimum arrival time of surface oil.

Figure 17: Maximum emulsion thickness of surface oil.

Shoreline

Figure 18: Probability that a shoreline cell could be impacted by oil.

Figure 19: Minimum arrival time of shoreline oil.

Figure 20: Shoreline contamination based on emulsion mass.

SURFACE MAPS

Release caused by damage to the PLEM structure and pipeline.

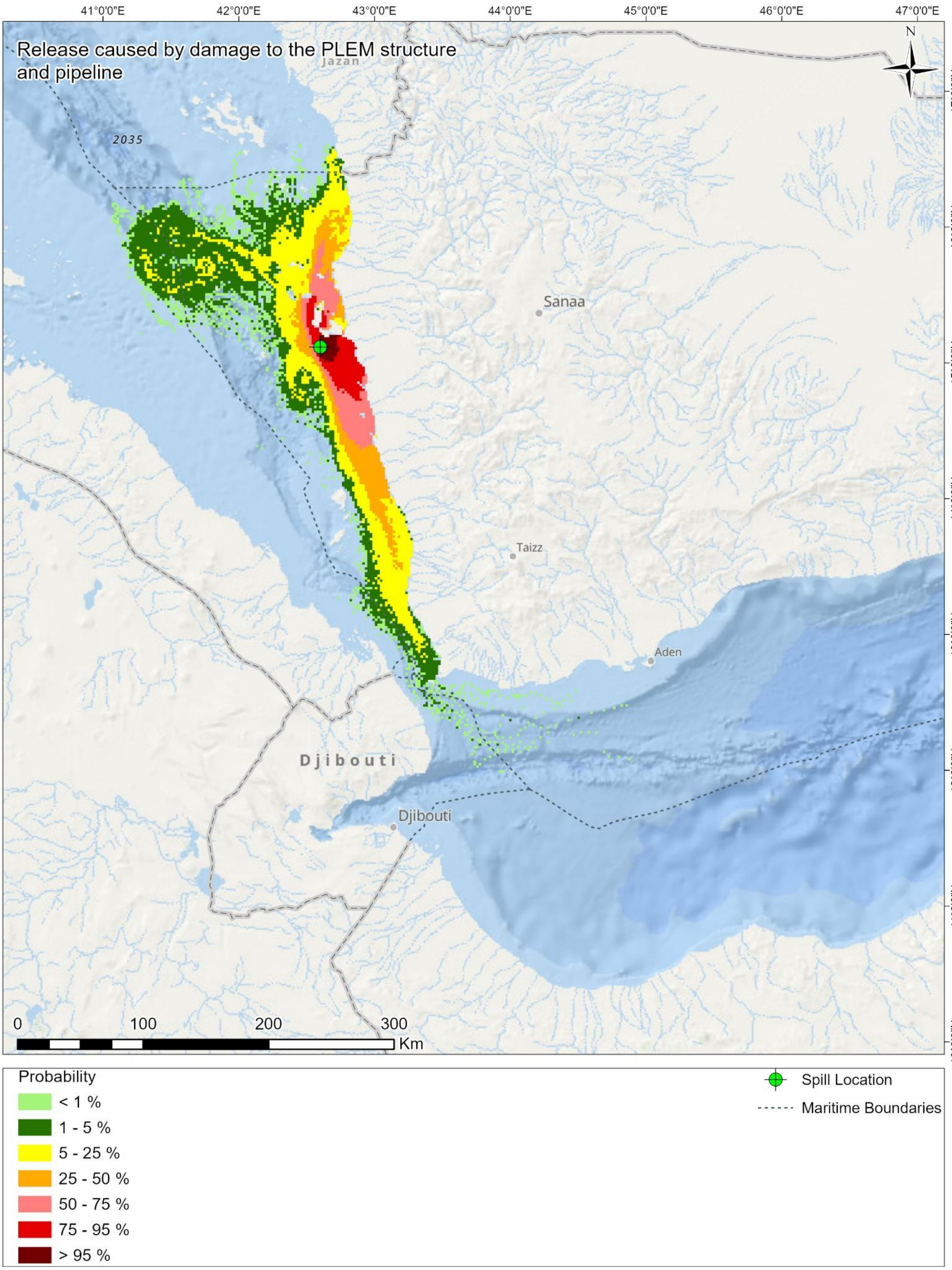


Figure 15: Probability that a surface cell could be impacted.

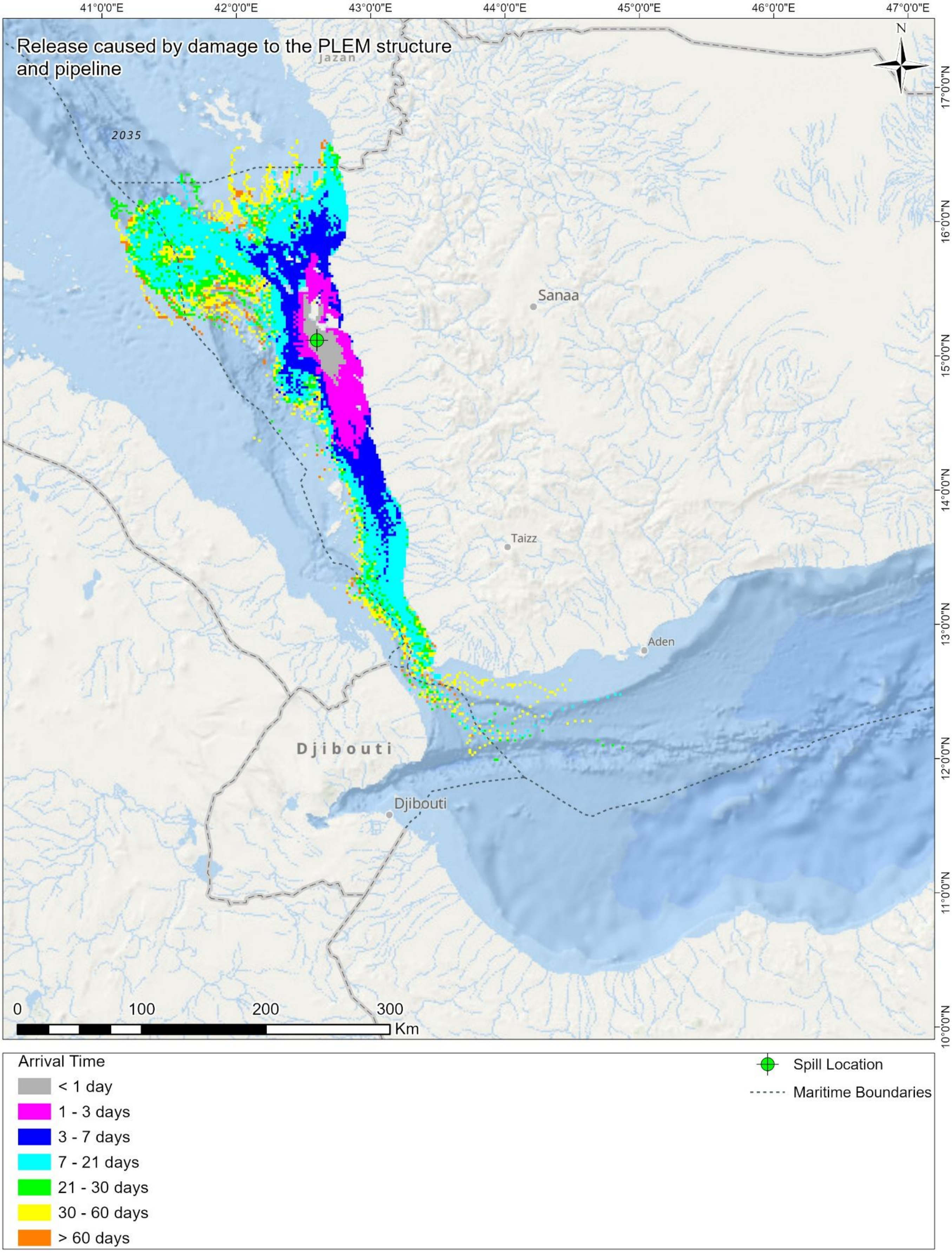


Figure 16: Minimum arrival time of surface oil.

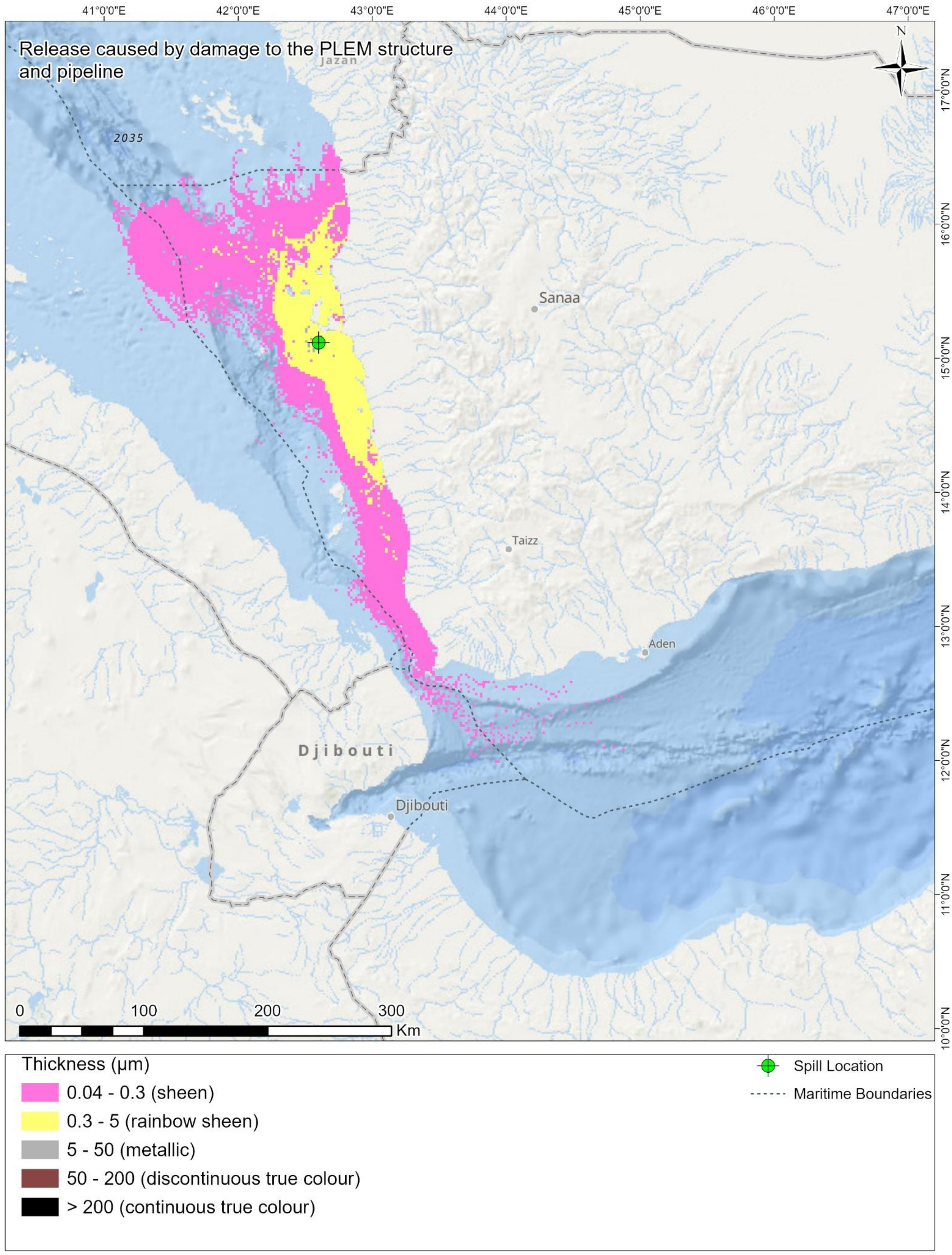


Figure 17: Maximum emulsion thickness of surface oil.

SHORELINE MAPS

Release caused by damages to the PLEM structure and pipeline.

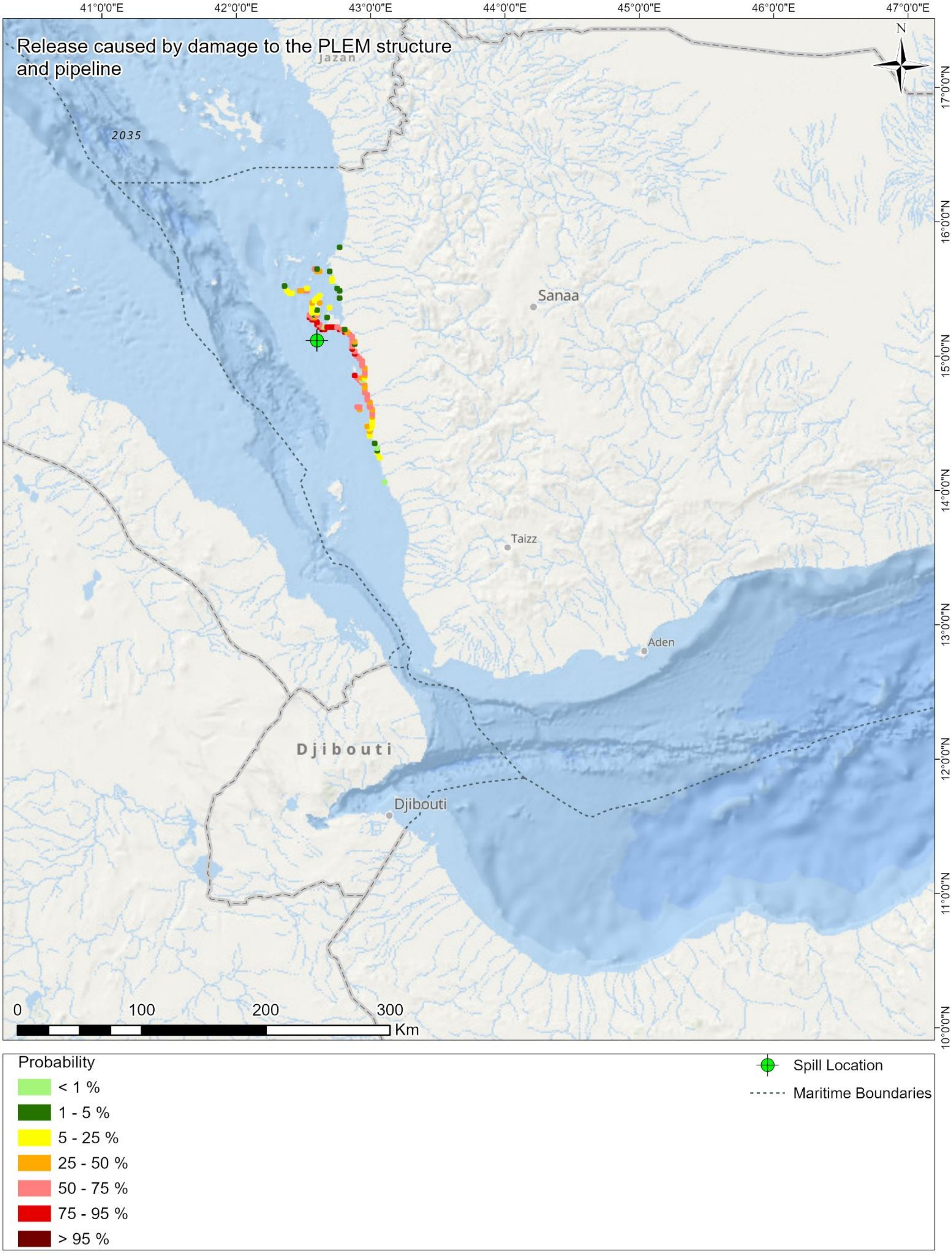


Figure 18: Probability that a shoreline cell could be impacted by oil.

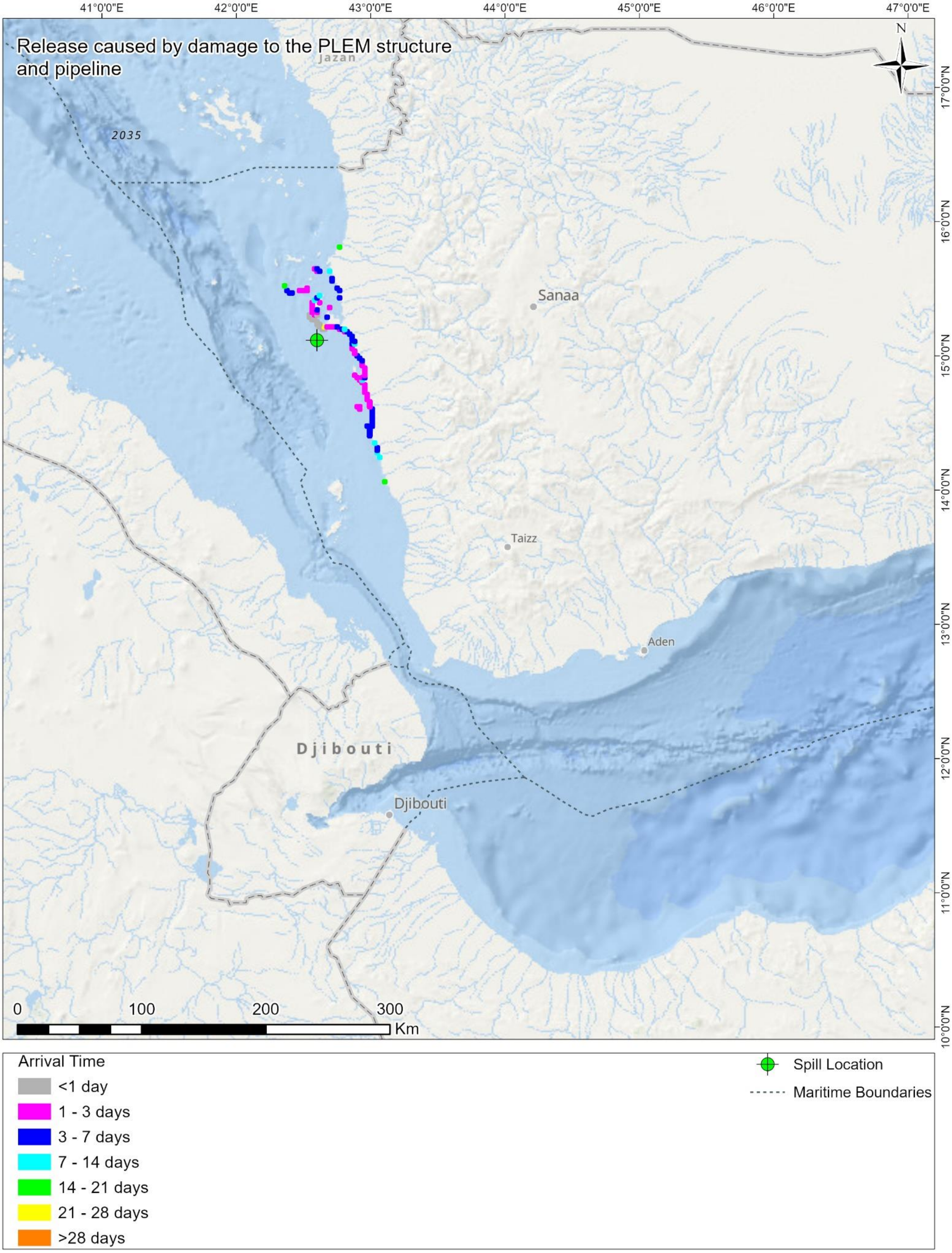


Figure 19: Minimum arrival time of shoreline oil.

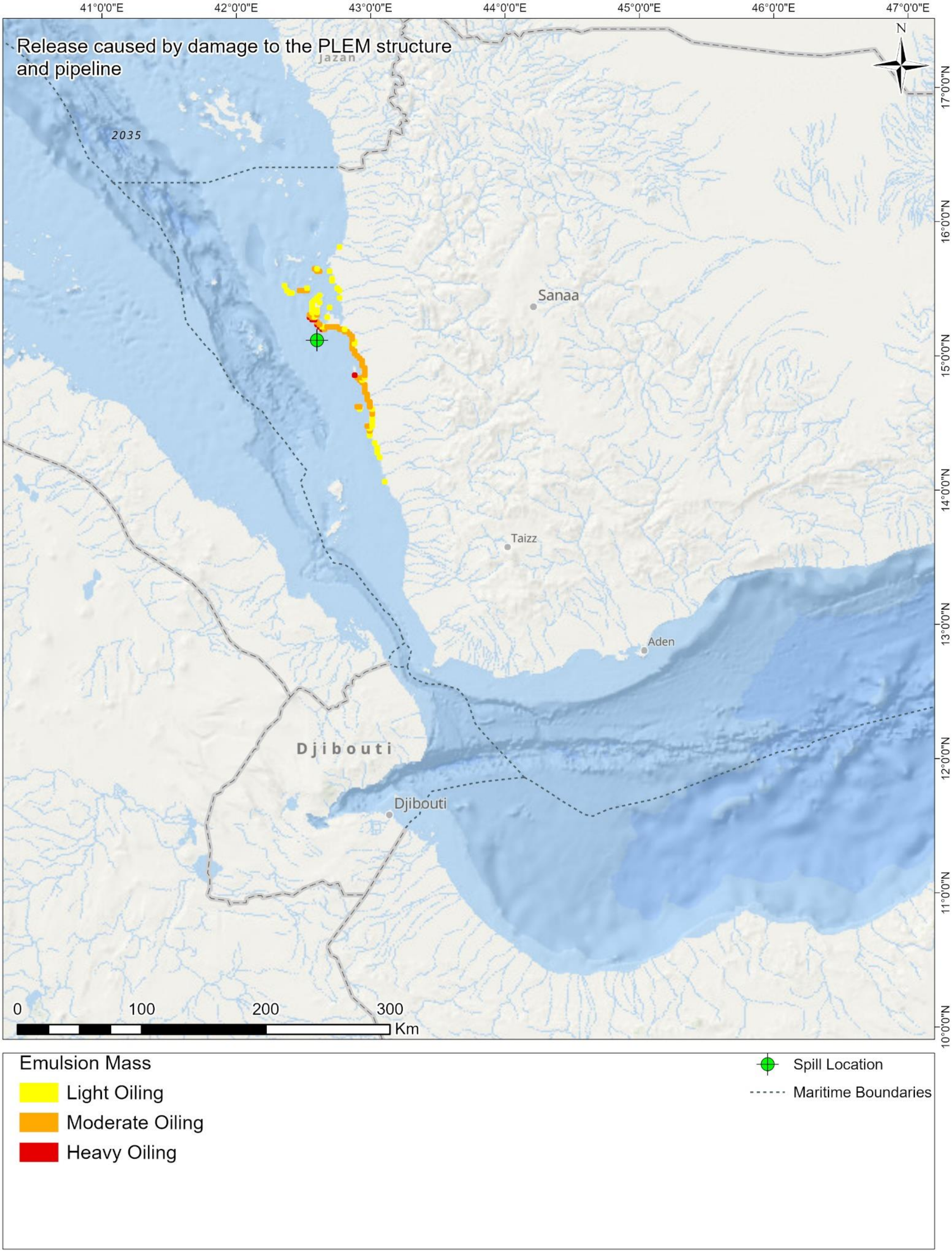


Figure 20: Shoreline contamination based on emulsion mass.

3.3.2 Statistical Analysis

Table 9: Statistical Analysis of Impact

Oil Spill Modelling Summary	
Spill Scenario/Description	Release caused by damages to the PLEM structure and pipeline
Median – Sea boundary Crossing	
Identified Median Line – Sea boundary	**Probability and shortest time to reach sea boundary; and maximum surface oil thickness**
	All Year
Djibouti	13% 12 days, 18 hours Sheen
Eritrea	31% 9 days, 18 hours Sheen
Saudi Arabia	15% 15 days, 21 hours Sheen
Yemen	100% (Spill originates within country) Rainbow
Landfall	
Identified Shoreline	**Probability and shortest time to reach shoreline; and maximum possible degree of shoreline oiling**
	All Year
Yemen	100% (Spill originates within country) 0 days, 4 hours Heavy Oiling
Maximum Volume Beached	
Mass of oil onshore	595 MT
Volume[7] of oil onshore	742 m^3
Water Content	85%
Volume of emulsion onshore	Up to 4,946 m^3

7 OSCAR does not provide the volume of oil onshore only the mass. To convert from mass to volume we assume that the density of the spilt oil is constant and the same as the source product (e.g., 0.843). In reality the density of the spill will be different over time and space, but the model is unable to capture this complex interaction. Therefore, the volume estimates presented in this report should be treated as approximate.

Table 10: Statistical Analysis of Key Sensitivities

Key Sensitivities at Risk[8]	
Al-Fazzah	27% 6 days, 9 hours
Bab al-Mandab - Mawza	7% 13 days, 9 hours
Bahr Ibn Abbas - Ra's Isa	100% < 1 hour
Farasan Islands	1% 34 days, 15 hours
Islands north of Al-Hudaydah	76% 2 days, 3 hours
Jaza'ir al-Hanish	13% 9 days, 0 hours
Jaza'ir al-Zubayr	3% 28 days, 6 hours
Les Sept Frères	5% 28 days, 9 hours
Midi - Al-Luhayyah	68% 3 days, 9 hours
Nukhaylah - Ghulayfiqah	71% 2 days, 6 hours

[8] A map showing the location of each sensitivity is presented in section 1.3

3.4 Scenario 4 - Worst case scenario

3.4.1 Stochastic Maps

The stochastic results for the worst case scenario were calculated using 150 trajectories at set intervals, for each of the four seasons. The trajectory involves the release of 1,140,000 barrels of oil over a period of 7.5 days, which is then tracked for a further 30 days.

The following results are presented:

Sea Surface

Figure 21: Probability that a surface cell could be impacted.

Figure 22: Minimum arrival time of surface oil.

Figure 23: Maximum emulsion thickness of surface oil.

Shoreline

Figure 24: Probability that a shoreline cell could be impacted by oil.

Figure 25: Minimum arrival time of shoreline oil.

Figure 26: Shoreline contamination based on emulsion mass.

SURFACE MAPS

Worst case scenario

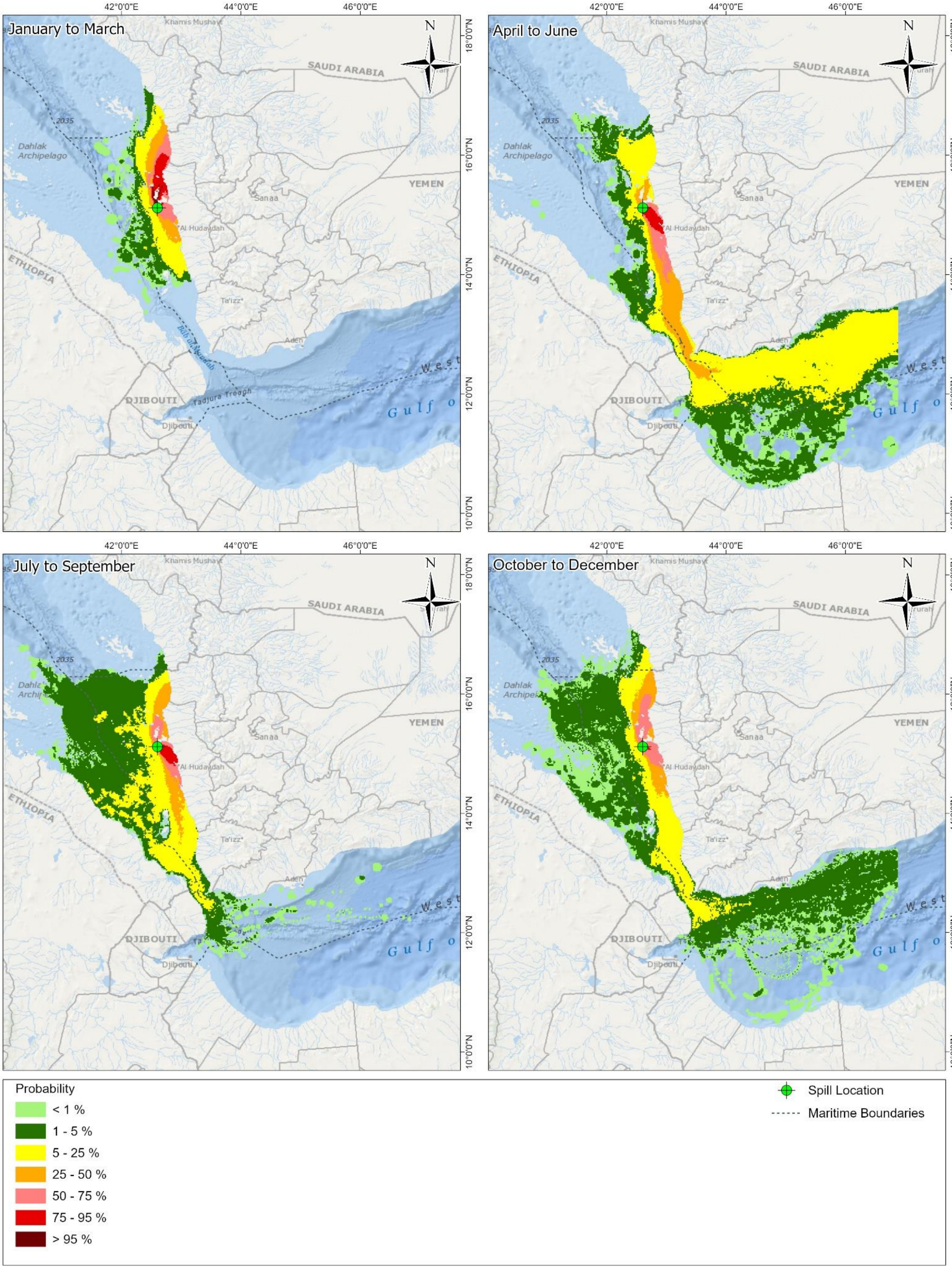


Figure 21: Probability that a surface cell could be impacted.

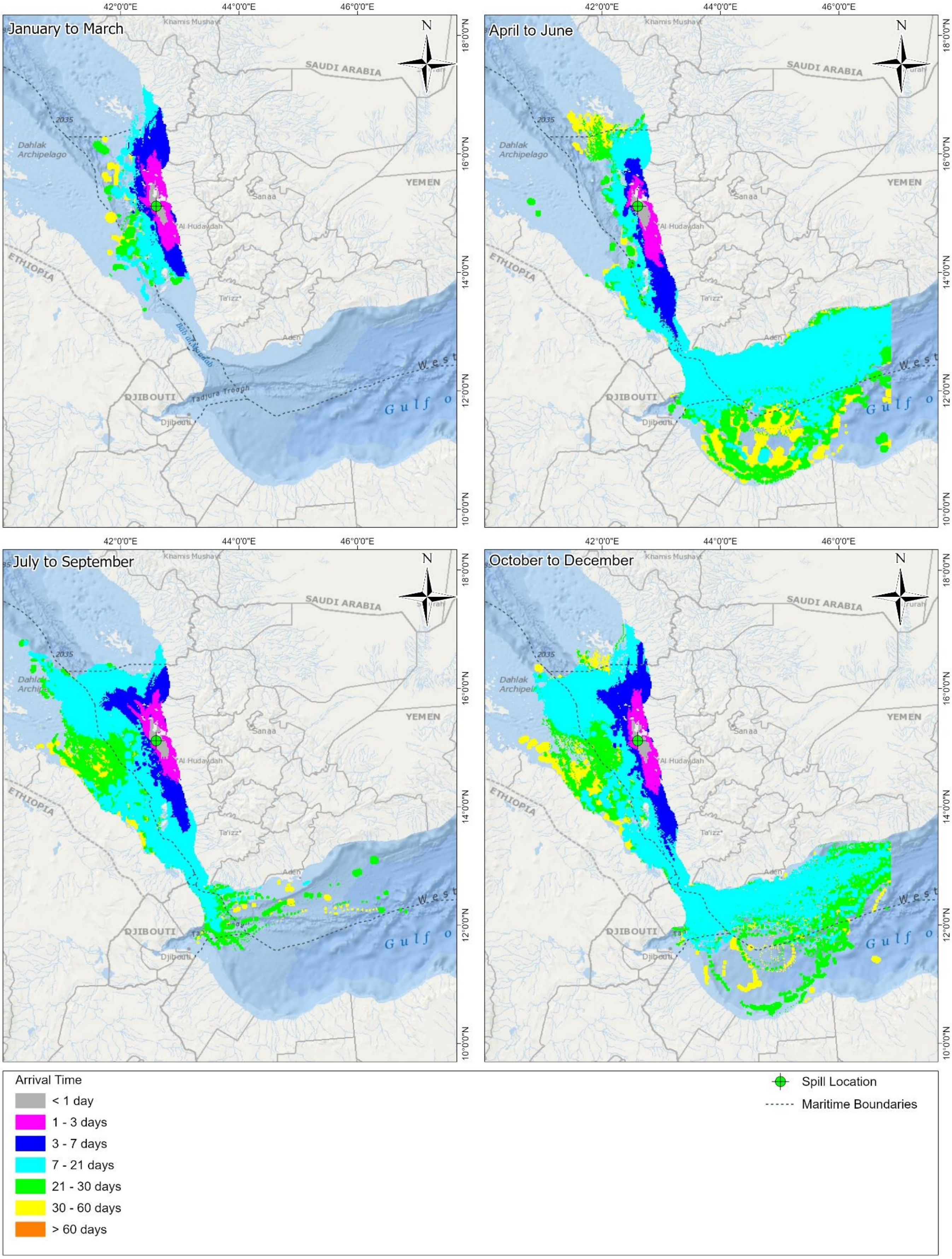


Figure 22: Minimum arrival time of surface oil.

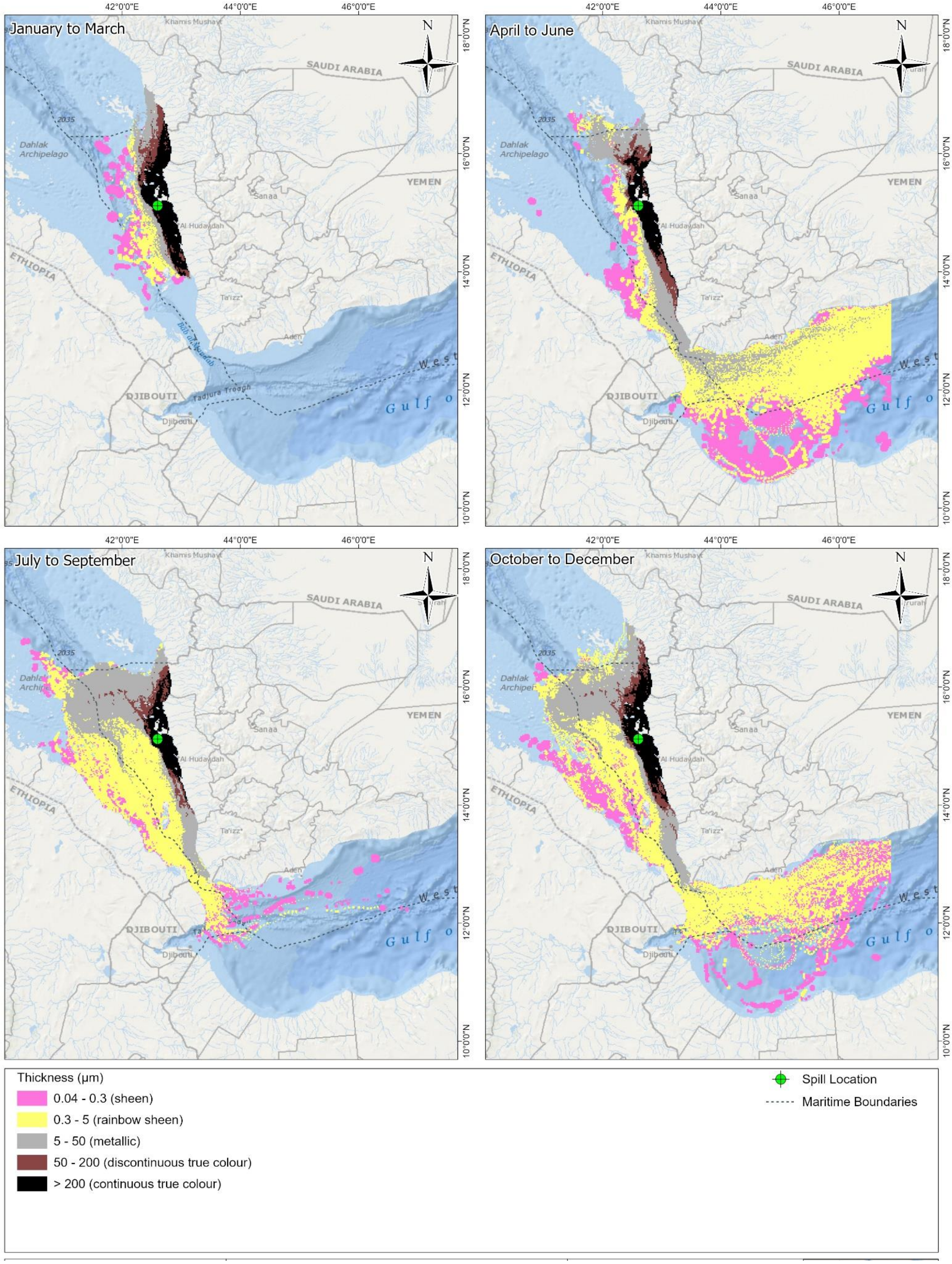


Figure 23: Maximum emulsion thickness of surface oil.

SHORELINE MAPS

Worst case scenario

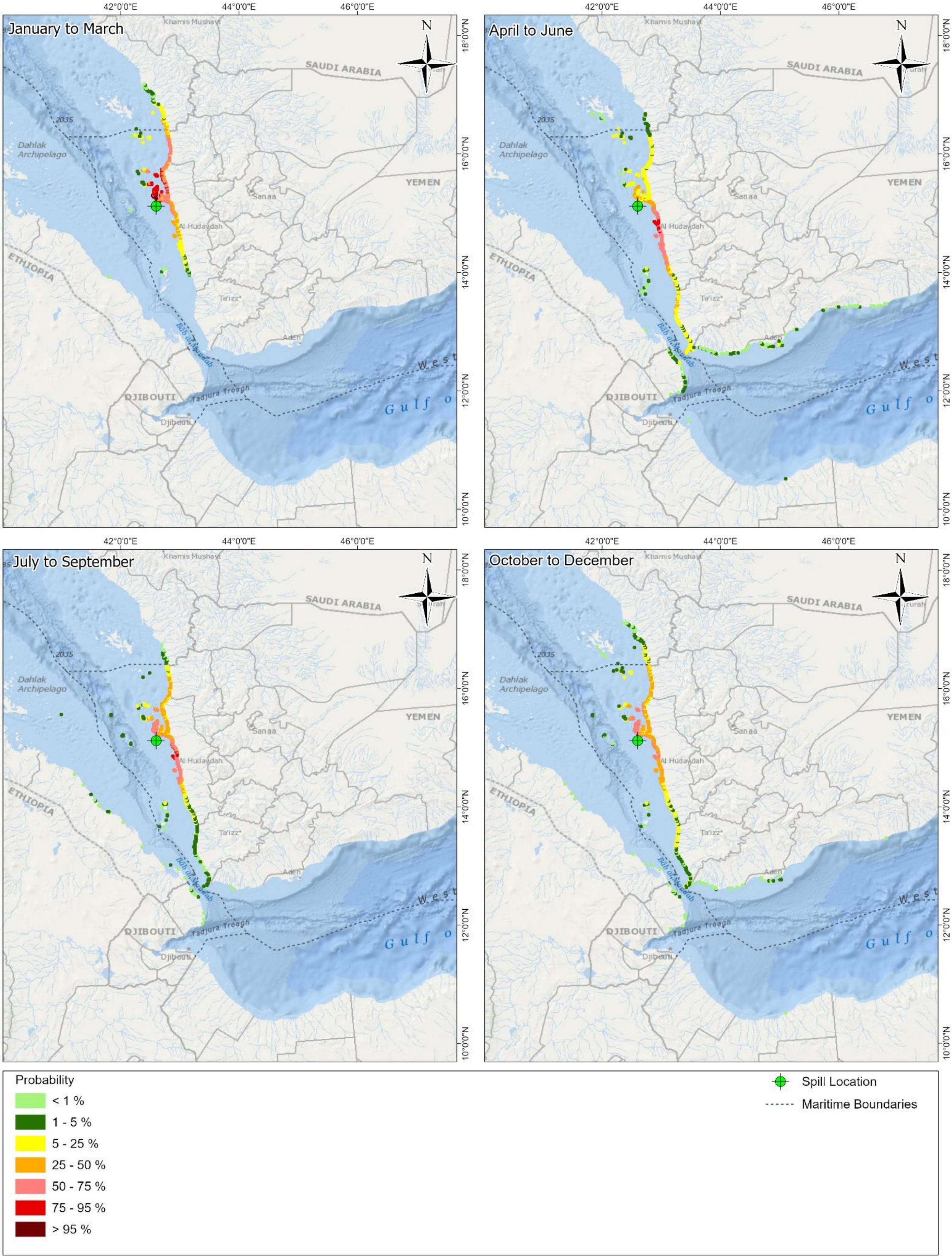


Figure 24: Probability that a shoreline cell could be impacted by oil.

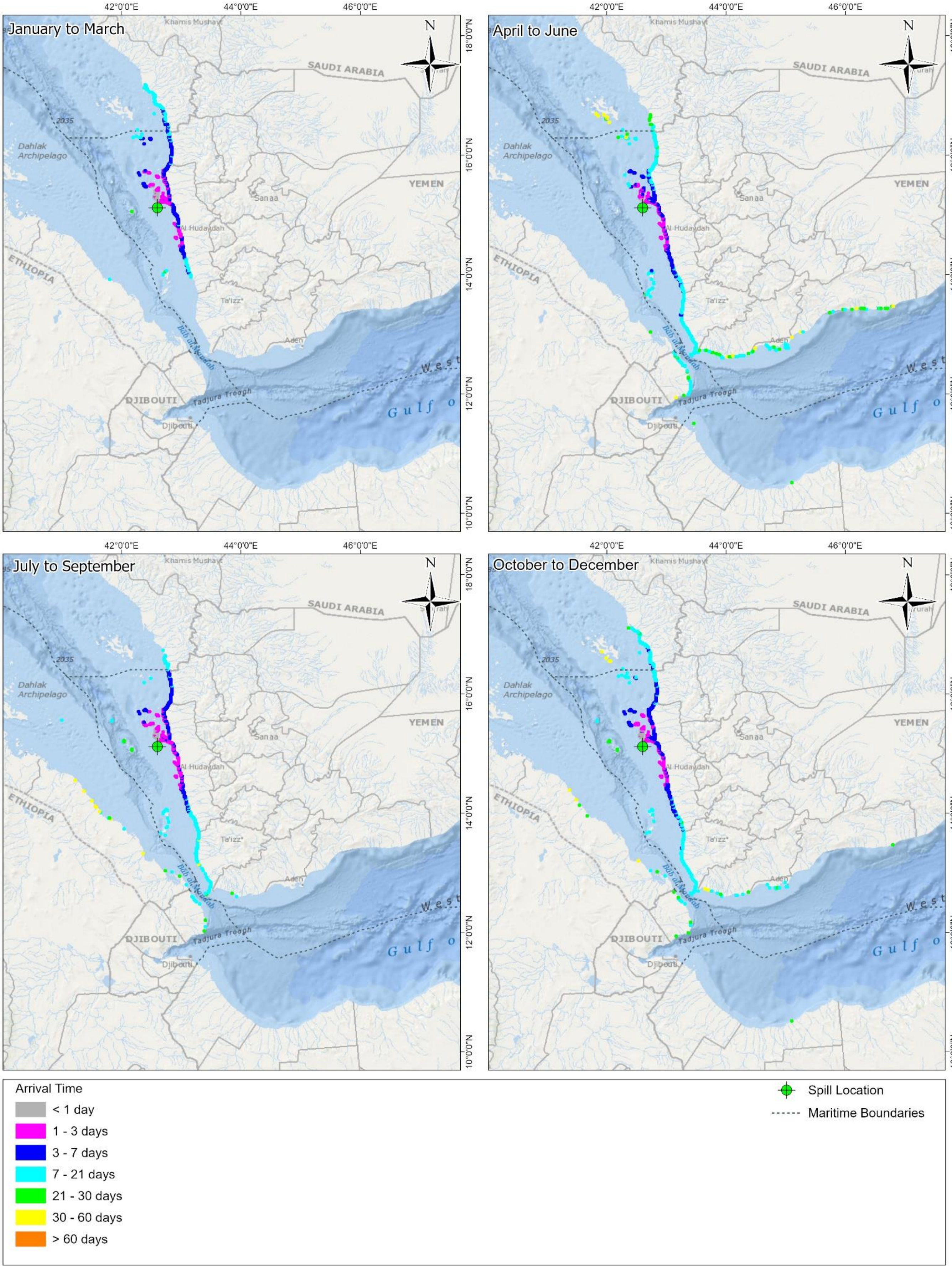


Figure 25: Minimum arrival time of shoreline oil.

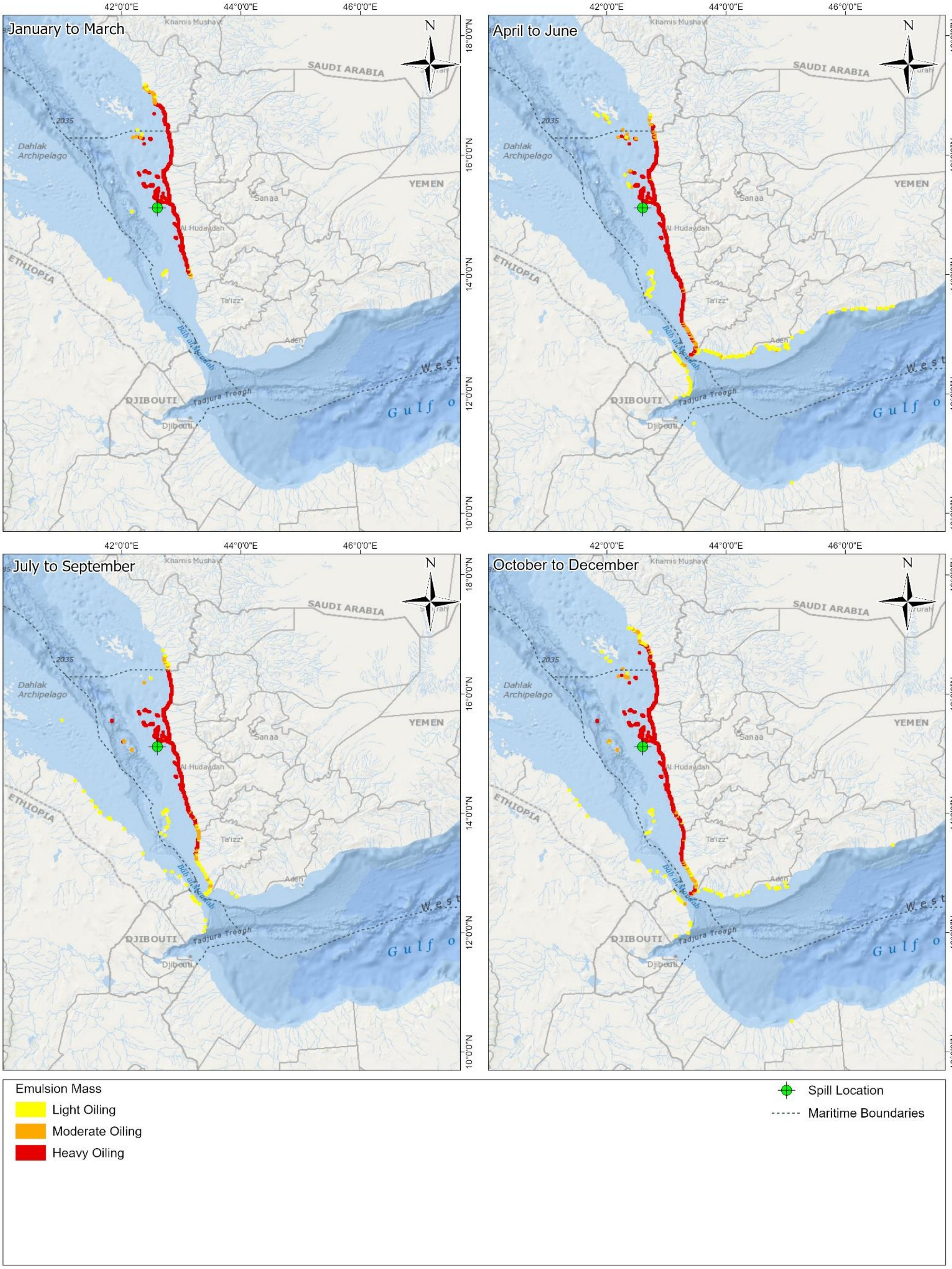


Figure 26: Shoreline contamination based on emulsion mass.

3.4.2 Statistical Analysis

Table 11: Statistical Analysis of Impact

Oil Spill Modelling Summary				
Spill Scenario/Description	Worst Case Scenario			
Median – Sea boundary Crossing				
Identified Sea boundary - Median Line	**Probability and shortest time to reach sea boundary ; and maximum surface oil thickness**			
	Jan-Mar	**Apr-Jun**	**Jul-Sep**	**Oct-Dec**
Djibouti	0% N/A	19% 14 days, 21 hours Metallic	54% 7 days, 0 hours Rainbow	18% 8 days, 15 hrs Metallic
Eritrea	5% 13 days, 6 hours Rainbow	49% 7 days, 21 hours Metallic	60% 5 days, 15 hours Discontinuous True	30% 7 days, 0 hrs Metallic
Saudi Arabia	49% 4 days, 9 hours Continuous True	10% 8 days, 15 hours Metallic	10% 17 days, 3 hours Metallic	31% 5 days, 0 hrs Continuous True
Somalia	0% N/A	5% 22 days, 3 hours Rainbow	35% 11 days, 15 hours Rainbow	7% 14 days, 12 hrs Rainbow
Yemen	100% (Spill originates within country) Continuous True			
Landfall				
Identified Shoreline	**Probability and shortest time to reach shoreline; and maximum possible degree of shoreline oiling**			
	Dec-Feb	**Mar-May**	**Jun-Aug**	**Sep-Nov**
Djibouti	0% N/A	2% 14 days, 23 hours Moderate oiling	15% 8 days, 14 hours Light oiling	4% 10 days, 2 hrs Moderate oiling
Eritrea	<1% 16 days, 10 hours Light oiling	10% 12 days, 17 hours Light oiling	<1% 21 days, 3 hours Light oiling	3% 17 days, 7 hrs Light oiling

Saudi Arabia	45% 5 days, 20 hours Heavy oiling	5% 9 days, 17 hours Moderate oiling	9% 19 days, 6 hours Heavy oiling	29% 5 days, 14 hrs Heavy oiling
Somalia	0% N/A	0% N/A	2% 21 days, 14 hours Light oiling	<1 % 26 days, 1 hr Light oiling
Yemen	100% 0 days, 3 hours Heavy oiling	100% 0 days, 4 hours Heavy oiling	100% 0 days, 4 hours Heavy oiling	100% 0 days, 4 hours Heavy oiling
Maximum Volume Beached				
Mass of oil onshore	61,259 MT	46,442 MT	48,520 MT	49,140 MT
Volume[9] of oil onshore	75,136 m^3	57,908 m^3	60,499 m^3	61,272 m^3
Water Content	85%	85%	85%	85%
Volume of emulsion onshore	500,906 m^3	386,052 m^3	403,325 m^3	408,479 m^3

Table 12: Statistical Analysis of Key Sensitivities

Key Sensitivities at Risk[10]				
Al-Fazzah	6% 6 days, 12 hrs	9% 6 days, 0 hrs	40% 4 days, 18 hrs	11% 4 days, 21 hrs
Al-Mukha - Al-Khawkhah	0% N/A	13% 8 days, 18 hrs	36% 6 days, 0 hrs	10% 6 days, 3 hrs
Bab al-Mandab - Mawza	0% N/A	6% 14 days, 9 hrs	37% 7 days, 21 hrs	9% 8 days, 15 hrs
Bahr Ibn Abbas - Ra's Isa	100% < 1 hour	76% < 1 hour	71% 0 days, 3 hrs	84% < 1 hour
Danakil lowlands	0% N/A	1% 32 days, 9 hrs	1% 13 days, 12 hrs	1% 26 days, 3 hrs
Dehalak Archipelago and offshore islands	0% N/A	12% 11 days, 21 hrs	9% 12 days, 12 hrs	5% 11 days, 21 hrs
Farasan Islands	5% 9 days, 0 hrs	0% N/A	7% 19 days, 18 hrs	5% 12 days, 3 hrs

[9] OSCAR does not provide the volume of oil onshore only the mass. To convert from mass to volume we assume that the density of the spilt oil is constant and the same as the source product (e.g., 0.843). In reality the density of the spill will be different over time and space, but the model is unable to capture this complex interaction. Therefore, the volume estimates presented in this report should be treated as approximate.

[10] A map showing the location of each sensitiviity is presented in section 1.3

Islands north of Al-Hudaydah	94% 1 day, 9 hrs	52% 1 day, 3 hrs	23% 2 days, 21 hrs	64% 1 day, 9 hrs
Jaza'ir al-Hanish	6% 6 days, 3 hrs	39% 5 days, 9 hrs	51% 4 days, 15 hrs	26% 7 days, 0 hrs
Jaza'ir al-Zubayr	<1 % 29 days, 18 hrs	7% 12 days, 3 hrs	<1 % 23 days, 18 hrs	4% 6 days, 6 hrs
Jizan Bay	<1 % 14 days, 12 hrs	0% N/A	0% N/A	0% N/A
Kadda Guéïni - Doumêra	0% N/A	10% 17 days, 18 hrs	25% 7 days, 18 hrs	10% 10 days, 12 hrs
Les Sept Frères	0% N/A	12% 15 days, 21 hrs	50% 8 days, 3 hrs	15% 9 days, 0 hrs
Midi - Al-Luhayyah	95% 2 days, 6 hrs	49% 1 day, 21 hrs	25% 3 days, 12 hrs	63% 2 days, 15 hrs
Nukhaylah - Ghulayfiqah	31% 1 day, 15 hrs	66% 1 day, 21 hrs	73% 2 days, 0 hrs	44% 2 days, 3 hrs

4 CONCLUSION

Four oil spill scenarios were modelled for the FSO SAFER, located off the western coast of Yemen. The scenarios included a release of oil in 3 tanks due to fire/explosion or cracking of hull spilling 24,000 m^3/day over 2 days; a release of 50% of oil in 1 tank, due to corrosion of bottom steel spilling 376 m^3/day over 21 days; a release of oil caused by damages to the PLEM structure and pipeline spilling 41.6 m^3/day over 60 days. These scenarios were modelled using metocean data for year round conditions. A worst-case scenario of an oil spill of 24,000 m^3/day over 7.55 days was also modelled during four separate 3 month seasons.

Scenario 1: Release of 3 tanks due to fire/explosion or cracking of hull

Sea Surface

Spilled oil has a low probability of impacting the sea areas of Djibouti (13%), Eritrea (24%), Kingdom of Saudi Arabia (15%) and Somalia (5%). The modelling predicts an oil spill will predominantly spread out within the Yemeni waters within the Red Sea and move southwards towards the Bab al-Mandab Strait and into the Gulf of Aden. Oil could begin to impact the waters of neighbouring counties after 5 days, 5 hours. Oil of thickness 'continuous true' may be found up to ~80 km from the release location and sheen and rainbow sheen can be expected up to ~740 km away.

Shoreline

The likelihood of shoreline oiling above the threshold of 0.1 litre/m^2 is low for Djibouti (1%, arriving after 8 days 18 hours), Eritrea (<1%, arriving after 19 days, 23 hours), Saudi Arabia (11%, arriving after 7 days, 17 hours). Heavy and moderate oiling is expected along the Yemeni coastline in the immediate vicinity of the FSO and up to ~300 km away. Light oiling may be found as far as Aden (~500 km) from release.

Scenario 2: Release of 50% of 1 tank, due to corrosion of bottom steel

Sea Surface

Spilled oil has a low probability of impacting the sea areas of Djibouti (3%), Eritrea (9%) and Kingdom of Saudi Arabia (10%). The modelling predicts that the spill will predominantly spread out within Yemeni waters within the Red Sea and move southwards towards the Bab al-Mandab Strait and into the Gulf of Aden. Oil could begin to impact the waters of neighbouring counties after 6 days, 12 hours. Oil of thickness 'discontinuous true' can be found up to ~30 km from release location and sheen and rainbow sheen can be expected up to ~700 km away.

Shoreline

There is a low probability of shoreline oiling above the threshold of 0.1 litre/m^2 impacting Saudi Arabia (5%, arriving after 16 days, 3 hours). Shoreline oiling of the Yemeni coastline will be heavy to moderate around the spill location. Light oiling may be found up ~250 km away. Shoreline oiling of the Yemen coastline could occur in as little as 3 hours after release.

Scenario 3: Release caused by damages to the PLEM structure and pipeline.

Surface

Oil is likely to remain within Yemeni waters with a low probability of surface oil impacting other Countries. The maximum oil thickness is predicted to be rainbow sheen up to ~250 km from release and sheen may be observed up to 360 km from release.

Shoreline

Heavy oiling of the coastline around Al Hudaydah is possible. Light oiling can be expected to be found up to 130 km from release location. Oiling is estimated to reach the coastline in as little as 4 hours of release.

Scenario 4: Worst case scenario

Sea Surface

An oil spill at any time of year is likely to impact the sea areas of Eritrea, Saudi Arabia, in addition to Yemen. An oil spill between April and December is also likely to impact the sea areas of Djibouti and Somalia. Spilled oil could travel up to 700 km from release, apart from in January to March where the oil is most likely to remain in closer proximity to the release location traveling up to 220 km away. Oil is likely to impact the sea areas of neighbouring countries within days (Djibouti (7 days), Eritrea (5 days 15 hours), Saudi Arabia (4 days, 9 hours), and Somalia (11 days, 15 hours)). Oil of thickness 'Continuous true' may be found up to ~150 km away (January to March), metallic and rainbow sheen may be observed up to ~700 km (April to June) from the release location.

Shoreline

Heavy shoreline oiling will likely impact the Yemeni coastline and moderate to light oiling of sections of coastline in Djibouti, Eritrea and Saudi Arabia may appear. Heavy oiling could be found up to ~280 km from release location. Oil could impact the Yemen coast within as little as 3 hours of release.

APPENDIX A. MODEL SETUP

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Description	Release of 3 tanks due to Fire/Explosion or Cracking of Hull	Release of 50% of 1 tank, due to Corrosion of Bottom Steel	Release caused by damage to the PLEM structure and pipeline	Worst case scenario
Latitude	15° 07.0′ N,	15° 07.0′ N,	15° 07.0′ N,	15° 07.0′ N,
Longitude	042° 36.0′ E	042° 36.0′ E	042° 36.0′ E	042° 36.0′ E
Time of Year	All year - 1 stochastic	All year - 1 stochastic	All year - 1 stochastic	January to March April to June July to September October to December
Release Depth	surface	surface	35m	surface
Release Rate	23,847 m^3/day	376 m^3/day	41.6 m^3/day	24,000 m^3/day
Release Duration	2 days	21 days	60 days	7.55 days
Duration After Cessation	30 days	30 days	30 days	30 days
Total Model Duration	32 days	51 days	90 days	38 days
API Gravity	44.9	44.9	44.9	44.9
Specific Gravity	0.802	0.802	0.802	0.802
Viscosity (cP)	5.0	5.0	5.0	5.0
Pour Point (°c)	-21.0	-21.0	-21.0	-21.0
Wax (%)	2.50	2.50	2.50	2.50
Asphaltenes (%)	0.20	0.20	0.20	0.20
Diameter of Release Hole (m)	N/A	N/A	0.1m	N/A
Gas to Oil Ratio (GOR, Sm^3/m^3)	N/A	N/A	0	N/A
Gas Density (kg/Sm^3)	N/A	N/A	N/A	N/A

APPENDIX B. METOCEAN DATA

Three-dimensional ocean current data is used to determine the movement of oil both on the sea surface and through the water column.

Table 13: Current Data – General Description

Dataset Name	Navy Coastal Ocean Model (NCOM)		
Reference	This study has been conducted using Fleet Numerical Meteorology and Oceanography Center (FNMOC) Information		
Description	The hydrodynamic database is constructed from 3D current velocity fields, suitable for use in oil model simulations. This comprises of ocean currents (non-tidal residual) from the HYCOM global ocean circulation model, combined with tidal current velocities. The tidal component of current velocity would be derived from BMT ARGOSS' tidal database. The tidal information is based on the integration of approximately 5000 tidal stations and 13 years of satellite radar altimeter into depth average global and regional tidal models (2DH model). For this area the spatial model resolution is 1 minute. The tidal model provides tidal currents (u, v components) as well as surface elevation.		
Start Time	January 2018	**Spatial Resolution**	1 km
End Time	December 2020	**Temporal Resolution**	1 hour
Depth Levels	1 - Surface layer only		

Two-dimensional wind data is used to enhance the prediction of movement of oil on the sea surface, estimate wave height, contribute to evaporation rates and capture mixing in the upper water column.

Table 14: Wind Data – General Description

Dataset Name	CFSR Winds		
Reference	Saha, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6513W89. Accessed Oct 2019.		
Description	The CFSR is a third-generation reanalysis product. It is a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system designed to provide the best estimate of the state of these coupled domains over this period. The CFSR includes (1) coupling of atmosphere and ocean during the generation of the 6-hour guess field. (2) an interactive sea-ice model, and (3) assimilation of satellite radiances. The CFSR global atmosphere resolution is ~38 km with 64 levels although the wind data we extract is at 1 level, 10 m above sea level.		
Start Time	January 2018	**Spatial Resolution**	~1/3°
End Time	December 2020	**Temporal Resolution**	1 hour
Further Information	"The Climate Data Guide: Climate Forecast System Reanalysis (CFSR)." Retrieved from https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr		

APPENDIX C. HABITAT GRID

Table 15: Habitat domain details

Name	Domain Extent			
	Bottom	Top	Left	Right
	10° 03' 13'' N	19° 56' 44'' N	037° 08' 42'' E	046° 54' 03'' E
	Number of Cells		Cell Resolution	
	East to West	North to South	East to West	North to South
P02048-S01-03	523	549	2 km	2 km
	Domain Size			
	East to West		North to South	
	1,046 km		1,098 km	

APPENDIX D. OIL CHARACTERISTICS AND BEHAVIOUR

The components found in crude oil are classified into two main groups: hydrocarbons and non-hydrocarbons (see Figure 27). If oil is rich in C1-12 alkanes, it is particularly light, as these are lighter components than the C25+ alkanes. Conversely, if oil contains high quantities of C25+ alkanes, resins and asphaltenes, it is heavy.

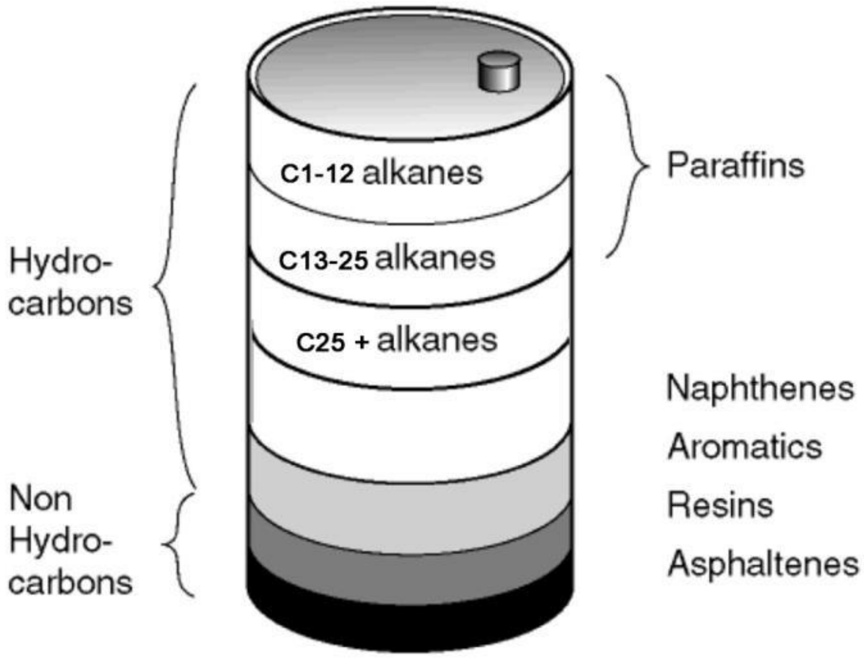


Figure 27: The chemical composition of crude oil

The chemical composition of oil is important when predicting how it will break down or weather. For example, oil containing mostly light components is likely to lose a greater volume to evaporation than heavy oil. Oils with carbon chains exceeding 15 (C15+) cannot evaporate, even during large storms. Long chains (for example, C25+ alkanes) take a long time to degrade in the water column. Asphaltenes can increase the stability of oil, allowing it to take up water but preventing the oil and water emulsion from breaking down.

As crude oil is a complicated mixture of organic compounds, its components must be analysed to characterise it successfully (LECO Corporation, 2012). The components of oil can be 'identified' and plotted using gas chromatography instruments which are coupled with mass spectrometers (see Bacher, 2014, for further information). The results of gas chromatography and mass spectrometry are converted into a list of 25 sub-components, as broken down in the OSCAR oil database. Each of the 25 sub-components is characterised by molecular weight, density, viscosity, boiling point, solubility in water, vapour pressure, and partition coefficient between oil and water.

The OSCAR Oil Database

A strength of the OSCAR model is its foundation on an observational database of oil weathering properties (maximum water content, viscosity, droplet size distribution, evaporation, emulsification and dispersion, which are measured in a wide range of conditions). The oil database contains complete weathering information for 340 crude oils and petroleum products. It also contains crude assay data for approximately 170 other crude oils (derived from the HPI database - HPI, 1987). But these oils have not been lab-tested so model estimates of the weathering process are used in place of observational data. This reduces the reliability of the model.

Oil Matching

Lab tested oils were selected for this modelling study based on the information provided by the IMO.

The properties of the modelled oil are shown in Table 16.

Table 16: Properties of the modelled oil

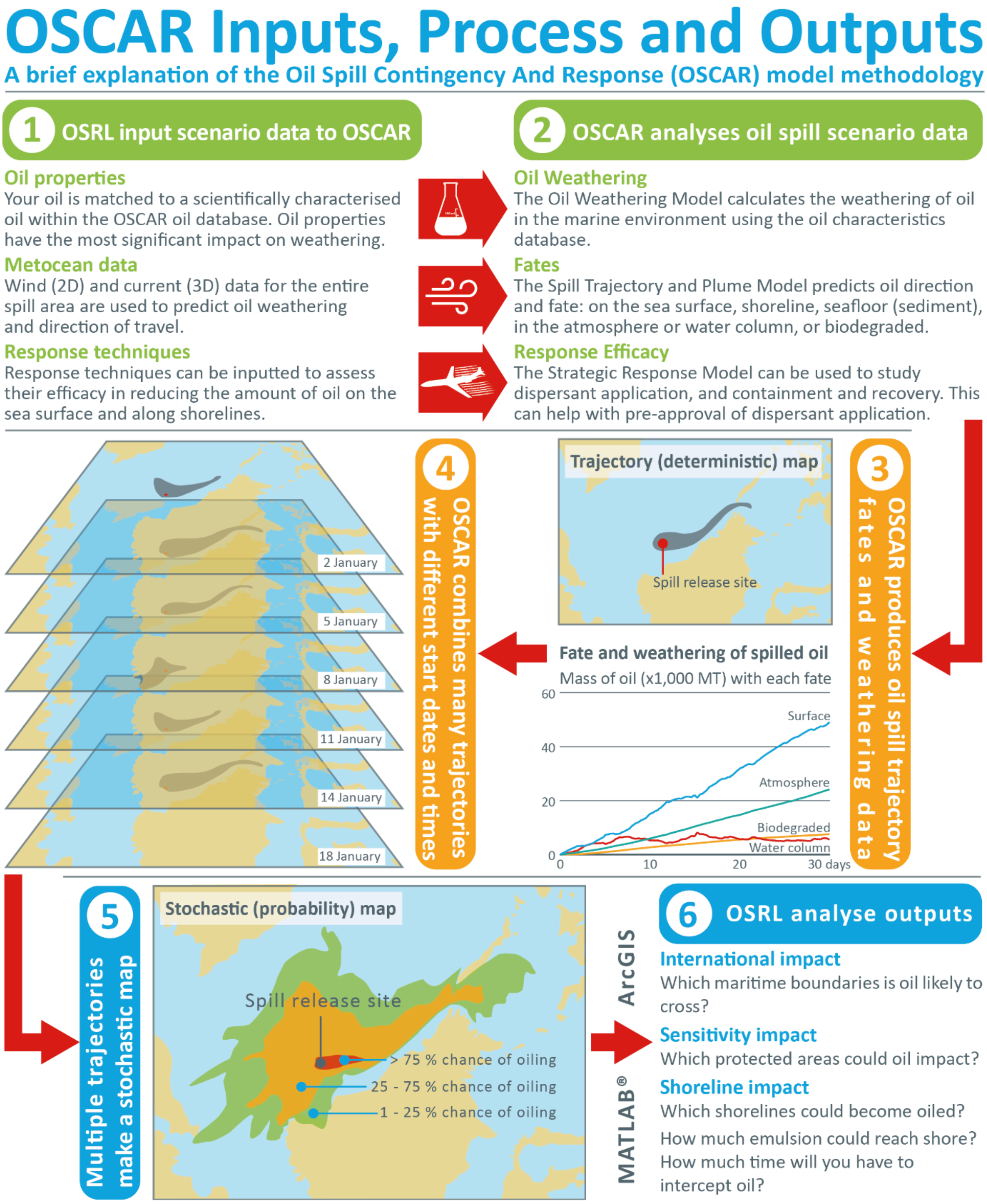
Name	API	Specific Gravity	Viscosity (cP)	Pour Point[11]* (°C)	Wax Content (%)	Asphaltenes (%)
Crude Oil	**45.2**	**0.8007**	**1.9**	**30.1**	**-**	**-**
Modelled Crude	44.9	0.802	5	-21	2.50	0.20

[11] Due to the algorithms in the model, Pour Point is of lesser importance when oil matching.

APPENDIX E. OIL SPILL MODELLING SOFTWARE AND METHODOLOGY

This project was completed using the version of OSCAR contained within the Marine Environmental Modelling Workbench (MEMW) 12.0, a model that has been fully validated and calibrated using various field observations from a number of experimental oil spills (Reed et al., 1995, 1996).

OSCAR predicts the movement of oil at the water's surface and throughout the water column. OSCAR consists of a number of interlocking modules that are activated as required. The following infographic illustrates the OSCAR modelling process.



APPENDIX F. LIMITATIONS

Any oil spill modelling is subject to limitations of accuracy in of how well the model can represent an actual spill. The main limitations are outlined below:

Oil Analogue

The degree of weathering of the oil on board the FSO is currently unknown. The model uses oil properties similar to those of a fresh Marib light crude. Without sampling the oil currently in the tanks, it is not possible to determine the degree to which these properties may have changed and how these changes might impact the modelled fate and behaviour of the oil. Evaporation of the oil's lighter factions and an increase in its viscosity would be expected over time. More details of the analogue oil selected are discussed in APPENDIX D.

Release Parameters

The release scenarios simulated were based on best estimates of likely scenarios that could occur. In an actual spill, oil may be released in a different manner. For example, periodically with tidal motion. More details of the release parameters used are given in APPENDIX A

Model Computation

OSCAR uses a set of equations and algorithms to predict the behaviour of the oil at regular timesteps. The methodology has been validated and calibrated through various field observations from several experimental oil spills. However, the equations and algorithms will never fully capture the actual behaviour of a spill. More details of the oil spill model are discussed in APPENDIX E.

Currents

Transportation of oil is partially driven by a dataset of the currents in the area. A high resolution (1km) dataset has been used, but this is also derived from a model and not all features will be captured. Smaller features or those near to shore may not be well represented. More details of the currents used are given in APPENDIX B.

Winds

Transportation of wind is also driven by a dataset of surface winds in the area. The dataset used is a subset of a global model and so may not capture all local features. Winds are represented on a larger grid, approximately 38 km resolution. Coastal wind effects may not be fully represented More details of the winds used are given in APPENDIX B.

Grid

Stochastic oil spill modelling requires use of a habitat grid to calculate and present the results. A grid with 2 km x 2km cells was used for this study. The geographic area and model results are represented at the resolution of the grid, and so any features smaller than a single grid cell may not be fully captured. More details on the habitat grid are given in APPENDIX C.

APPENDIX G. GLOSSARY OF TERMS, ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius (1.0°C = 33.8° Fahrenheit)
µm	Micrometre (1.0 µm = 10^{-6} m)
API	American Petroleum Institute
API Gravity	API Gravity, like specific gravity, is a ratio between the densities of oil and water. Unlike specific gravity, API gravity is only used to describe oil, which it characterises as: • Light - API > 31.1 • Medium - API between 22.3 and 31.1 • Heavy - API < 22.3 • Extra Heavy - API < 10.0 API Gravity is converted to Specific Gravity using the following formula: *API gravity = (141.5/Specific Gravity) – 131.5* An API of 10 is equivalent to water, so oils with an API above 10 will float on water while oils with an API below 10 will sink. See also: *Specific Gravity, API*
Asphaltenes	The asphaltenes present the crude oil components that are (1) insoluble in n-heptane at a dilution ratio of 40 parts alkane to 1 part crude oil and (2) re-dissolves in toluene. The asphaltenes include the crude oil material highest in molecular weight, polarity and aromaticity.
bbls	Barrels of oil (a unit of volume). (1.0 bbls = 0.15899 m^3 and 1.0 m^3 = 6.2898 bbls) The conversion between mass and volume requires knowledge of the oil density. See also: *MT, API Gravity, Specific Gravity*
bbls/day	Barrels of oil per day (rate).
BONN Agreement	The BONN Agreement is an international standard and agreement on how to characterise and respond to pollution. Although aimed at pollution in the North Sea (Europe) many of the characterisation standards are internationally recognised.
GOR	Gas to Oil Ratio - the ratio of volumetric flow of produced gas to the volumetric flow of oil. Although GOR is a ratio, the volume units must be known since gas and oil volumes are measured differently. GOR changes with temperature and pressure so the condition under which GOR is measured must be known.
ITOPF	The International Tanker Owners Pollution Federation Limited
km	Kilometres (1.0 km = 1,000 m) See also: *m*
m	Metres (1.0 km = 1,000 m) See also: *µm, km*
MEMW	Marine Environmental Modelling Workbench - the modelling software package developed by SINTEF. The MEMW consists of three models:

	• **DREAM (Dose, Risk and Effects Assessment Model)** • **OSCAR (Oil Spill Contingency and Response Model)** • **ParTrack Model** When combined, these three models quantify the environmental effect of most chemical pollution activities. See also: *OSCAR, SINTEF*
MT	Metric Tonnes - this is a unit of oil mass. (1.0 MT = 1,000 kg) The conversion between mass and volume requires knowledge of the oil's API or Specific Gravity as follows: *Barrels per metric ton = 1/[(141.5/(API + 131.5) x 0.159]* See also: *bbls, API Gravity, Specific Gravity*
NOAA	National Oceanic and Atmospheric Administration – an American scientific agency focussed on metocean conditions
OSCAR	Oil Spill Contingency and Response A state of the art 3D oil spill model and simulation tool for predicting the fates and effects of oil released into the marine environment. Developed by SINTEF, it sits within the larger MEMW application. See also: *SINTEF, MEMW*
OSRL	Oil Spill Response Limited
Pour Point	The pour point of a liquid is the lowest temperature at which it shows flow characteristics. If ambient temperature is less than the liquid's pour point it will begin to solidify.
SINTEF	SINTEF is an independent research organisation in Norway which developed the OSCAR model used in this study.
Specific Gravity	Specific gravity is a ratio of the density of one substance to the density of a reference substance, usually water. Specific gravity of oil is a ratio of the density of oil to the density of water. See also: *API Gravity, bbls, MT*
Stochastic	Stochastic (or probabilistic) results show the probability or likelihood of an event occurring. They provide statistical data that can be used to assess risk and identify worst-case scenarios. Stochastic results are achieved by combining many different trajectory simulations. See also: *Trajectory*
Trajectory	Trajectory or deterministic results show the impact of a single spill event over time. Can be used to assess different response options such as booms, skimmers and dispersant. See also: *Stochastic*
UTC	Coordinated Universal Time
Wax Content	Represents the crude oil components that are soluble in higher molecular weight normal alkanes (n-heptane) but are insoluble in lower molecular weight alkanes (n-pentane).

APPENDIX H. REFERENCES

Bacher, A.D. (2014) 'Gas Chromatography Theory', accessible online via: http://www.chem.ucla.edu/~bacher/General/30BL/gc/theory.html, last accessed 27th June 2014.

The International Tanker Owners Pollution Federation Limited (ITOPF) (n.d.) 'Technical Information Paper 02: Fate of marine oil spills', accessible online via: http://www.itopf.com/knowledge-resources/documents-guides/document/tip-2-fate-of-marine-oil-spills/, last accessed 9th July 2014.

The International Tanker Owners Pollution Federation Limited (ITOPF) (n.d.) 'Technical Information Paper 06: Recognition of oil on shorelines', accessible online via: http://www.itopf.com/knowledge-resources/documents-guides/document/tip-6-recognition-of-oil-on-shorelines/, last accessed 29th October 2014.

LECO Corporation (2012) 'Analysis of Light Crude Oil Using Gas Chromatography – High Resolution Time-of-Flight Mass Spectrometry', Form No. 203-821-410 Rev0, accessible online via: http://www.leco.com/index.php/component/edocman/?task=document.download&id=404&Itemid=404, last accessed 27th June 2014.

National Oceanic and Atmospheric Administration (NOAA, 2014) *National Oceanographic Data Center (NODC)*, World Ocean Atlas Select (WOA*select*), accessible via: http://www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html, last accessed 14th April 2014.

Reed, M., French, D., Rines, G. and Rye, H. (1995) 'A three-dimensional oil and chemical spill model for environmental impact assessment', paper presented at 1995 International Oil Spill Conference, pp.61-66.

Reed, M., Aamo, O.M. and Downing, K. (1996) 'Calibration and Testing of IKU's Oil Spill Contingency and Response (OSCAR) Model System', paper presented at 1996 AMOP Oil Spill Conference.

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, and Co-authors, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91, 1015–1057.

Saha, S., S. Moorthi, X. Wu, J. Wang, and Co-authors, 2014: The NCEP Climate Forecast System Version 2. Journal of Climate, 27, 2185–2208.

SINTEF (2014) 'OSCAR – Oil Spill Contingency and Response', accessible online via: http://www.sintef.no/home/SINTEF-Materials-and-Chemistry/About-us/Software-development/OSCAR--Oil-Spill-Contigency-and-Response-/, last accessed 14th April 2014.