Appendix 6

Produced water discharge modelling

ICHTHYS GAS FIELD DEVELOPMENT PROJECT

PRODUCED WATER DISCHARGE MODELLING

JULY 2009

Prepared for INPEX Browse, Ltd.

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STUDY DATUMS

Water depths and levels presented in this report are with respect to Mean Sea Level (MSL) unless otherwise stated and are in units of meters.

Positions are satellite derived from the Global Positioning System using the WGS84 datum, unless stated otherwise. Position units are in latitude/longitudes.

All units are in standard SI units.

EXECUTIVE SUMMARY

INPEX Browse Ltd will be the operator of the Ichthys Field in the Browse Basin, offshore of Western Australia. As part of the project, Asia-Pacific Applied Science Associates (APASA) was commissioned to model the mixing and dispersion of treated produced water (indicative of commingled condensed water and formation water) for the Ichthys project, Browse Basin. The treated low density (highly buoyant) produced water will be discharged continuously, 15 m below the sea surface, from the hull of the FPSO (Floating Producing Storage and Offloading) facility. The discharged water will have a temperature of up to 50 °C, and salinity levels much lower than the ambient seawater, estimated at between 1 and 12 parts per thousand (ppt) depending on the composition. The water will contain an estimated 20 mg/L of residual oil.

To cover the possible rates of discharge, two different cases were assessed with different combinations of discharge rate and salinity:

- Scenario 1 with 100% condensed water and 0% formation water; 2000 m^3/day flow rate; salinity of 1 ppt
- Scenario 2 with 50% condensed water and 50% formation water; 5000 m^3/day flow rate; salinity of 12 ppt.

Both scenarios were assessed during summer and winter conditions.

To simulate the release of treated produced water, the modelling study was carried out as three independent, yet integrated stages. Firstly, a validated ocean/coastal hydrodynamic model (HYDROMAP) was used to generate three-dimensional current data for the study area. Secondly, a near-field discharge model (UM3) was used to assess the dilution of the plume under a range of ambient summer and winter current conditions. Finally, the generated currents and near-field mixing estimates were used as input into the far-field advection and dispersion model, MUDMAP, to predict the temporally and spatially varying concentrations of oil within the stream. The main objective of the far-field modelling was to estimate the extent and shape of the mixing zones setup by the oil concentrations.

The near-field modelling showed that due to the orientation of the pipe (vertically downward), the plume would initially plunge downward creating a turbulent mixing zone approximately 1 m below the discharge pipe. Once the initial jet momentum ceased, the plume remained sufficiently buoyant to rise to the surface and to continue to mix with ambient waters, though at a slower rate. As a result of the mixing during the initial plunge and buoyant rise, the salinity and temperature of the plume were predicted to reach background levels over a short distance (~10 m) irrespective of the ambient conditions and flow rates. The plume temperature easily meets the temperature criteria of < 3 °C difference with ambient seawater temperature within 100 m from the discharge point.

Modelling also revealed that the rate of near field dilution for the oil would be affected by the flow rate. During a static weak current a dilution of 1:121 was achieved for Scenario 1 compared to 1:55 for Scenario 2, essentially halving the dilution performance. This was attributable to the current mixing the plume laterally with the receiving waters and the volume of ambient water intersecting the plume as it rises.

Since the rates of dilutions were lower than the desired dilution (1:158) determined from ecotoxicological testing, far-field modelling was employed for both scenarios and seasons.

Far-field results indicated that once the plume reached the surface it would remain in the top layer where the near-surface currents would affect overall transport. It was predicted to oscillate and change direction with each flood and ebb tide event. On the ebb tide, the plume was pulled in a south-easterly direction, momentarily paused and then was forced towards the northwest during the flood tide. Lower concentrations (higher dilution rates) were occurring during stronger currents, whereas patches of higher concentrations (lower dilution rates) tended to build up at the turn of the tide and weaker current events.

Using the 30-day far-field modelling results dilution contours were calculated to define the field of effect for each scenario and season. The area of coverage below the dilution requirement of 1:158 was approximately 0.0061 km^2 from a 5000 m^3/day flow rate for both seasons with a maximum distance of 60 m from the release site. The area of coverage below the dilution requirement of 1:158 for the 2000 m^3/day flow rate was less than 0.000025 km^2 (25 m^2).

1 INTRODUCTION

INPEX Browse, Ltd. (INPEX) proposes to develop the natural gas and associated condensate contained in the Ichthys Field in the Browse Basin at the western edge of the Timor Sea about 200 km off Western Australia's Kimberley coast. The field is about 850 km west south west of Darwin in the Northern Territory.

The two reservoirs which make up the field are estimated to contain 12.8 tcf (trillion cubic feet) of sales gas and 527 MMbbl (million barrels) of condensate. INPEX will process the gas and condensate to produce liquefied natural gas (LNG), liquefied petroleum gas (LPG) and condensate for export to overseas markets.

For the Ichthys Gas Field Development Project (the Project), the company plans to install offshore facilities for the extraction of the natural gas and condensate at the Ichthys Field and a subsea gas pipeline from the field to onshore facilities at Blaydin Point in Darwin Harbour in the Northern Territory. A two train LNG plant, an LPG fractionation plant, a condensate stabilisation plant and a product loading jetty will be constructed at a site zoned for development on Blaydin Point. Around 85% of the condensate will be extracted and exported directly from the offshore facilities while the remaining 15% will be processed at and exported from Blaydin Point.

In May 2008 INPEX referred its proposal to develop the Ichthys Field to the Commonwealth's Department of the Environment, Water, Heritage and the Arts and the Northern Territory's Department of Natural Resources, Environment and the Arts. The Commonwealth and Northern Territory ministers responsible for environmental matters both determined that the Project should be formally assessed at the environmental impact statement (EIS) level to ensure that potential impacts associated with the Project are identified and appropriately addressed.

Assessment will be undertaken in accordance with the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth) (EPBC Act) and the *Environmental Assessment Act* (NT) (EA Act). It was agreed that INPEX should submit a single EIS document to the two responsible government departments for assessment.

Asia-Pacific ASA (APASA) was commissioned to carry out produced water discharge modelling associated with INPEX's preparation of the EIS and this technical report was prepared in fulfilment of that commission.

As part of the offshore facility operation, produced water will be extracted from the gas and condensate to prepare the hydrocarbon streams for water-free export. The produced water will be a mixture of condensed water extracted from the reservoir as a gas, and formation water extracted from the reservoir as a liquid. The treated low density (highly buoyant) wastewater will be discharged continuously, through a caisson which will pass through the hull of the FPSO (Floating Production Storage and Offloading) vessel approximately 15 m below the sea surface (13°57′57″S, 123°18′34″E, Figure 1). Water depth below the FPSO is approximately 250 m.

As the discharged treated wastewater will be hotter (50 °C) and contain oil concentrations higher than the receiving water, INPEX commissioned APASA to model the likely mixing and dispersion of the plume. The main aims of the modelling study were to assess:

1. The distance from the release site at which the effluent temperature and oil content of the plume comply with environmental guidelines
2. The size of the active mixing zone during summer and winter conditions.

The following report documents the methodology and findings of the above study.

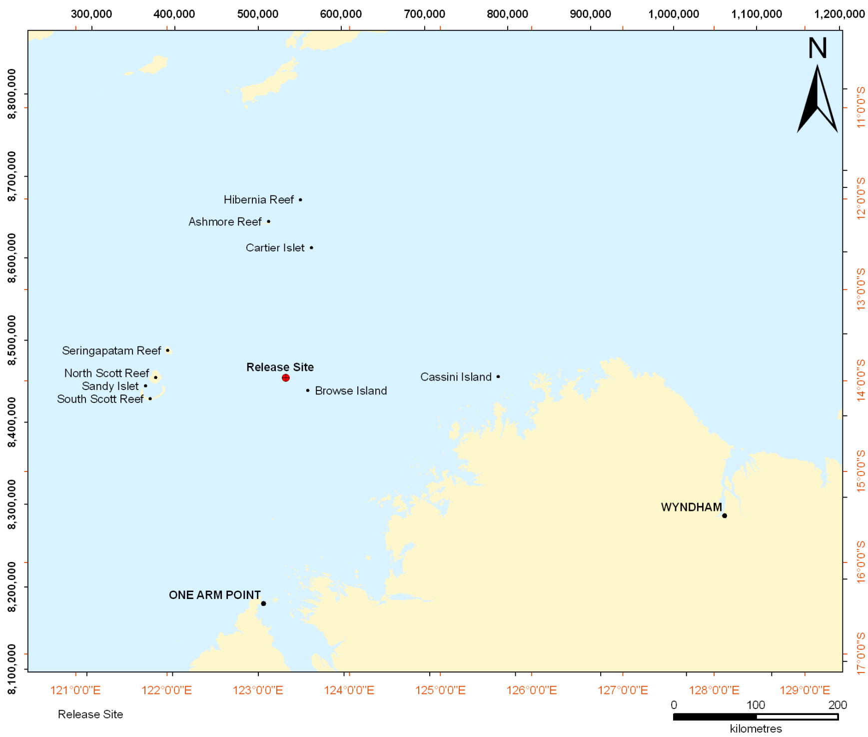


Figure 1: Location of the produced water release site, Browse Basin, Western Australia

1.1 Scope of work

The scope of work consisted of the following tasks:

1. To develop the current database for environmental dispersion modelling
2. To assess near-field mixing and dilution zones for two discharge cases (each of them with a different discharge rate and salinity) under representative summer and winter conditions
3. To establish and run a far-field model simulating the likely mixing and dispersion of the produced water plumes under the influence of summer (January) and winter (June) current conditions for the 2000 m^3/day and 5000 m^3/day flow rates
4. To estimate the extent and shape of the mixing zones for the two discharge rates for each season

5. To generate a composite mixing zone from the seasonal results for the two discharges.

The physical mixing of produced water can be separated into two distinct zones: (a) near-field; and (b) far-field. The limits of the near-field zone are defined by the area where the levels of mixing and dilution are controlled by the plume's initial jet momentum and the buoyancy flux, resulting from the density difference. When the plume encounters a boundary such as the water surface, seabed or density stratification layer, the near-field mixing is complete and the far-field mixing begins. During the far-field phase, the plume is transported and mixed by the ambient currents.

Therefore, to accurately determine the dilution of the discharge and the mixing zone, the effect of near-field mixing needs to be considered first, followed by investigations of the far-field mixing.

2 DEVELOPMENT OF HYDRODYNAMIC DATA

2.1 Hydrodynamic model

To simulate the likely advection and dispersion of the discharged produce water, it was necessary to predict the regional currents driven by winds and tides. ASA's three-dimensional ocean/coastal circulation model, HYDROMAP was used to predict the circulation (or current patterns) of the receiving waters. HYDROMAP has been successfully applied in many regions around the world (Isaji et al. 2001, Zigic et al. 2003) and has recently been validated for the study area as part of the INPEX oil spill simulation study. Full details of the model set-up and operation are provided in APASA (2009). A brief summary of the hydrodynamic modelling is given herein.

HYDROMAP simulates the flow of ocean currents within a model region due to forcing by astronomical tides, wind stress and bottom friction for any location on the globe. The model employs a sophisticated nested-gridding strategy, supporting up to six levels of spatial resolution, halving the grid cell size as each level of resolution is employed. This allows for higher resolution of currents within areas of greater bathymetric and coastline complexity, and/or of particular interest to a study. To simulate the ocean-circulation over any area of interest, the model was provided with the following input data:

1. Measured bathymetry for the area, which defined the shape of the seafloor
2. The amplitude and phase of tidal constituents, which were used to calculate sea heights over time at the open boundaries of the model domain. Changes in sea heights were used, in turn, to calculate the propagation of tidal currents through the model domain region
3. Wind data to define the wind shear at the sea surface.

The numerical solution methodology follows that of Davies (1977 a, b) with further developments for model efficiency by Owen (1980) and Gordon (1982). A more detailed presentation of the model can be found in Isaji and Spaulding (1984).

2.2 HYDROMAP model setup

The current data were generated on a model domain 720^{o}km by 655^{o}km, as shown in Figure 2. The large grid domain was selected to capture the full effects of tide and wind induced forcing over the shelf waters around the FPSO location.

The final grid consisted of 9 579 active computational water cells, with the grid-cell resolution ranging from 5.0 km over the open sea and down to 1.2 km around the islands and into the near shore waters off the Australian coast. The higher resolution grid cells were used to resolve detailed circulation patterns and important coastal influences.

The bathymetric data used to describe the shape of the seabed was derived from the Geoscience Australia national bathymetric dataset, which has a nominal resolution of approximately 250 m by 250 m (see Figure 2).

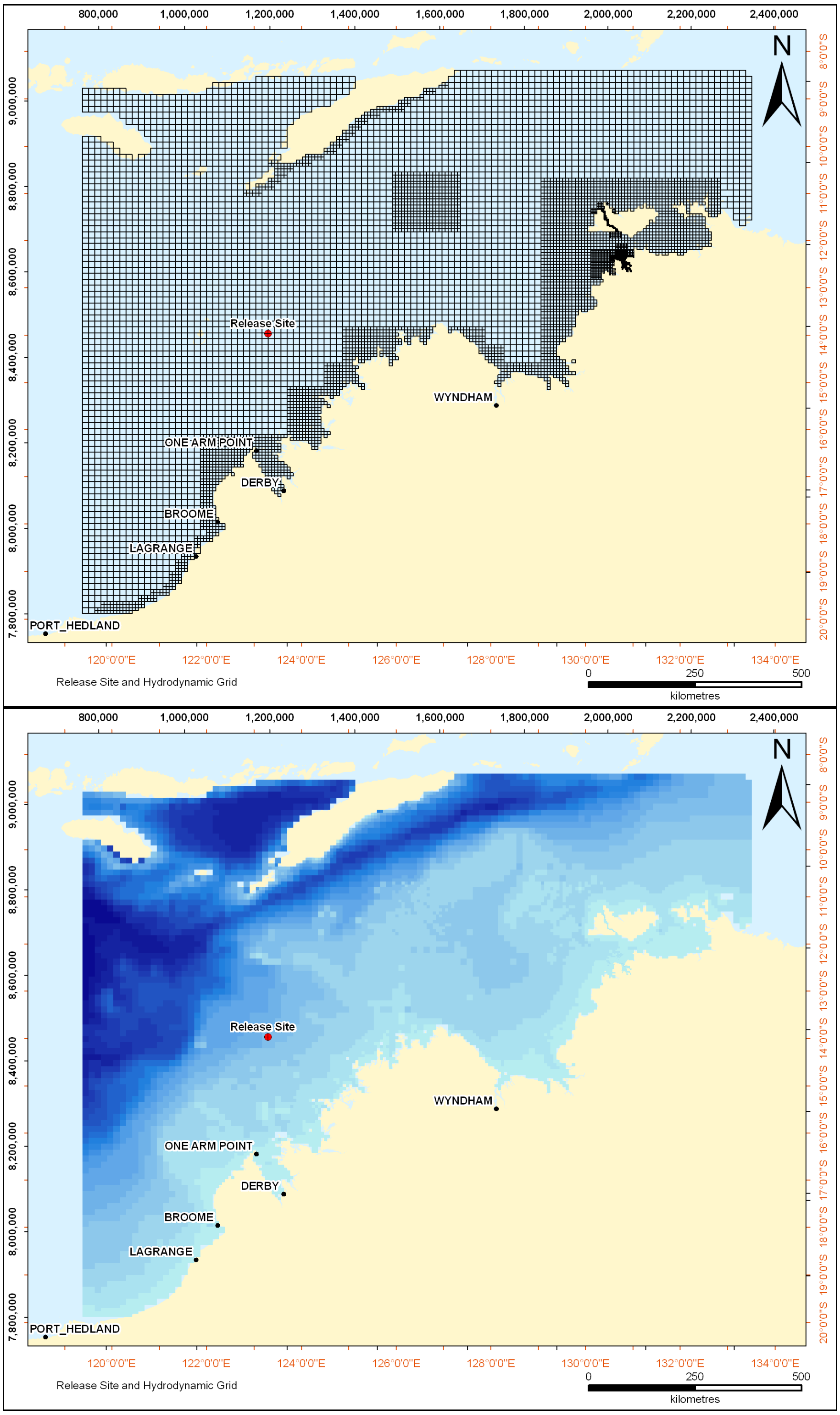


Figure 2: Extent of the used computational grid (top panel) and the model bathymetry (bottom panel)

The astronomical tides were defined at all open boundaries of the model grid, in the form of amplitude and phase records, which were extracted from latest Topex Poseidon global tidal set (TPX0 version 7.0; source: NOAA). Using the tidal data, surface heights were firstly calculated along the open boundaries, at each time step in the model, using the 8 largest and most significant tidal constituents for the area (M_2, S_2, K_1, O_1, N_2, P_1, K_2, and Q_1). The model then circulated the water mass over the entire grid and calculated the sea heights and resulting tidal currents at each cell.

2.3 Model validation

To verify that the model was accurately representing the water levels and currents within the study region, modelled data was compared against measurements collected by MetOcean Engineers at the Titanichthys site (see Figure 3) over two deployment periods (16–30 September 2004 and 16–31 January 2005). Wind data measured at that current meter mooring was used as input into the model for the validation

Time series plots of the tidal variations, shown in Figure 4, demonstrate that the model was accurately reproducing the magnitude and timing of tidal variations over each tidal variation for the two deployment periods (for 14 days each).

Figure 5 shows the comparisons between the measured currents and the HYDROMAP model results for the two periods. The scatter plots confirm that model predictions compared very well with the measured data, in terms of both current speed and direction. This confirms that the wind and tides used as input into the model were capable of replicating the currents in the study area and that the large scale currents have minimal affect at the site.

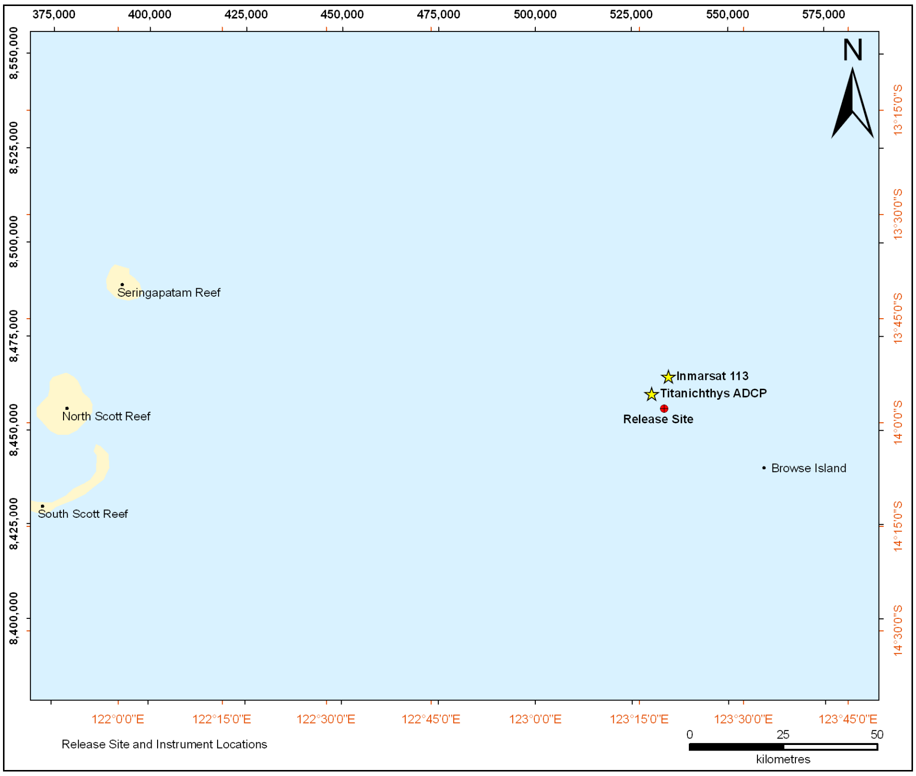
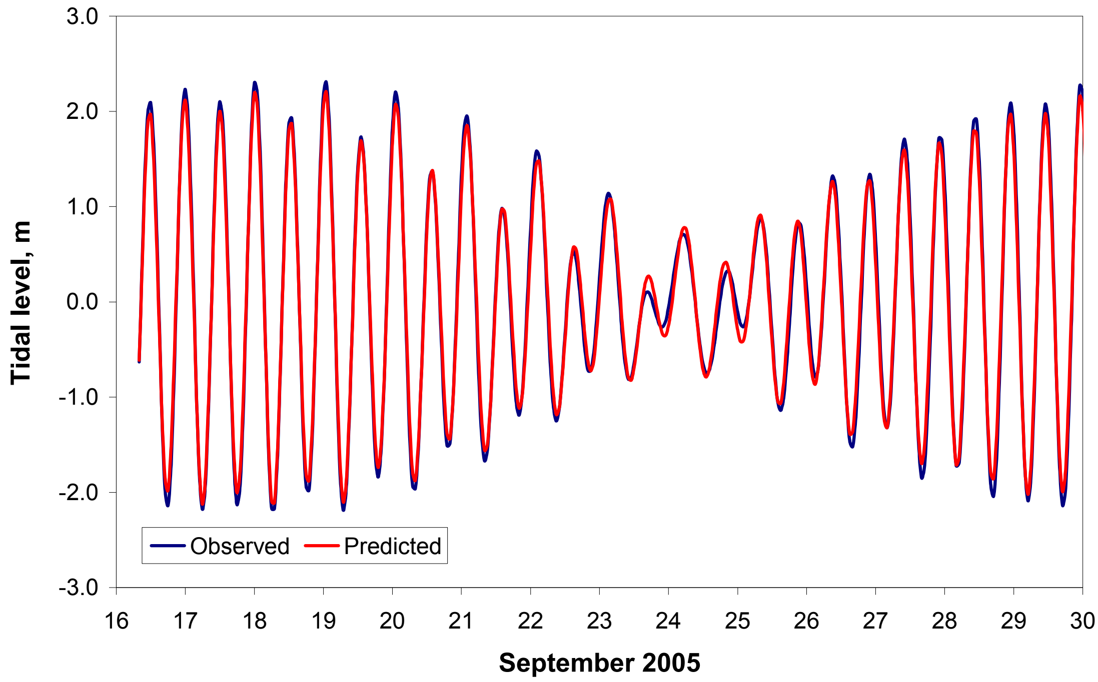


Figure 3: Locations of current measurement (Titanichthys ADCP) and wind measurement (Inmarsat 113) sites near the proposed release site



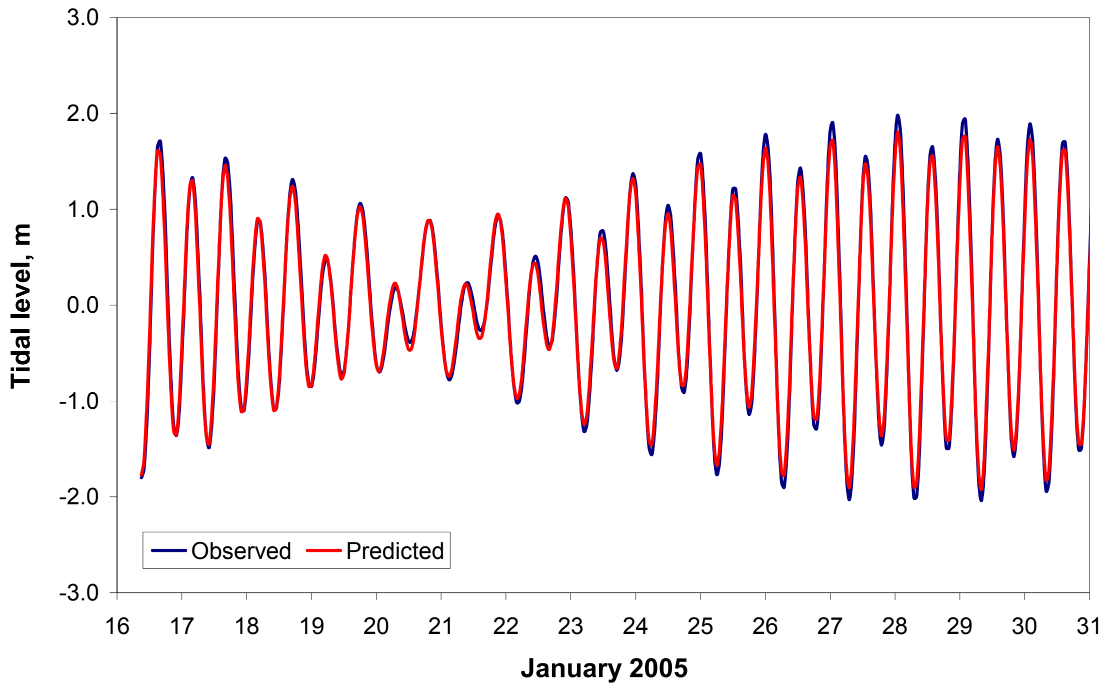


Figure 4: Comparison of the measured and predicted tidal elevations at the Titanichthys site over 16-30 September 2004 (top panel) and 16-31 January 2005 (bottom panel)

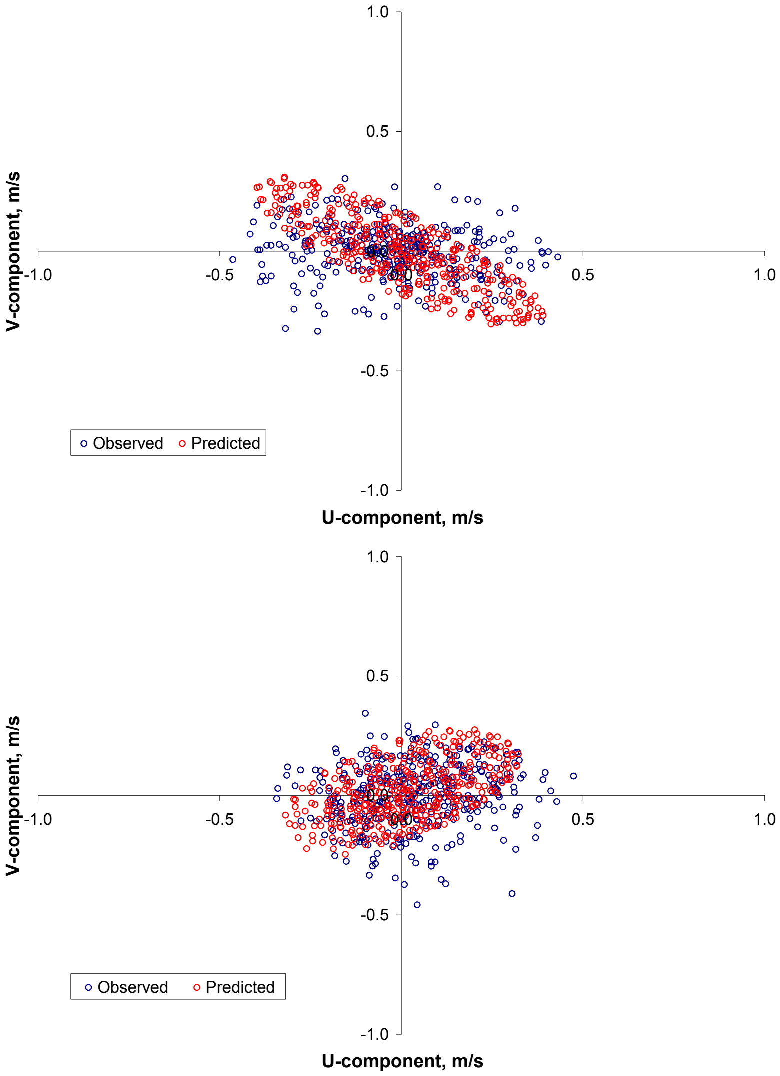


Figure 5: Comparison of the predicted and measured current speeds and directions at the Titanichthys site over 16-30 September 2004 (top panel) and 16-31 January 2005 (bottom panel)

3 CURRENT DATA

Using the model settings validated above, the three-dimensional hydrodynamic model was re-run using local historic winds (provided by the NOAA-CIRES Climate Diagnostics Center in Boulder, Colorado) and tidal conditions for summer (January 2006) and winter (June 2006), to generate current data for the assessment.

Figure 6 shows the January and June monthly wind roses summarising the distribution of wind speeds and directions according to the NCEP (National Centers for Environmental Prediction) data. Note that the atmospheric convention for defining wind direction is used to reference wind direction throughout this report (i.e. axes indicate the direction the wind blows from, e.g. an axis pointing up the page from the centre of the wind-rose designates winds from the north). Each branch of the rose represents the winds blowing from that direction, with north to the top of the diagram. Sixteen directions are used. The branches are divided into segments of different thickness, which represent wind speed ranges for each direction.

Speed intervals of 5 knots are used in these wind roses. The width of each segment within a branch is proportional to the frequency of winds within the corresponding range of speeds from that direction.

The data indicated that during January the winds were relatively strong (mean 15 knots; maximum 38 knots) and were predominantly westerly. In contrast the winds during June were mostly from the east and south-east.

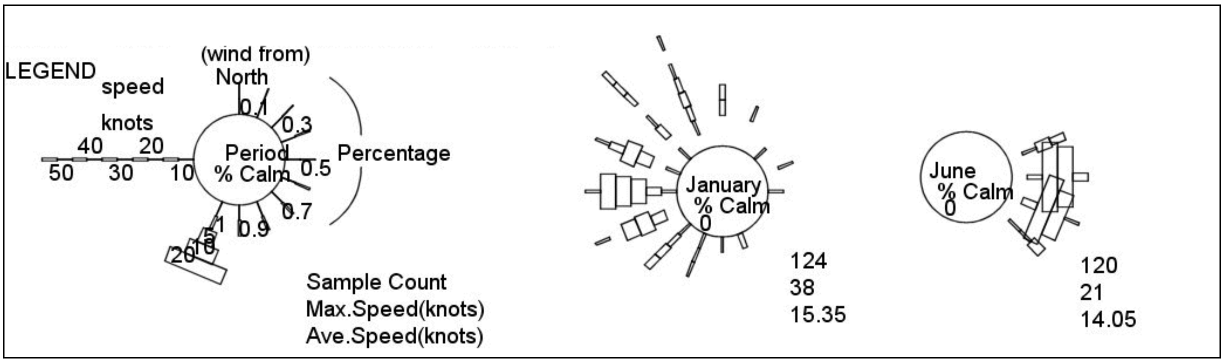


Figure 6: January 2006 and June 2006 monthly wind rose distributions and directions from the closest (~60 km) NCEP (National Centers for Environmental Prediction) station to the release site

Figure 7 shows the near surface current roses for the two months. The bottom panels show the predicted current speeds as a function of time for each month. The direction axis indicates the direction the current is heading towards.

From examination of the 30-day current roses, it follows that the wind shear had a significant influence steering the currents. During January the currents exhibit a bias towards the north and eastern sector, due to the prevailing westerly and southwest winds. The winds were stronger at times and sustained with surface current speeds reaching a maximum of 0.7 m/s. The currents for June 2006 were generally weaker, reaching a maximum of ~0.4 m/s and typically from the west and south-south-east.

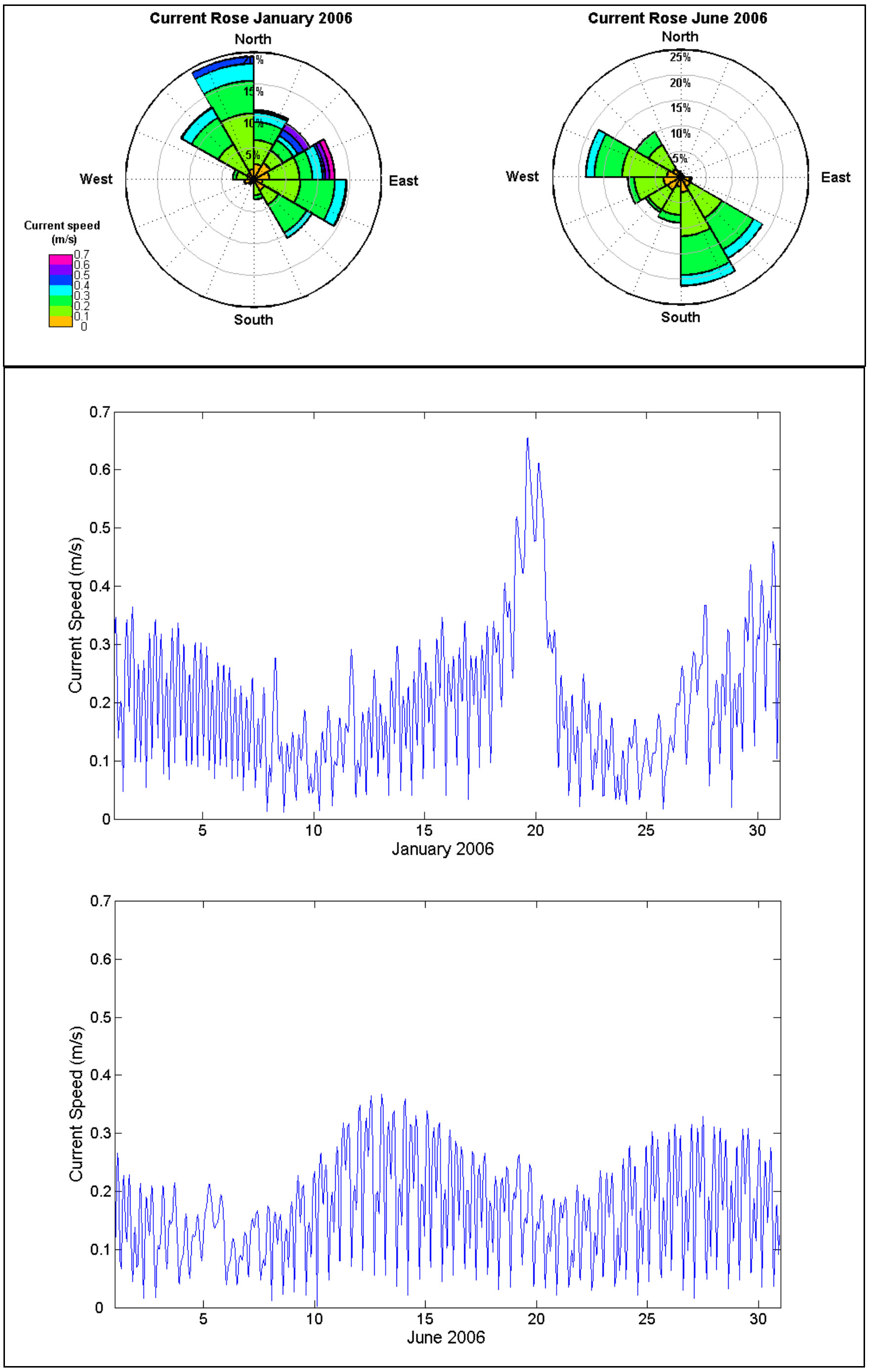


Figure 7: Current roses for near surface currents (top panel) during summer (January 2006) and winter (June 2006) seasons and corresponding current speeds as a function of time (middle and bottom panels).

4 PRODUCED WATER PROPERTIES

To cover the possible range of discharge rate and salinity of the produced water discharge, two different discharge cases were assessed, being combinations of discharge rate and salinity (the temperature was assumed to be 50 °C and oil content was assumed to be 20 mg/L for all cases):

> Scenario 1, which assumes the maximum volume of produced water from the Brewster reservoir, prior to introducing the Plover reservoir water. Almost 100% of the produced water will be condensed from the gas, with almost no formation component. This is a minimum salinity case.
>
> Scenario 2, which represents the maximum flow rate over the project life occurring around year 28, during which the produced water from the Brewster reservoir has begun to decline but the discharge from the Plover reservoir is at peak rates. Hence, this case explores a 50/50 mix of produced and condensed water. This is a maximum salinity case.

The characteristics for the two scenarios are summarised in Table 1. The treated produced water will have a temperature of 50 °C and salinity levels lower than the ambient seawater, between 1 and 12 ppt depending on the composition of the stream.

Table 1: Summary of the produced water characteristics for the two assessed cases

Input	*Scenario 1 (Year 17)*	*Scenario 2 (Year 28)*
Flow rate of whole produced water stream (Continuous)	2000 m^3/day	5000 m^3/day
Relative amounts of formation water and condensed water in the discharge	0% formation water 100% condensed	50% formation water 50% condensed.
Salinity of produced water plume	1 ppt	12 ppt
Temperature of produced water plume	50 °C	50 °C
Oil content	20 mg/L	20 mg/L

The criteria, which should be considered when studying the discharged produced water, are as follows.

<u>Temperature</u>

The World Bank environmental standards state that the effluent should result in a less than 3 °C temperature increase within 100 m from the release site. To meet this in general terms a dilution of up to 7 would be required for the range of temperature discharges considered in this study.

According to ANZECC (2000), Section 3.3.2.4, “for stressors that cause problems at both high and low values (e.g. *temperature*, salinity, pH), the desired range for the *median* concentration is defined by the 20th percentile and 80th percentile of the reference distribution.

By applying this guideline the ambient surface temperature (see Section 5.2), the percentile range was between 26.8 °C (20th percentile of winter and summer moths average temperatures) and 29.6 °C (80th percentile of winter and summer moths average temperatures) with the median of 28.6 °C. Therefore the median temperature increase outside of the agreed mixing zone would need to be less than approximately 1 °C during the year. For a 50 °C discharge during winter, this would require a dilution of greater than 22.

Ecotoxicity testing

INPEX commissioned WET (Whole Effluent Toxiticy) testing, which involved ecotoxicological tests on the weathered Gorgonichthys-1 and Titanichthys-1 condensate samples. This method represents a possible toxicity value of the produced water prior to discharge into the marine environment. The benefit of such a testing practice is that it directly relates to the effluent stream that is being discharged and takes into consideration the condensate hydrocarbons (oils) likely to be present within the produced water.

Each sample was mixed and weathered to assess impacts using a variety of marine species (Geotechnical Services 2007). Results of 1 hour EC50 (Effect Concentration to 50% of the population), EC10, NOEC (No Observed Effect Concentration) and LOEC (Lowest Observed Effect Concentration) have been expressed as dilution percentages in Table 2.

The trigger value of 0.63% was set to represent the lowest dilution affecting the analysed species. Thus, based on an initial oil concentration of 20 mg/L, the dilution threshold was set to 1:158 (1/0.0063) or 0.126 mg/L (20/158) as a concentration. The lowest value was selected on the basis that it would provide a conservative estimate of the mixing zone required.

Table 2: Summary of ecotoxicity tests of weathered condensate, expressed as dilution (%) required.

Test	*EC/IC50 (%)*	*EC/IC10 (%)*	*LOEC (%)*	*NOEC (%)*
72 hour algal	>83.3	>83.3	>83.3	>83.3
72 hour macroalgal	>100	>100	>100	>100
48 hour oyster	32	24.3	50	25
21 day copepod reproduction *2 day pulse*	43	9.8	45.5	22.7
7 day larval fish growth	14.7	10.1	1.25	0.63

Source: Geotechnical Services 2007.

Produced water discharges also contain a mixture of other hydrocarbons, production chemicals and formation water in addition to condensate. The concentrations vary depending on the field and production systems employed.

There are relatively few studies that consider the chronic toxic effects of produced water. Black et al. (1994) cite a study by Girling (1989) in which the adverse chronic toxicity effects were observed for *Acartia tonsa* (a copepod) at concentrations equivalent to between 0.5 and 7% produced water. Mesocosm studies have demonstrated marked reduction in copepod populations after chronic exposure to concentrations equivalent to about 0.02 to 0.05% produced water (Davies et al. 1981). Using these estimates of chronic toxicity thresholds provides a range of 0.02% (1:5000 dilution) to 7% (1:14 dilution) produced water exposure over a period of weeks to months as the dosage required to elicit a chronic toxicity response. The lowest reported LC_{50} acute toxicity for produced water (i.e. the most toxic response) occurred at 8000 ppm (equivalent to dilution of 125 times) (Black et al. 1994).

Following these findings, the lowest reported dilutions for acute toxicity of 1:158 and chronic toxicity of 1:5000 have been selected on the basis that they provide a conservative estimate for the mixing zones.

5 NEAR FIELD MODELLING

5.1 Model Description

The near-field mixing of the discharged produced water was predicted using the fully three-dimensional flow model, Updated Merge (UM3) model. UM3 is a plume model for simulating single and multi-port submerged discharges, available in the US Environmental Protection Agency interface Visual Plumes (VP) (Frick et al. 2000). The UM3 model was selected since it has been extensively tested for various discharges and found to predict the observed dilutions more accurately (Roberts and Tian, 2004) than other near field models (e.g. RSB or CORMIX).

In this Lagrangian model, the equations for conservation of mass, momentum, and energy are solved at each time step, giving the dilution along the plume trajectory. To determine the growth of each element, UM3 uses the shear (or Taylor) entrainment hypothesis and the projected-area-entrainment hypothesis. The flows begin as round buoyant jets issuing from one side of the diffuser and can merge to a plane buoyant jet (Carvalho *et al*. 2001). Model output consists of plume characteristics, including centerline dilution, rise-rate, width, centreline height and diameter of the plume. Dilution is reported as the "effective dilution", which is the ratio of the initial concentration to the concentration of the plume at a given point, following Baumgartner *et al.* (1994). The model includes corrections for a reduction in surface area that is available for mixing that occurs with merging plumes, created by discharge through multiple adjacent ports.

5.2 Ambient Environmental Conditions

The near-field modelling requires specification of typical ambient environmental conditions, including vertical density structure and background currents. The vertical density structure is defining for plume behaviour due to the importance of the relative (to the ambient waters) buoyancy of the diluting plume. The buoyancy dynamics in this case will be dominated by the temperature and salinity differences between the discharge and receiving waters.

The temperature structure at the site varies seasonally. A seasonal parameterisation was made using the monthly median temperatures at different depths. The data was taken from the ocean temperature climatology and ocean salinity climatology of the region provided by the *World Ocean Atlas 2001*. The *World Ocean Atlas 2001* provides statistical data and analysed field data for one-degree and five-degree (latitude/longitude) squares generated from the *World Ocean Database 2001*. The data point closest to the FPSO was selected for the analysis. Figure 8 shows the summer and winter monthly average temperature profiles for the study region.

The sea surface temperature during summer is approximately 29-30 °C and 26-28 °C during winter. The temperature profiles exhibit only minor thermal stratification during the summer months. During winter the thermal stratification is completely eroded and the water column is thermally uniform 20 m below the water surface.

Monthly average salinity profiles are plotted in Figure 9. The salinity levels were more consistent between the seasons (34.4 to 35.1 ppt) and exhibit a vertically well mixed water body. Table 3 is a summary of the seasonal temperature structure at the proposed release site for summer and winter conditions.

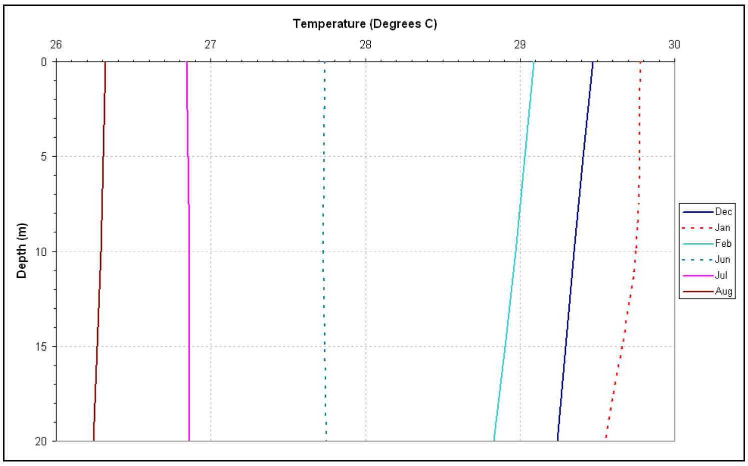


Figure 8: Monthly average temperature profiles for the study region. Coloured dashed lines depict the adopted temperature profiles for summer and winter conditions

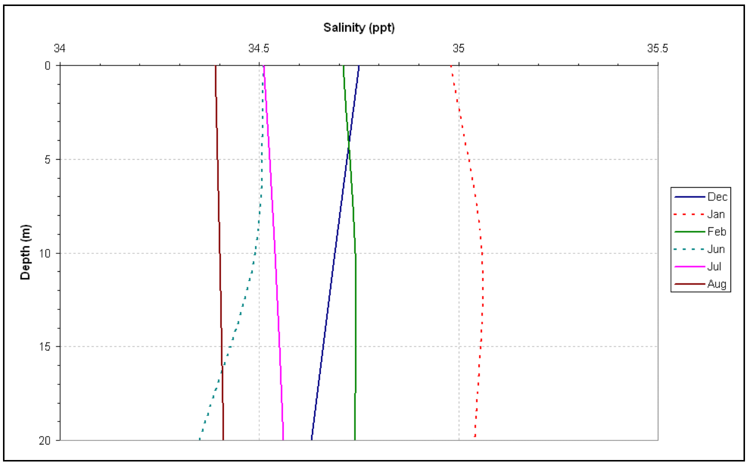


Figure 9: Monthly average salinity profiles for the study region. Coloured dashed lines depict the adopted temperature profiles for summer and winter conditions

Table 3: Seasonal temperature structure at the proposed release site for summer and winter conditions.

Depth (m)	*Summer (January)*		*Winter (June)*	
	Temperature (°C)	*Salinity (ppt)*	*Temperature (°C)*	*Salinity (ppt)*
0	29.78	34.98	27.74	34.51
10	29.75	35.06	27.73	34.49
20	29.55	35.10	27.75	34.35

Based on these considerations, January and June were selected to represent above average summer and extreme winter temperature and salinity conditions respectively.

Ambient currents were assessed seasonally through the upper portion of the water column (where the plume was expected to be located) from the previously developed current dataset.

Table 4 presents the 5th, 50th and 95th percentiles of current velocities. The 5th percentile of current velocity of ~0.05 m/s was extracted to gain an understanding of the minimum current speed that would occur 95% of the time (US EPA 2006). The 95th percentile current is predicted to be exceeded only 5% of the time. Note that the summer and winter current conditions are comparable, however the difference in the temperature structure is likely to result in varied dilution performance.

These conditions reflect two contrasting cases:

1. 5th percentile current velocity: slow currents, low dilution and slow advection
2. 95th percentile current velocity: fast currents, high dilution and rapid advection to nearby areas.

Table 4: Ambient summer and winter current conditions

Parameter	*Summer (m/s)*	*Winter (m/s)*
5th percentile	0.054	0.048
50th percentile	0.186	0.164
95th percentile	0.422	0.305
Maximum	0.655	0.368

5.3 Discharge Pipe Configuration

The discharge of wastewater is proposed to occur through a single outlet 1 m (internal diameter) through the hull of the FPSO, which would be approximately 15 m below the water surface (Table 5).

Table 5: Summary of the discharge pipe configuration

Outlet pipe diameter (m)	1 m
Pipe orientation (°)	90 (vertically downwards)
Depth of pipe below sea surface (m)	15

5.4 Near field modelling results

The near-field modelling revealed that the plume would initially plunge downward creating a turbulent mixing zone within 1 m below the discharge pipe (approximately 16 m below MSL). After the initial plunge, the plume loses momentum and remains sufficiently buoyant to rise to the surface. As the plume rose through the water column, the model predicted that it would continue to mix with ambient waters, though at a slower rate.

The results from the UM3 near-field model were interrogated to provide predictions of the initial plume parameters for input into the far field model, and to also provide estimates of the decay of temperature and dilution of oil in the plume. A summary of the results for the two release rates and seasons are shown in Table 6 and Table 7.

Due to the turbulent mixing caused by the initial plunge and buoyant rise, the salinity and temperature of the plume were predicted to return to within background upon hitting the surface and within 10 m in the horizontal from the pipe irrespective of the ambient conditions and flow rates (see Table 6 and Table 7).

Modelling did reveal that the increase in flow halved the dilution performance during weak currents. The change in the rate of dilution was even more evident during average and static current speeds. This phenomenon can be seen more clearly in Figure 10 and Figure 11, which show the rate of dilution as a function of current speed and flow rate for summer and winter conditions, respectively. This would be attributed to the ability of the current to mix the plume laterally with the receiving waters and the volume of ambient water intersecting the plume as it rises.

For both scenarios and seasons examined the primary factor influencing the dilution, was the speed of the current. The weak current had little effect on the plume during the rise process and it reached the surface quickly, slowing the rate of dilution. The strong current was capable of pushing the buoyant plume horizontally, allowing for additional mixing prior to reaching the surface. The distance to the end of the near-field phase are given in the last column of each of the results tables.

Table 6: Summary of the near field modelling results for the proposed release rates and summer static current speeds

Flow Rate (m^3/day)	*Current Speed (m/s)*	*Plume Diameter*	*Final salinity (ppt)*	*Final Temp (°C)*	*Dilution*	*Maximum Horizontal Distance (m)*
2000	0.054	4.6	34.7	29.9	121.4	5
	0.186	11.0	34.9	29.8	772.7	28
	0.422	11.8	35.0	29.8	1926.4	88
5000	0.054	4.3	34.6	30.1	55.54	4
	0.186	8.1	34.9	29.9	176.9	15
	0.422	10.4	34.9	29.8	597.6	53

Table 7: Summary of the near field modelling results for the proposed release rates and winter static current speeds

Flow Rate (m^3/day)	*Current Speed (m/s)*	*Plume Diameter*	*Final salinity (ppt)*	*Final Temp (°C)*	*Dilution*	*Maximum Horizontal Distance (m)*
2000	0.048	4.4	34.1	26.5	114.4	5
	0.164	10.4	34.3	26.4	607.8	22
	0.305	11.8	34.4	26.3	1513.2	62
5000	0.048	4.2	34.0	26.7	54.44	4
	0.164	9.3	34.3	26.4	209.1	16
	0.305	8.6	34.3	26.4	322	29

Hence, for 95% of the time the near-field results can be summarised as follows:

- Scenario 1 summer - will have > 121 times dilution within a 5 m horizontal distance from the release site.
- Scenario 2 summer - will have > 55 times dilution within a 5 m horizontal distance from the release site.

- Scenario 1 winter - will have > 114 times dilution within a 5 m horizontal distance from the release site.
- Scenario 2 winter - will have > 54 times dilution within a 5 m horizontal distance from the release site.

Even though the level of dilution for Scenario 1 was only slightly lower than required (1:158), it was foreseen necessary to employ far-field modelling for both scenarios and seasons.

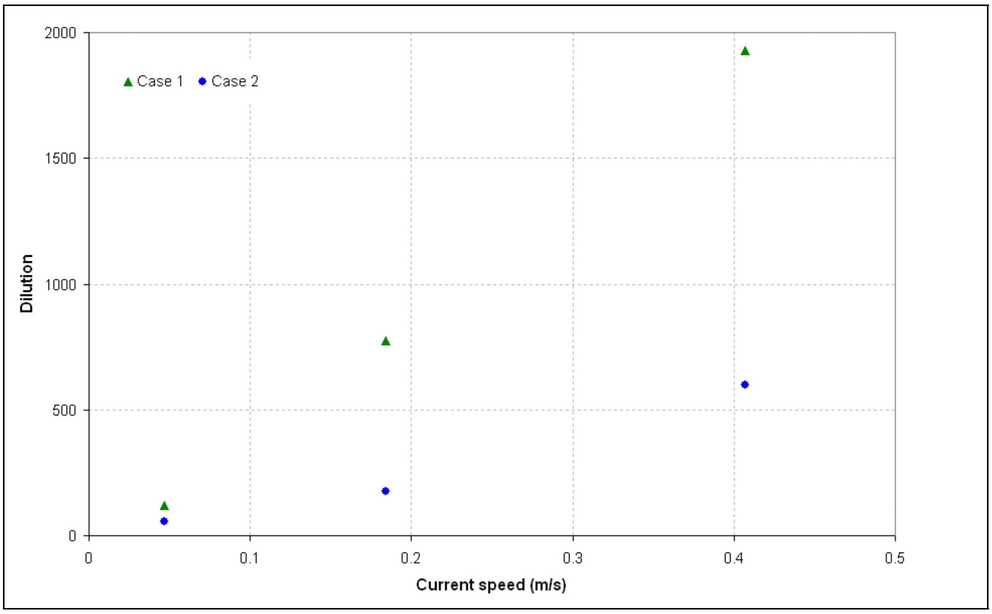


Figure 10: Near-field dilution results for Scenario 1 (2000 m^3/day) and Scenario 2 (5000 m^3/day) as a function of summer static current speeds

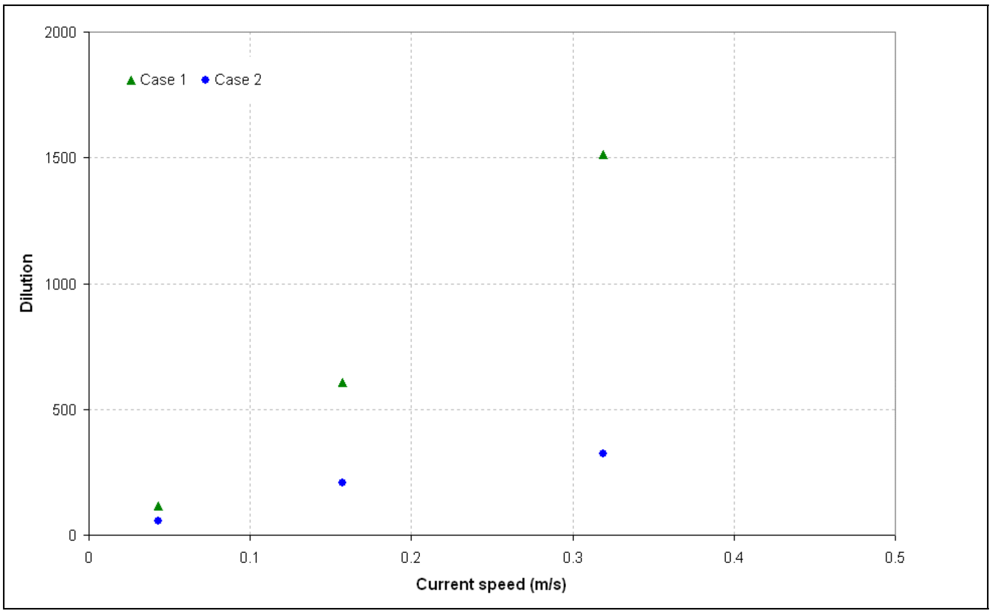


Figure 11: Near-field dilution results for (2000 m^3/day) and Scenario 2 (5000 m^3/day) as a function of winter static current speeds

6 FAR-FIELD MODELLING

6.1 Background

To quantify the likely far-field mixing and dispersion of the oil within the produced water, detailed modelling was carried out using an advanced three-dimensional plume behaviour model, MUDMAP. MUDMAP simulated the wastewater discharge as a conservative tracer (no reaction or decay applied) into a time-varying current field with the initial dilution set by the near-field modelling described in Section 5. The main objective of the far-field modelling was to predict the extent and shape of the mixing zones to meet the required dilution level under summer (January) and winter (June) current conditions.

The far-field modelling augments the near-field work by allowing the time-varying nature of currents to be included, together with the potential for recirculation of the plume back to the discharge location. In the latter case near-field concentrations can be increased due to the discharge plume mixing with the remnant plume from an earlier time.

6.2 Model Description

The three-dimensional plume behaviour model, MUDMAP, was used to simulate the wastewater mixing and dispersion. MUDMAP is an industry standard computerised modelling system, which has been applied throughout the world to predict the dispersion of sediment (cuttings and muds) and liquid (produced water) discharges since 1994 (Spaulding, 1994). The model is a development of the Offshore Operators Committee (OOC) model and like the OOC model calculates the fates of discharges through three known distinct integrated stages (Koh and Chang, 1973; Khondaker 1999). The stages are:

Stage 1: **Convective descent/jet stage** – The first stage determines the initial dilution and spreading of the material in the immediate vicinity of the release location. This is calculated from the discharge velocity, momentum, entrainment and drag forces

Stage 2: **Dynamic collapse stage** – The second stage determines the spread and dilution of the released material as it either hits the sea surface or sea bottom or becomes trapped by a strong density gradient in the water column. Advection, density differences and density gradients drive the transport of the plume; and

Stage 3: **Dispersion stage** – In the final stage the model predicts the transport and dispersion of the discharged material by the local currents. Dispersion of the discharged material will be enhanced with increased current speeds and water depth and with greater variation in current direction over time and space.

Including these 3 stages as part of the predictions is necessary as the material will go through these distinct phases over different time and distance scales. The governing equations and solution methodology in MUDMAP build on the formulation originally developed by Koh and Chang (1973) and extended by the work of Brandsma and Sauer (1983). The far-field calculation (passive dispersion stage), employs a particle-based, random walk procedure.

The system has been extensively validated and applied for discharge operations in Australian waters (e.g. Burns *et. al.*, 1999; King and McAllister, 1998, 1997).

The model predicts the dynamics of the discharge plume and resulting concentrations and plume thickness over the near field (i.e. the immediate area of the discharge) and far-field (the wider region). The discharged material is represented by a large sample of Lagrangian particles. These particles are moved in three-dimensions over each subsequent time step according to the current data and horizontal and vertical mixing coefficients.

6.3 Discharge Input Data

The detailed input data used in the discharge model setup included:

- The relative temperatures, salinities and densities of the discharge and receiving waters;
- The rate of discharge of the wastewater;
- The size and orientation of the discharge pipe;
- The velocity of the discharge jet;
- The height of the discharge point relative to mean sea level; and
- Current data to represent local physical forcing.

Table 8 presents a summary of the far-field model parameters used to simulate the produced water discharges during the two seasons.

Based on the near-field modelling results, a minimum dilution of 1:100 at a distance of 5 m was used to account for the jet plume and buoyancy dynamics adjacent to the release site for Scenario 1 and 1:55 for Scenario 2. This involved releasing the plume within the near surface waters (~1 m) and selecting appropriate mixing coefficients, which is described below.

Table 8: Summary of the MUDMAP model to simulate the produced water discharges at the FPSO

Number of Months Simulated	2 (January and June)
Discharge Rate	A (2000 m^3/day); B (5000 m^3/day)
Period of discharge	30 days
Period of Discharge	Continuous
Discharge Water Temperature.	50 $^{\circ}$C
Discharge Water Salinity	1 ppt; 12 ppt

6.4 MUDMAP Mixing Parameters

The horizontal and vertical dispersion coefficients represent the mixing and diffusion caused by turbulence, both of which are sub-grid processes on the scales of hydrodynamic modelling. Both of these coefficients are expressed in units of rate of area change m^2/s. Increasing the horizontal dispersion coefficient will increase the horizontal spread of the discharge plume and decrease the centreline concentrations. Increasing the vertical dispersion coefficient spreads the discharge across the vertical layers.

Spatially constant, conservative horizontal and vertical dispersion coefficients of 1.5 m^2/s and 0.0005 m^2/s were used to control the exchange of the wastewater in the horizontal and vertical directions respectively. Each of the mixing parameters was selected following an extensive sensitivity testing to recreate plume characteristics, which were reported in the near-field modelling section.

6.5 MUDMAP Grid Configuration

MUDMAP uses a three-dimensional grid to represent the water depth and bathymetric profiles of the study area. Due to the rapid mixing and small-scale affect of the discharge, it was necessary to use a very fine grid with a resolution of 5 m by 5 m to track the movement and fate of the plume. The extent of the grid region measured approximately 5 km (longitude or x-axis) and 5 km (latitude or y-axis). It is also important to note, that the 5 m grid cell sizes were selected following extensive sensitivity testing so as to achieve similar dilution rates as calculated by the near-field modelling.

6.6 Far-Field Modelling results

Far-field modelling results indicated that due to the buoyant nature of the produced water plume, it would remain in the surface layer (top 2 metres), while the near-surface currents would affect overall transport.

The plume was predicted to oscillate and change direction with each flood and ebb tide event. On the ebb tide, the plume was pulled in a south-easterly direction, momentarily paused and then forced towards the northwest during the flood tide. As a result of the change in directions and current velocities, the concentrations would be variable over time. Lower concentrations (higher dilution rates) were occurring during stronger currents, whereas patches of higher concentrations (lower dilution rates) tended to build up at the turn of the tide or weaker current events. The higher concentration patches would move as a unified group as the current speeds increased again and tended to be present within the wider plume at any one time. These findings are in agreement with the research of King and McAllister (1997, 1998) who also noted that concentrations of oil within produced water plumes generated by Harriet Alpha platform were patchy and peak around the turn of the tides.

Figure 12 shows a sample series of the plume movements causing a build up in concentration during a January 2006 period. This patch of higher concentration would then be advected away from the release site as current speeds increase.

Figure 13 shows a sample series graph of the predicted oil concentrations within the release site cell. The graph in the top panel highlights that the concentrations (within 5 m of the discharge) would vary over time with the tidal cycle and episodes of stronger and weaker currents. This is emphasized by the graph in the bottom panel, which shows the predicted surface currents for the corresponding period.

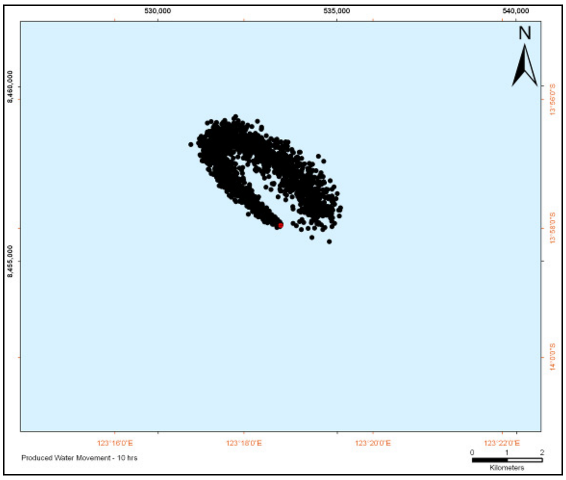
To define the field of effect for each scenario and season dilution contours were calculated from the 30-day simulations and summarised in Figure 14 and Figure 15. Table 9 shows the predicted area of coverage and maximum distance from the release site for each dilution zone of effect.

The area of coverage below the dilution requirement of 1:158 was 0.0058 km^2 during summer compared to 0.0061 km^2 for winter from a 5000 m^3/day flow rate. The 1:158 contour was within 60 m from the release site for both seasons. The area of coverage below the dilution requirement of 1:158 for the 2000 m^3/day flow rate was less than 0.000025 km^2 (25 m^2).

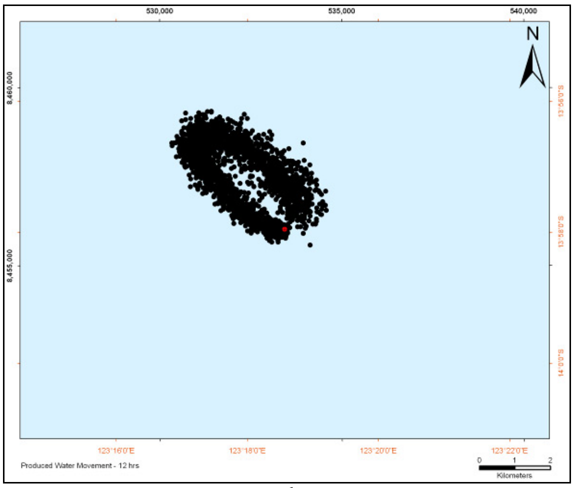
The extent of the 1:5000 dilution contour was found to be sensitive to the rate of discharge. The results had shown that the contour was approximately 1.1 km from the release site for the 2000 m^3/day flow rate and about 3.6 km for the 5000 m^3/day. The field of effect from a 5000 m^3/day discharge during summer conditions was 9.29 km^2 compared to 6.62 km^2 under winter currents.

Figure 16 is a composite of the seasonal results, for the two examined flow rates. In general the area of coverage and maximum distance for the 1:158 dilution remained the same.

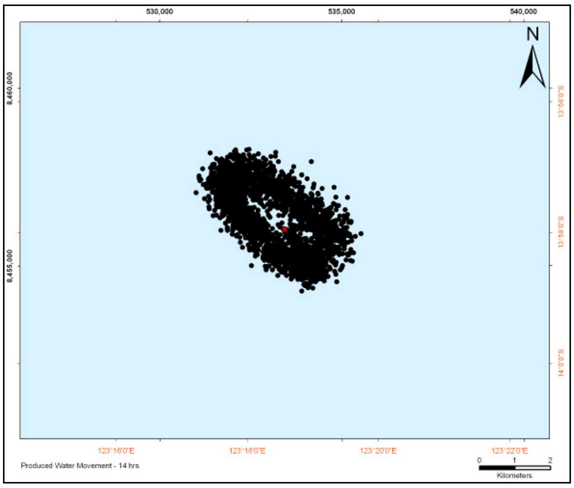
(a) 12:00 pm 2nd January 2006



(b) 2:00 pm 2nd January 2006



(c) 4:00 pm 2nd January 2006



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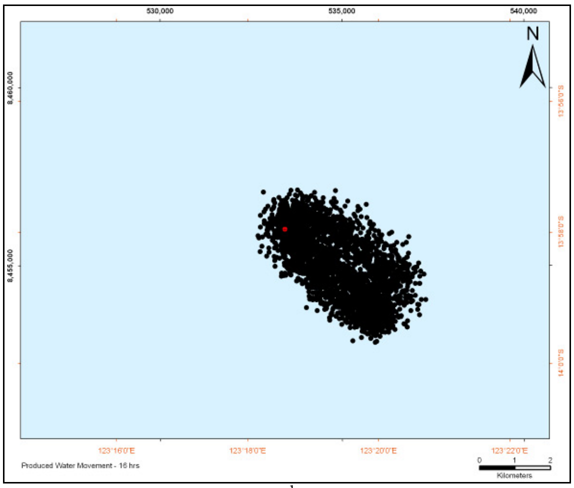
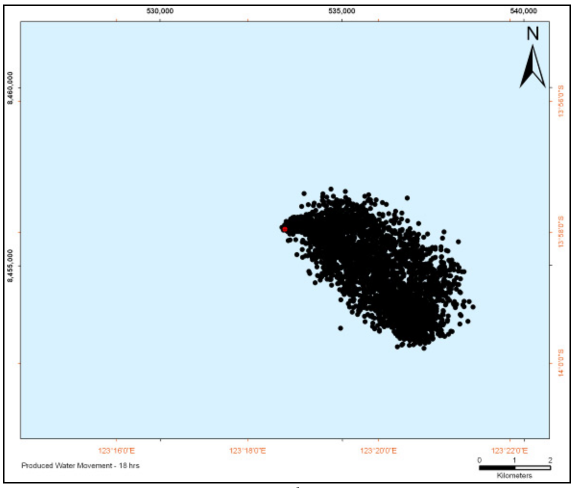


(e) 8:00 pm 2nd January 2006



(f) 10:00 pm 2nd January 2006

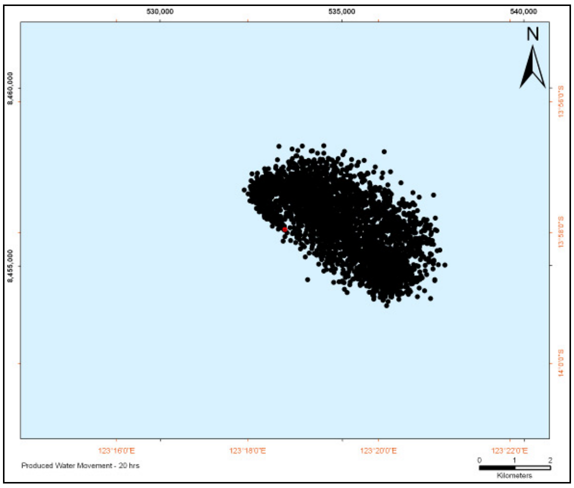


Figure 12: A 10-hour time-series of the particle movement, during sample January 2006 current conditions

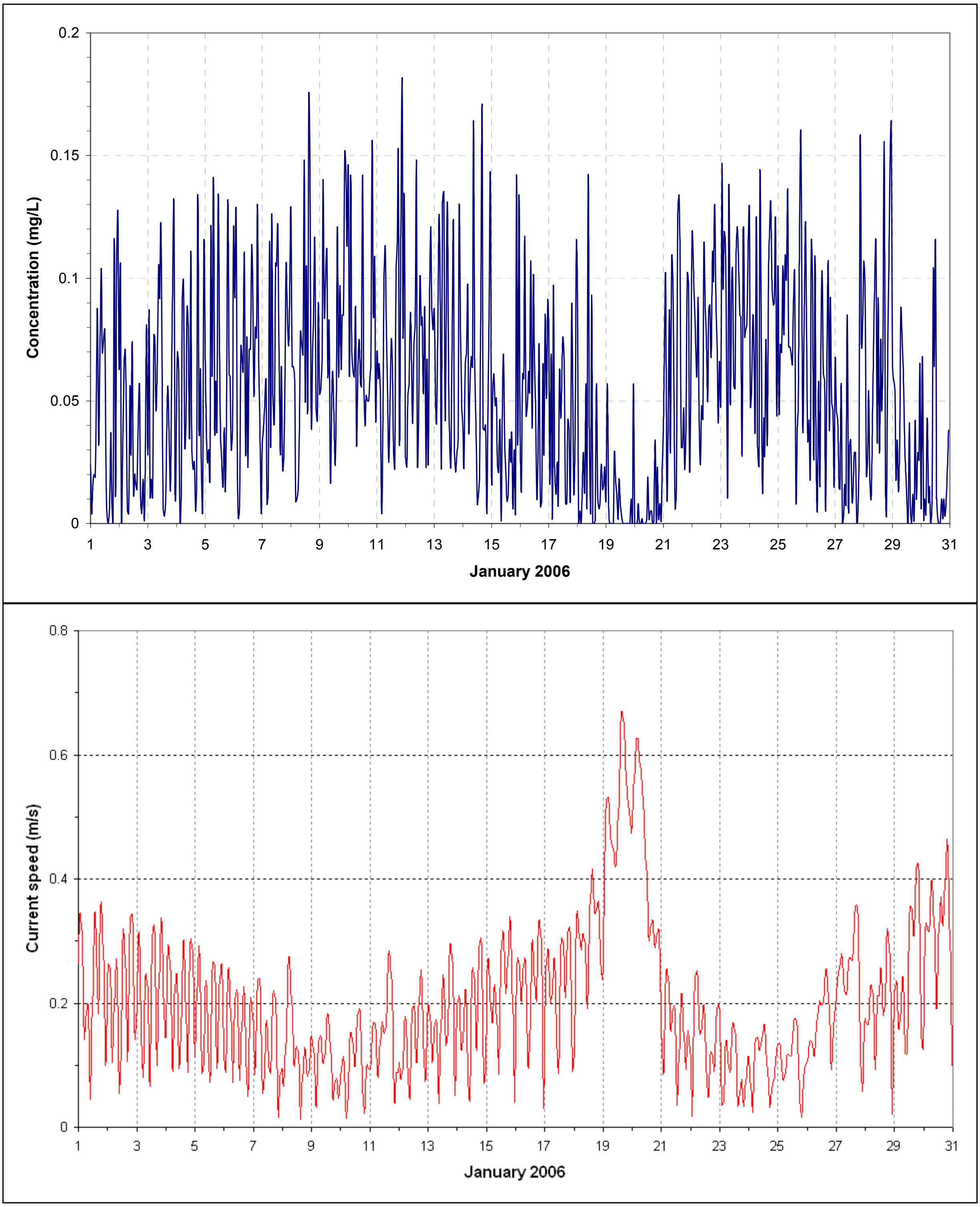


Figure 13: Time series graph (top panel) of the predicted maximum oil concentrations (5000 m^3/day discharge with 20 mg/L initial concentration) at the proposed outfall location and corresponding surface current speeds for January 2006 (bottom panel)

Table 9: Predicted area of coverage and maximum distance from the release site for the defined dilution for each season and flow rate

Dilution	*Area (km^2)*				*Maximum Distance (km)*			
	January Case 1	*January Case 2*	*June Case 1*	*June Case 2*	*January Case 1*	*January Case 2*	*June Case 1*	*June Case 2*
1:125	<0	0.0031	<0	0.0031	<0	0.045	<0	0.050
1:158	<0	0.0027	<0	0.0030	<0	0.060	<0	0.060
1:300	0.0026	0.0155	0.0025	0.0134	0.040	0.120	0.045	0.110
1:500	0.0069	0.0454	0.0074	0.0395	0.085	0.235	0.085	0.230
1:5000	1.2329	9.2278	0.9384	6.5645	1.100	3.100	1.100	3.600

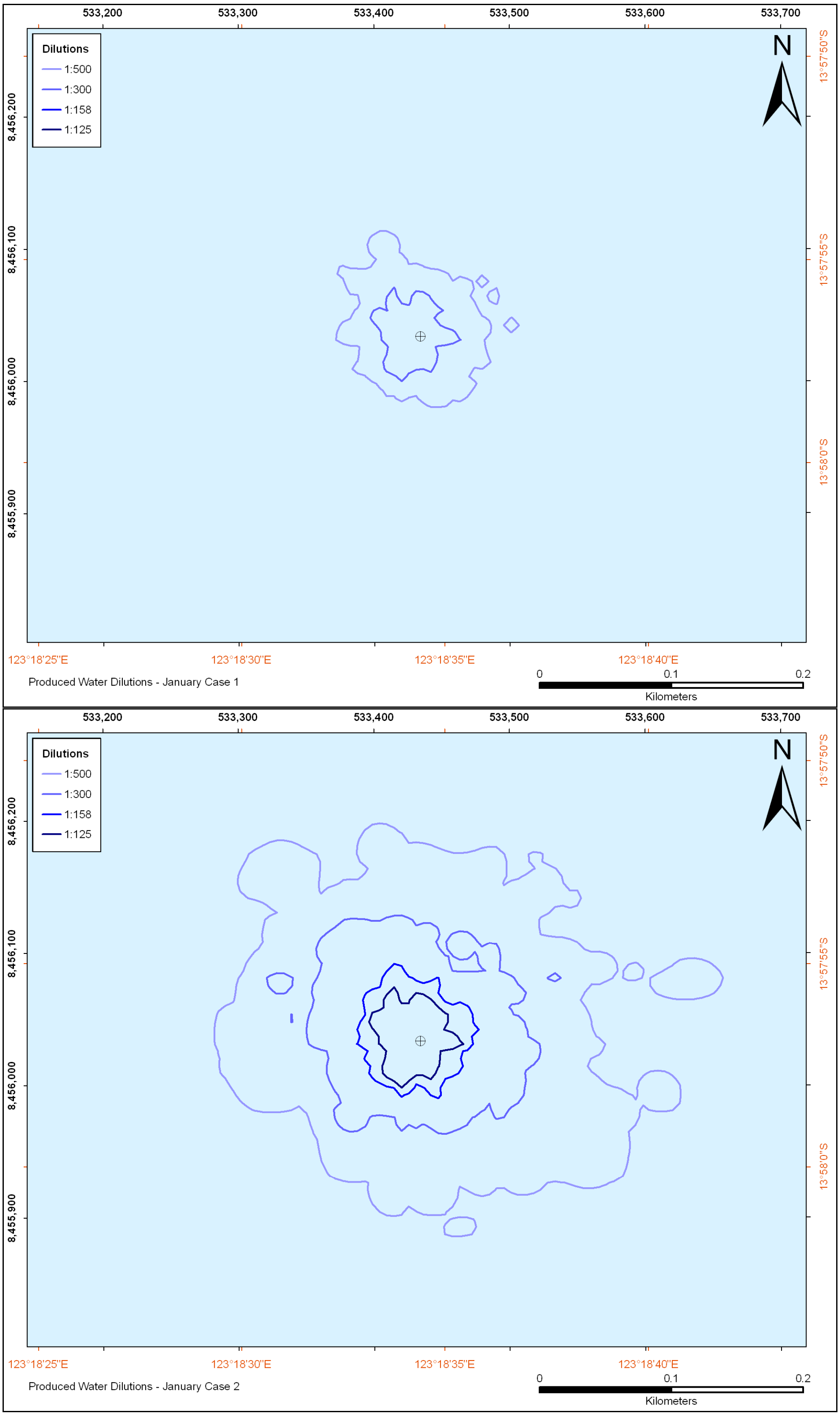


Figure 14: Predicted extent of the dilution zones, based on the maximum value occurrences at each cell, for the 2000 m^3/day (top panel) and 5000 m^3/day (bottom panel) discharges, under sample summer (January 2006) current conditions

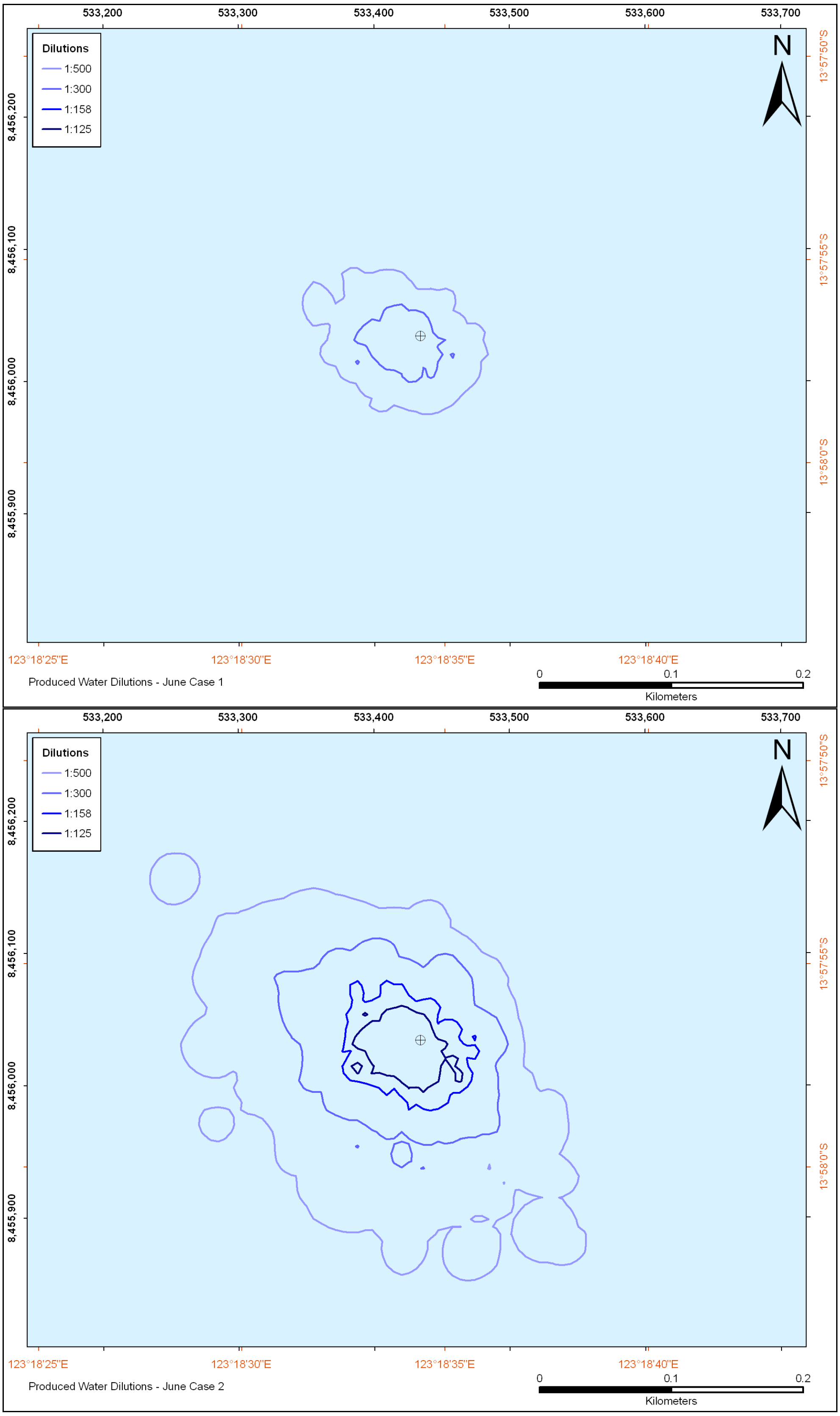


Figure 15: Predicted extent of the dilution zones, based on the maximum value occurrences at each cell, for the 2000 m3/day (top panel) and 5000 m3/day (bottom panel) discharges, under sample winter (June 2006) current conditions

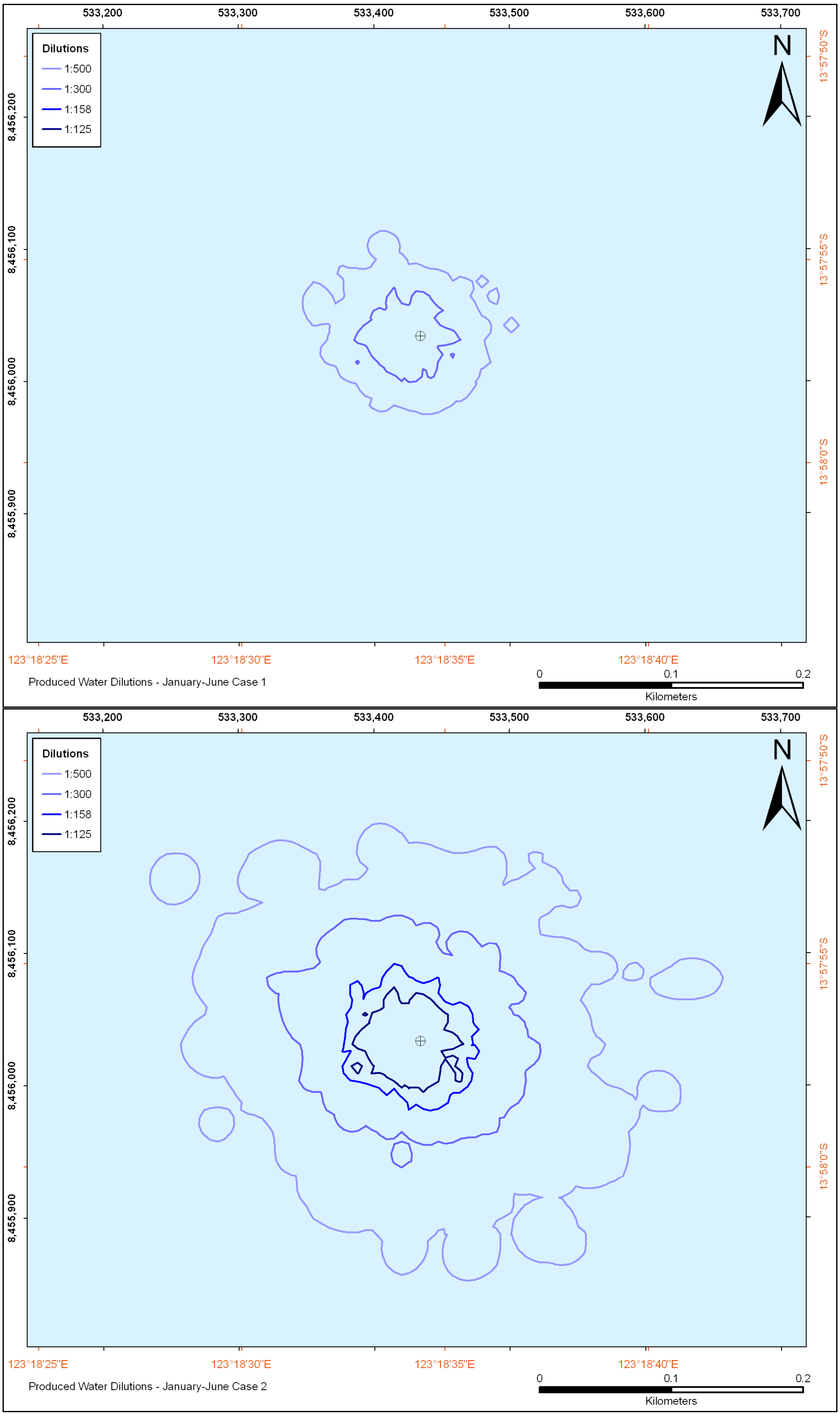


Figure 16: Predicted extent of the dilution zones, based on the maximum value occurrences at each cell, for the 2000 m3/day (top panel) and 5000 m3/day (bottom panel) discharges, under combined summer (January) and winter (June 2006) current conditions

7 CONCLUSIONS AND RECOMMENDATIONS

A dispersion modelling study was carried out to simulate the discharge of produced water streams as part of the Ichthys project. Two flow rates were assessed, 2000 m^3/day and 5000 m^3/day, indicative of the project life and seasons (summer and winter) were analysed. The main objectives were to estimate:

- The distance from the release site at which the effluent temperature and oil content comply with the selected environmental criteria
- The size of the active mixing zone for the oil.

The near-field modelling showed that the mixing zone requirements for temperature (< 3 °C increase) would be met within 10 m of the release site under a wide range of static current conditions. However, the desired dilution for the oil was not met in the near-field for either scenario. Therefore, far-field modelling was carried out for both scenarios and two seasons to define the extent of the mixing zone.

Based on the dilution requirement of 1:158, defined through ecotoxicity testing, the area of coverage was 0.0058 km^2 during summer compared to 0.0061 km^2 for winter from a 5000 m^3/day flow rate. The maximum distance from the release site was 60 m. The area of coverage below the dilution requirement of 1:158 for the 2000 m^3/day flow rate was less than 0.000025 km^2 (25 m^2).

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