5.1 Water Quality

The water quality objectives (WQOs) for the treated water discharge have been developed from ANZECC (2000) guidelines, from ambient seawater concentrations, and in one instance (manganese) from specific research.

The fundamental principle of the approach in selecting the WQOs is that the process involves an appreciation of the potential risks that these concentrations present to the marine environment including the broader marine ecosystem and in most circumstances includes an appreciation of the risk of bioaccumulation.

The Queensland EPA considers the proposed WQOs to represent chronic toxicity trigger levels and these terms are used interchangeably in this report.

GPNL proposes to adopt the following WQOs for Port Curtis.

Table 5-1 Water Quality Objectives

Constituent	Chronic Toxicity Trigger Value (µg/L)[1]
Nickel	7[2]
Cobalt	1[3]
Manganese	140[4]
Cadmium	0.2[5]
Chromium 3+	27.4[3]
Chromium 6+	4.4[3]
Zinc	15[3]
Iron	n/a[6]
Aluminium	n/a[7]
Magnesium	n/a[8]
Calcium	n/a[8]
Chloride	n/a[8]
Sulfate	n/a[8]

[1] NOEC values- No Observed Effect Concentration

[2] ANZECC/ARMCANZ- Guidelines for Fresh and Marine Water Quality, Chapter 3 (99th protection of species level)

[3] ANZECC/ARMCANZ- Guidelines for Fresh and Marine Water Quality, Chapter 3 (95th protection of species level)

[4] Provided by CSIRO – (Appendix B1)

[5] ANZECC/ARMCANZ- Guidelines for Fresh and Marine Water Quality, Chapter 3 (protection of species for human protection)

[6] Iron is the fourth most abundant element on earth and concentrations in natural waters are influenced by the surrounding geology. ANZECC has not derived an Australian trigger value for iron due to a lack of toxicity data but a Canadian guideline of 300 µg/L is presented as an interim indicative level until additional data are established. The additional data in Table 4-6 show that the site-specific ambient iron concentrations in Port Curtis are less than the Canadian guideline and it is proposed that the values in Table 4-6 be used as the baseline iron concentration values for determining future impacts from discharges containing iron. The Queensland Water Quality Guidelines 2006 support this approach as they state that using a small departure from natural baseline conditions as a guideline is acceptable if there is good knowledge of baseline conditions. For Port Curtis there is a good knowledge of baseline conditions as 10 years of data are available.

[7] ANZECC 2000 identifies a protection level of 0.5 µg/L for dissolved aluminium. As can be seen in Table 4-6, the ambient dissolved aluminium concentrations in Port Curtis are significantly higher than the ANZECC guideline. However, the 0.5 µg/L trigger value referenced was based on "*low reliability data*". Low reliability values are derived from limited data and analyses and should not be used as final guidelines but as indicative

interim figures, which if exceeded, suggest the need to obtain further data. ANZECC states that interim working level should be revisited as additional data become available. The additional data in Table 4-6 show that the site-specific ambient aluminium concentrations in Port Curtis are significantly greater than 0.5 µg/L and it is proposed that the values in Table 4-6 be used as the baseline aluminium concentration values for determining future impacts from discharges containing aluminium. The Queensland Water Quality Guidelines 2006 support this approach as they state that using a small departure from natural baseline conditions as a guideline is acceptable if there is good knowledge of baseline conditions. For Port Curtis there is a good knowledge of baseline conditions as 10 years of data are available.

[8] Chronic Toxicity Trigger Values have not been nominated for Magnesium, Calcium, Choride and Sulfate as ambient levels are significantly abundant in seawater. These are four of the components that make seawater salty.

By achieving the above WQOs close to the diffuser discharge pipe, GPNL considers that there will be no significant effect on local marine flora, fauna and human health, and by extension, the local recreational and commercial fishing activities.

5.2 Human Health

GPNL is sponsoring a PhD student to study the behaviour of metals in Port Curtis over a period of 2-3 years. The proposed study aims to investigate the dynamics of trace metals in Port Curtis under naturally occurring environmental conditions, and the bioaccumulation potential and toxicity of trace metals to biota. The study consists of two phases:

- Phase 1. Through laboratory assessments the project will investigate the binding capacity of manganese oxides for trace metals under various simulated natural conditions (pH and dissolved oxygen). The bioaccumulation of trace metals in biota (oysters, prawns etc.) and passive sampling devices (DGT) through spiking manganese aggregates will also be assessed under similar conditions. Environmental harm to biota through toxicity testing would also be determined concurrently. An assessment of the light reducing properties and settling rates of the aggregates will also be determined
- In situ studies in the field and/or through the use of mesocosms will be utilised to validate the results of the laboratory studies.

With the continuing advance in the understanding of the water quality in Port Curtis and the potential bio-accumulation properties of key metals and the local species, relationships to the potential risks to human health can be developed. Currently there are not adequate data for a comprehensive and robust human health risk assessment to be carried out. GPNL has used available research material to develop WQOs which are not only aimed at protecting marine aquatic species but also to protect human health (see key metals discussed below).

The ANZECC Water Quality Guidelines (ANZECC, 2000) state that *"...at this stage there is insufficient formal international guidance to confidently calculate guideline figures to account for this phenomenon [bioaccumulation] (Bro- Rasmussen et al. 1994). Hence, if no such data are available for chemicals that have the potential to bioaccumulate, the 99% protection level is recommended as a default for slightly to moderately disturbed ecosystems*."

By achieving the proposed WQOs close to the diffuser discharge pipe, GPNL considers that there will be no significant effect on local marine fauna and human health and by extension the local recreational and commercial fishing activities.

GPNL will support and participate in a broad industry and government based assessment of the potential human health impacts from Port Curtis. GPNL is willing to consider implementing an ecotoxicological program of research to assess the specific properties of the nickel plant discharge in the early years of operation which could lead to a specific human health risk assessment based on more rigorous environmental data.

GPNL commits to monitoring the discharge water quality and the receiving environment waters to confirm the effectiveness of the diffuser and dispersion into the Port Curtis area.

Cadmium

The WQO selected for cadmium is 0.2 µg/L. The ANZECC water quality guidelines comments: "*To protect against chronic toxicity to related species and bioaccumulation of cadmium, use of the 99% protection level (0.7 µg/L) is recommended for slightly to moderately disturbed ecosystems. If in an area where shellfish are likely to be used for human consumption, the trigger value should be reduced to 0.2 µg/L*." This WQO selected for the GPNL assessment therefore includes an appreciation of the potential human consumption risks.

Cobalt

There is limited information available on the potential bioaccumulation of cobalt in marine waters. In the absence of more detailed research information the WQO was taken from the ANZECC guidelines. These guidelines state: "*Some aquatic organisms may accumulate cobalt [this has been demonstrated as dietary bioaccumulation, and therefore needs to be in a solid form to bond to particles that would then transfer to the organisms gut], particularly some aquatic plants and benthic organisms (Cole & Carson 1981)." However "A marine high reliability trigger value for cobalt of 1 µg/L was calculated using the statistical distribution method at 95% protection*."

Manganese

The refinery discharge into Port Curtis contains dissolved manganese emanating from its association with cobalt in nickel-cobalt laterite ores. Since the ANZECC/ARMCANZ (2000) criteria only includes a "low reliability" trigger value for manganese in marine waters, it was determined that a detailed investigation of the potential impacts of dissolved manganese in the marine environment was required to adequately assess this specific aspect of the refinery discharge. Investigation of the oxidation of dissolved manganese and precipitation and potential settling of manganese compounds was also required.

The Centre for Environmental Contaminants Research, CSIRO Land and Water was engaged to conduct critical reviews of relevant literature and desk-top studies searches (Appendix B5 and Appendix B6). CSIRO was also engaged to undertake a critical review of relevant literature and desk-top studies of the oxidation rate of manganese once it is discharged to seawater (Appendix B2 and Appendix B3).

The manganese trigger value to protect 95% of species derived by Appendix B5 and Appendix B6 has a higher reliability than the ANZECC/ARMCANZ (2000) trigger value and can be considered a "moderate reliability" guideline as it has been derived from sufficient data on acute toxicity. The majority of trigger values nominated in ANZECC/ARMCANZ (2000) are moderate reliability trigger values, as high reliability trigger values can only be derived from chronic toxicity data, which are limited in quantity. The derived moderate reliability trigger value including coral data is 140 µg/L and without coral data is 340 µg/L. These trigger values are based on manganese (II).

The available data suggest that manganese is one of the least toxic metals to marine biota. However, no data on the toxicity of manganese to seagrasses and mangroves were available. For this reason, a conservative trigger value of 140 µg/L is proposed as the WQO for Port Curtis.

The initial field and laboratory manganese studies conducted by CSIRO and Central Queensland University indicated that the oxidation of dissolved manganese in the surface waters of Port Curtis may occur over timescales of weeks to months. It was noted that further work was required in order to accurately determine the rate of oxidation and also to understand the environmental factors affecting oxidation rates.

Further work by CSIRO included the assessment of manganese oxidation rates in the laboratory under controlled incubation conditions over a 6-week period. These experiments used waters from Port Curtis containing ambient suspended sediment concentrations supplemented with added inorganic Mn(II).

The study showed that for the manganese-spiked seawater samples, complete oxidation and precipitation of the added dissolved manganese (3000 µg/L) occurred within 21 days. The estimated half-life of dissolved manganese was between 10-11 days. Based on the results of this investigation, a half-life of 10 days for manganese has been used in the revised modelling of the refinery's discharge to Port Curtis.

Nickel

The WQO used for nickel is based on the ANZECC guidelines which state "*A marine high reliability guideline value of 70 µg/L was derived for nickel using the statistical distribution method at 95% protection. The 99% protection level was 7 µg/L and is recommended for slightly-moderately disturbed marine systems*."

Chromium III and VI

The WQO used for Chromium III is based on Table 3.4.1 of the ANZECC guidelines.

The WQO used for Chromium VI is based on the ANZECC guidelines which state "*A marine high reliability trigger value for chromium (VI) of 4.4 µg/L was derived using the statistical distribution method at 95% protection. The guideline figure is close to the geometric mean of 3 out of 36 species (4.0, 4.8 and 5 µg/L) but, as these were NOEC figures, the 95% protection value should be sufficiently protective in most slightly-moderately disturbed systems.*"

5.3 Risk Assessment

The ANZECC guidelines acknowledge that aquatic ecosystems are variable and complex and difficult to manage. As such, rather than impose the requirement for a full risk assessment to be undertaken on every project, it has proposed a set of *trigger values*.

The trigger values represent bioavailable concentrations, and are generally accepted as conservative estimates of concentrations which are unlikely to cause a risk to the ecosystem.

The trigger values are designed such that, if the trigger value is not exceeded, the risk of an impact is considered low, and no further action is required. However, if the trigger value is exceeded, the values trigger the incorporation of additional information or further investigation to determine whether or not a real risk to the ecosystem exists, and where possible, to adjust the trigger values into regional, local or site-specific guidelines.

GPNL has adopted the trigger values as the water quality objectives. By complying with the trigger values presented in the ANZECC guidelines, the risk assessment used to generate the ANZECC guidelines have been applied to this project.

5.4 Temperature

Discussions have been held with the EPA regarding a temperature condition of discharge. GPNL proposes that a 3°C differential between the discharge and the ambient water temperature be accepted as a condition of discharge as this will not impact significantly the marine environment in and around RG Tanna in Port Curtis. This has been accepted by the EPA given that the proposed discharge configuration will reduce the differential to below 2°C (ANZECC guideline) very close to the diffuser ports (<2 m).

6.1 Dispersion Models

Three models have been developed to predict the dispersion of the constituents in the refinery's effluent to be discharged to Port Curtis at Clinton Wharf:

- Far-Field
    - RMA-11 three-dimensional finite element model, developed by Resource Modelling Associates (RMA-11); and
- Near-Field
    - CORMIX model (1-dimensional); and
    - Computational Fluid Modelling (CFD) analysis (3-dimensional).

The modelling was undertaken by BMT WBM. A copy of their report is given in Appendix A.

6.1.1 Far-Field: RMA-11 Model

RMA-11 is a far-field model used as the advection dispersion model to predict the water quality impacts of the refinery's discharge. RMA-11 was run in two-dimensional mode for this study.

The model network extends over an area of some 635 km^2, incorporating Port Gladstone and the main inter-tidal areas between Curtis Island and the mainland. The model extent includes all the predominant tidal flows into Port Curtis being the main ocean entrance at the eastern model boundary, the North Channel between Facing Island and Curtis Island, and through the Narrows. The tidal tributaries including Calliope River, Auckland Inlet, South Trees Inlet and the Boyne River have also been incorporated into the model.

Field data were collected between April and May 2006 to provide information for model calibration. The data collected included continuous time series of tidal water elevations using fixed point tide gauges and flow/velocity distribution data for defined transects using acoustic Doppler current profilers (ADCPs). Further calibration data was obtained from a bottom mounted ADCP in the main channel. The model was simulated over the April-May monitoring period which included numerous tidal cycles with representative spring and neap tide conditions. The calibration results in terms of comparison of simulated water levels and flow rates against observed data were acceptable and showed that the model accurately predicted the hydrodynamic conditions in Port Curtis.

6.1.2 Near-Field

As the study progressed, two modelling packages were used to investigate near-field plume behaviour. The first model used was CORMIX, but due to limitations becoming apparent in the latter stages of this study, a second, more detailed computational fluid dynamics (CFD) model was adopted to provide a more robust assessment of the near-field plume dynamics particularly very close to the discharge ports.

CORMIX Model

The CORMIX modelling package (http://www.cormix.info/) was initially used to describe the near-field plume dynamics. It is a one dimensional model that uses flow regime parameters and outfall design characteristics to predict the steady state evolution of effluent plume dynamics. CORMIX can simulate a variety of diffuser configurations, including single and multiport arrangements.

The model has the ability to capture the following key phases of plume evolution:

- Near-field: the region where plume dynamics are dominated by the momentum of the discharge.
- Buoyant spreading: the region where the buoyancy of the effluent stream is dynamically important. Depending on ambient flow conditions, this regime may lead to either restratification or full vertical mixing.
- Ambient spreading: the region where full vertical mixing has occurred and the effluent stream is largely controlled by the ambient flow regime.

The locations and characteristics of these phases determine the efficacy of the selected diffuser arrangement in dispersing the effluent stream.

Computational Fluid Modelling (CFD) Analysis

The CFD package OpenFOAM (Open Field Operation and Manipulation) was used during low tidal velocity periods as it is more robust at modelling of the conditions than CORMIX. OpenFOAM can simulate complex fluid flows involving chemical reactions, turbulence and heat transfer.

OpenFOAM uses finite volume numerics to solve systems of partial differential equations ascribed on any three-dimensional unstructured mesh of polyhedral cells. The fluid flow solvers are developed within a robust, implicit, pressure-velocity, iterative solution framework, although alternative techniques are applied to other continuum mechanics solvers.

6.2 Modelling Methodology

CORMIX was used to examine near-field effects (i.e. short term – minutes to hours) and the RMA-11 models (hydrodynamics and advection-dispersion) were used to investigate far-field impacts (i.e. longer term – months to a year).

The modelling methodology involved evaluation of the far-field effects using an initial discharge arrangement. The near-field model was then run and the design of the diffuser altered to achieve optimum results and to ensure that full vertical mixing occurs. This is a valid linkage with the far-field model. The far-field model was finally rerun with the selected discharge arrangement.

To reduce complexity and modelling time, a ‘dilution’ approach was adopted whereby a passive tracer was inserted into both models. The dispersion and dilution of that tracer was used to calculate the likely near and far-field concentrations of the constituents in the discharge (following adjustments for ambient conditions). The tracer was inserted at a concentration of 100 units. Predicted concentrations were compared against the WQOs to assess the level of impact.

The near-field model was run with a variety of tidal velocities as it is a steady state model. The far-field model was run to simulate approximately 10 months of tidal cycles to reach steady state, and then hot-started for a two-week period full tidal cycle over which results were derived. The underlying hydrodynamic model was run on a cyclical basis to support the progression of advection-dispersion modelling.

CFD modelling was run to predict near-field impacts for the low velocity flows (7000 seconds) with a tracer at a fixed distance 3 m away from the discharge port, with the location initially being upstream of the diffuser. The vertical profile of the tracer concentration was plotted over time of the simulation duration. This was done for three profiles, the first exactly between ports (i.e. 1.25 m along the diffuser axis), the last is at the port centreline, and the second at the midpoint between the first and last (i.e. 0.625 m along the diffuser axis from the port).

Finally, the far-field RMA-11 model was reintegrated to qualitatively assess the likelihood of water that initially flows over the diffuser returning at subsequent tidal states. This return flow of all waters is an implicit assumption of the CFD model. This investigation was undertaken by inserting numerical drogues into the RMA-11 hydrodynamic results, and allowing these drogues to be advected by the ambient velocity field over several tidal cycles.

6.3 Stage 1 Results

6.3.1 RMA-11 Modelling

The proposed Stage 1 configuration consists of a single diffuser line running along the approach jetty to the RG Tanna wharf (Figure 6-1).

Within the far-field model, the diffuser line was assigned an inflow accompanied by a tracer. The total discharge through the diffuser was 17,100 m^3/hr. The tracer was assigned a half-life transformation rate of 10 days for manganese, and a zero decay rate for all other parameters. The resulting advection dispersion model simulation covered approximately 10 months, which allowed the tracer to approximate steady state within Port Curtis.

Figure 6-1 Model Elements Selected to Represent Diffuser Lines. Stage 1 Employed Diffuser 1 Only, and Stage 2 Employed both Diffusers

The results are presented above. Note that concentration contours, averages and time series are presented only for the zero decay rate simulation results. These results do not apply for manganese concentration, as this parameter has been applied a 10 day half life rate. Specific results for manganese are only reported. It should be noted that the contours do not have near-field concentrations included.

Spatial and Temporal Concentrations at Steady State

The spatial extent of the tracer covered a large proportion of Port Curtis. However, most of the high concentrations of the tracer were contained between Gladstone Marina, Wiggins Island and the downstream reach of the Calliope River. There was little variation between the 6-hourly and 12-hourly maximums and the maximum concentration (~0.06%) was found in the immediate vicinity of the diffusers. The remainder of the receiving waters exhibited tracer concentrations of approximately 0.01%.

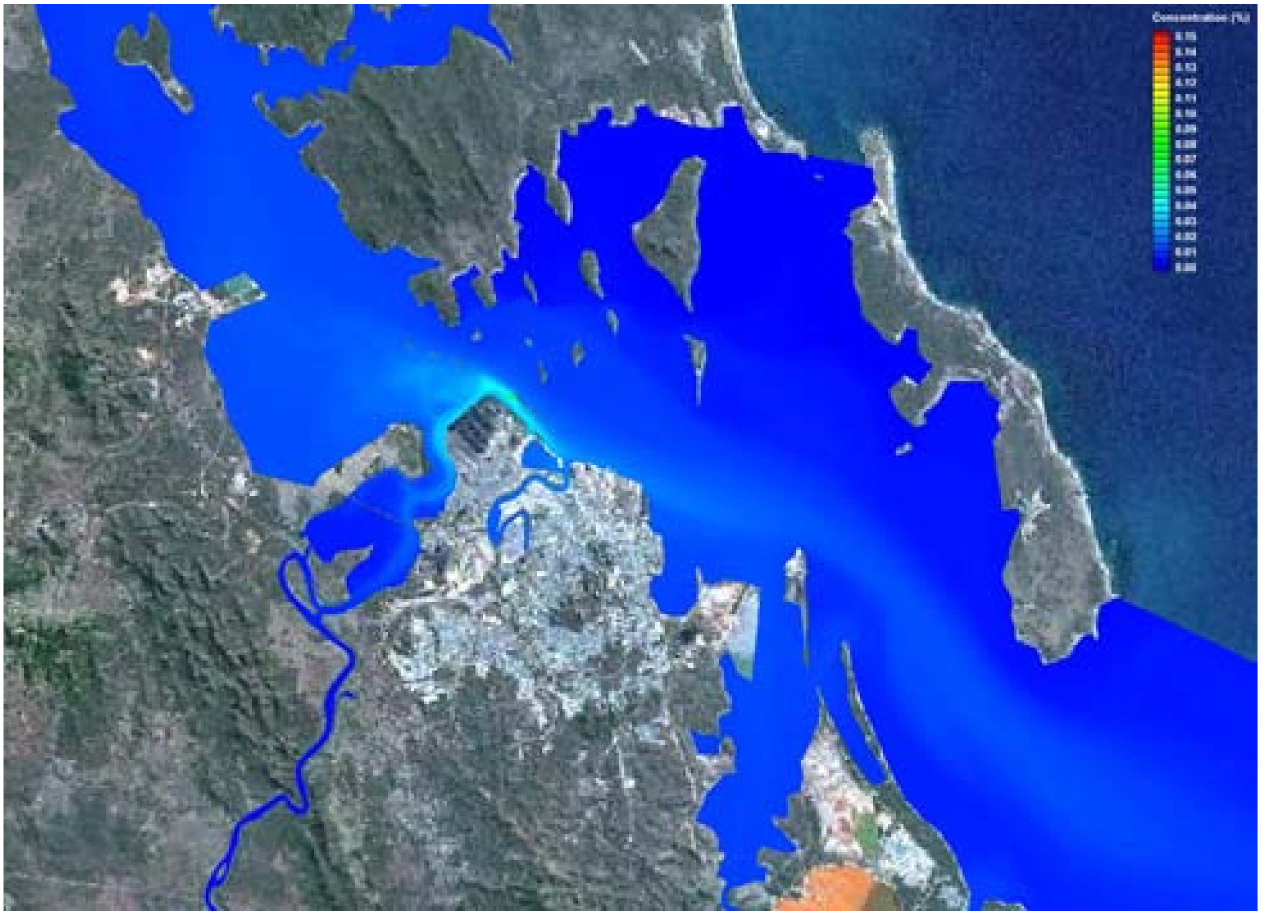


Figure 6-2 6-hourly Maximum Concentrations of the Tracer in Port Curtis – Stage 1

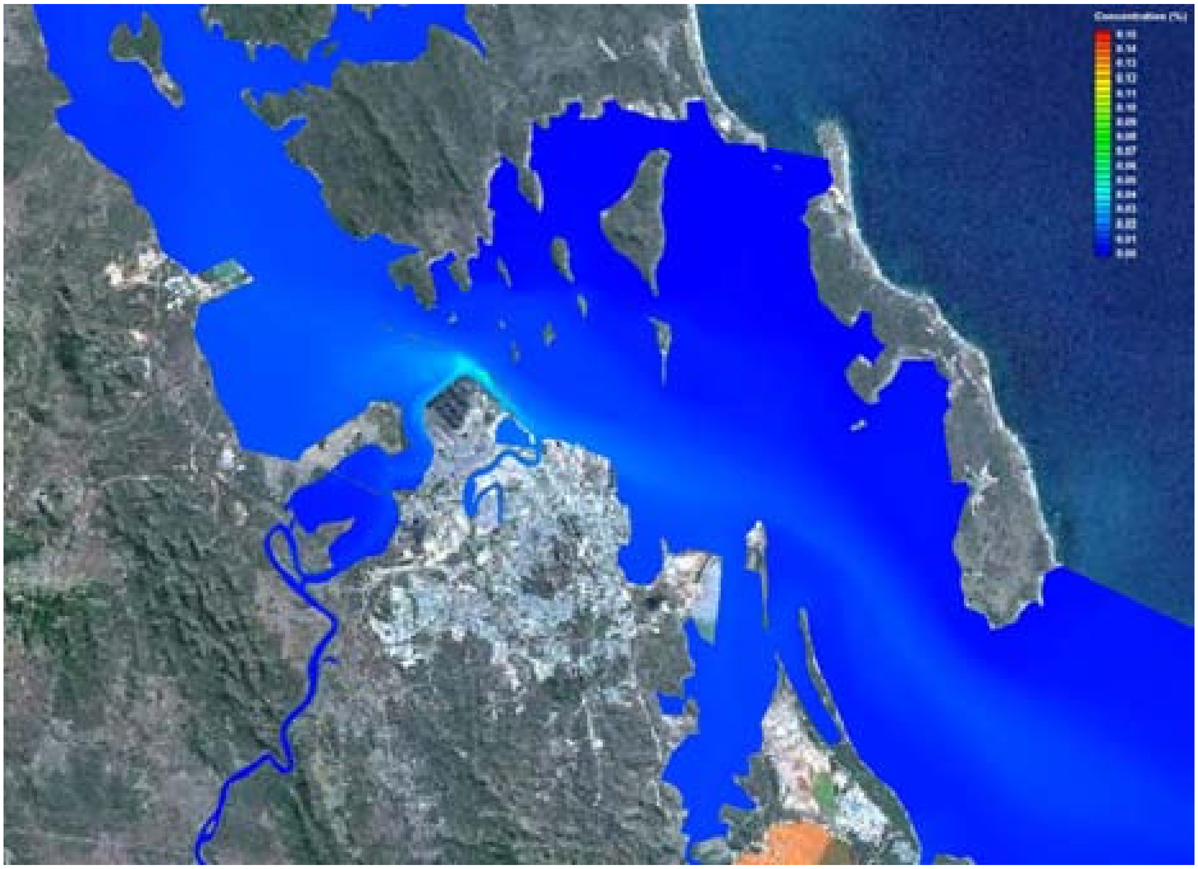


Figure 6-3 12-hourly Maximum Concentrations of the Tracer in Port Curtis – Stage 1

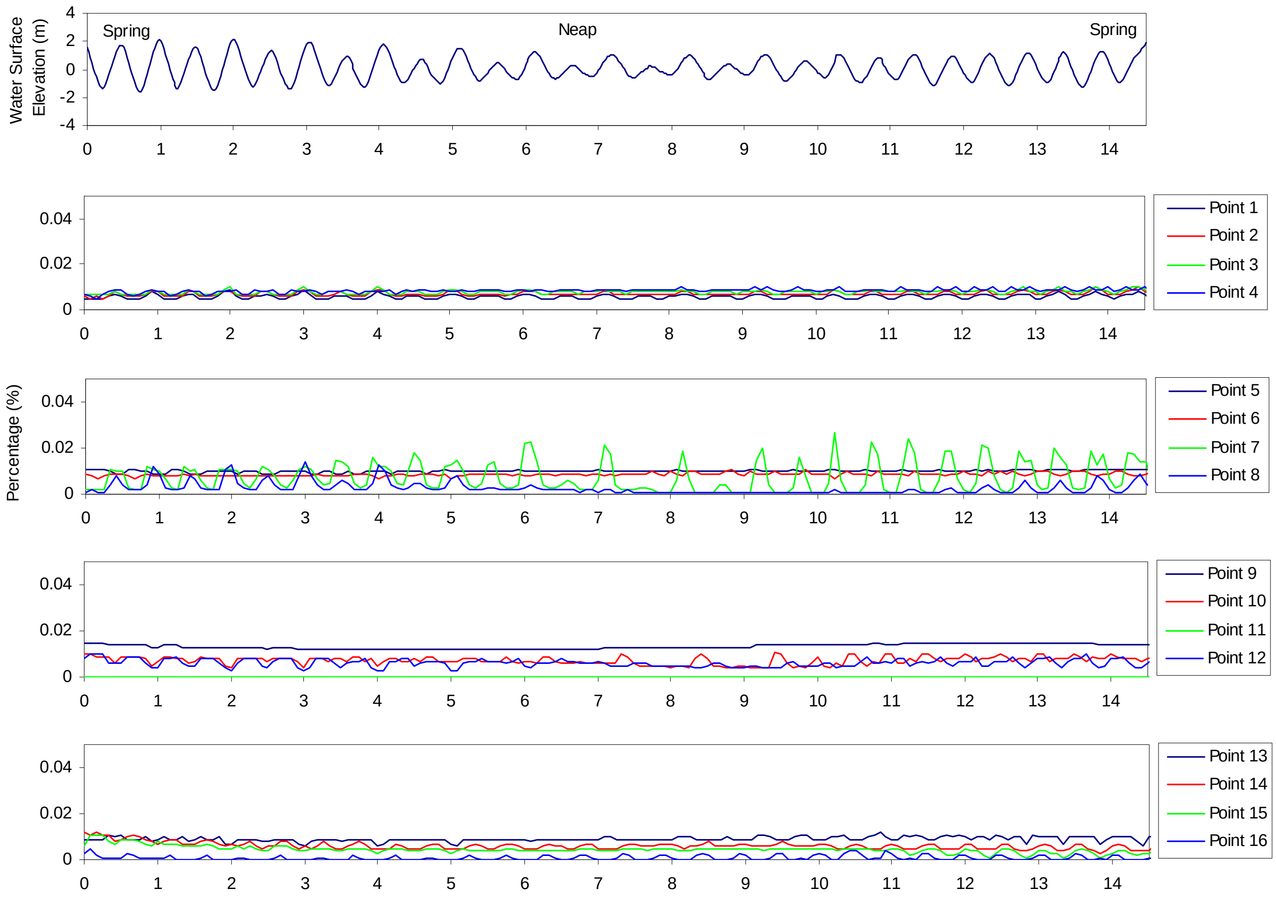


Figure 6-4 Time Series of Concentrations at 16 Locations Within Port Curtis – Stage 1

Figure 6-5 Location of Tracer Concentrations Time Series Data at Steady State

6.3.2 CORMIX Modelling

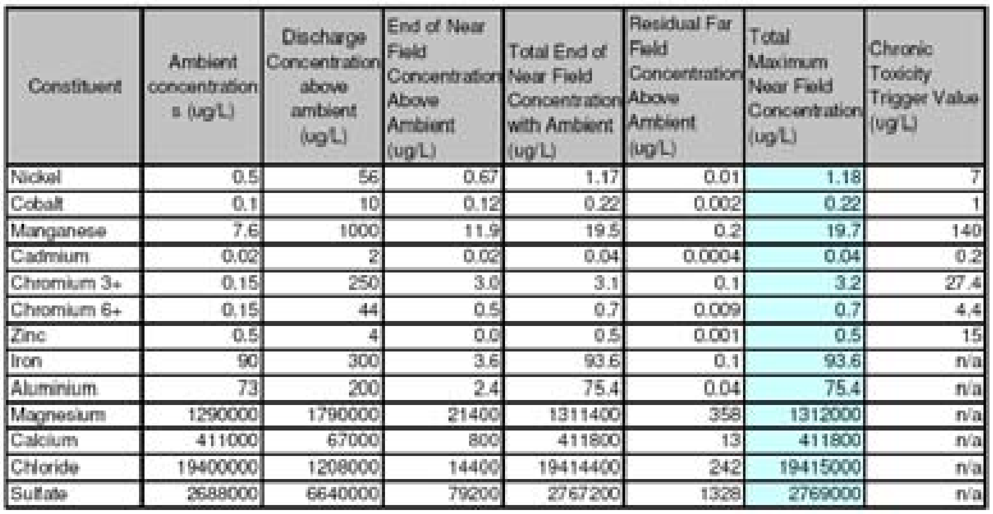
The CORMIX dilutions factors for Diffuser 1 were applied to the discharge concentrations to estimate the concentrations at the end of the mixing zone (as defined by CORMIX) as follows:

- Far-field concentrations were computed from the far-field model results near the proposed diffuser location. Average concentration increases of 0.02% were considered for Stage 1 for parameters with no decay, and average concentration increases of 0.015% were considered for Stage 1 for manganese (half life decay). This is believed to be reflective of long term background concentration increases in the vicinity of the diffuser.
- These far-field concentrations were added to the ambient Port Curtis water quality to compute the absolute background concentrations in the vicinity of the diffuser.
- CORMIX dilution values were applied to the discharge concentrations to provide an estimate of the additional concentrations at the end of Diffuser 1 mixing zone.
- The predicted CORMIX concentrations were added to ambient and far-field concentrations to provide a final near-field concentration. This provided the overall total maximum near-field concentrations at the end of the mixing zone (as defined by CORMIX).

This approach was adopted to assess the likely cumulative effect of the discharge on ambient pollutant concentrations, taking into account both near and far-field effects.

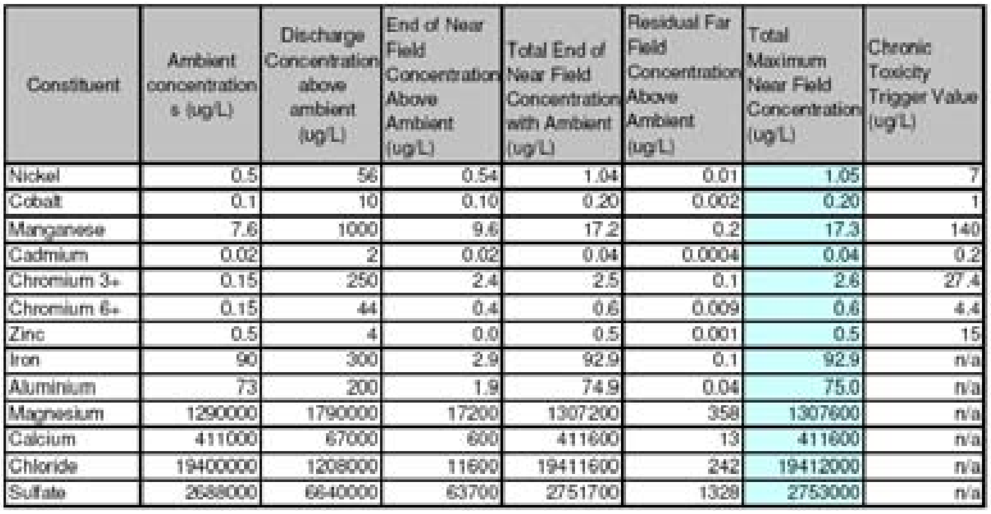
Results are reported in Table 6-1 to Table 6-5 for the five ambient velocities considered.

Table 6-1 Near-Field Pollutant Concentrations (End of Near-field Region) - Stage 1 Ambient Velocity of 0.16 m/s



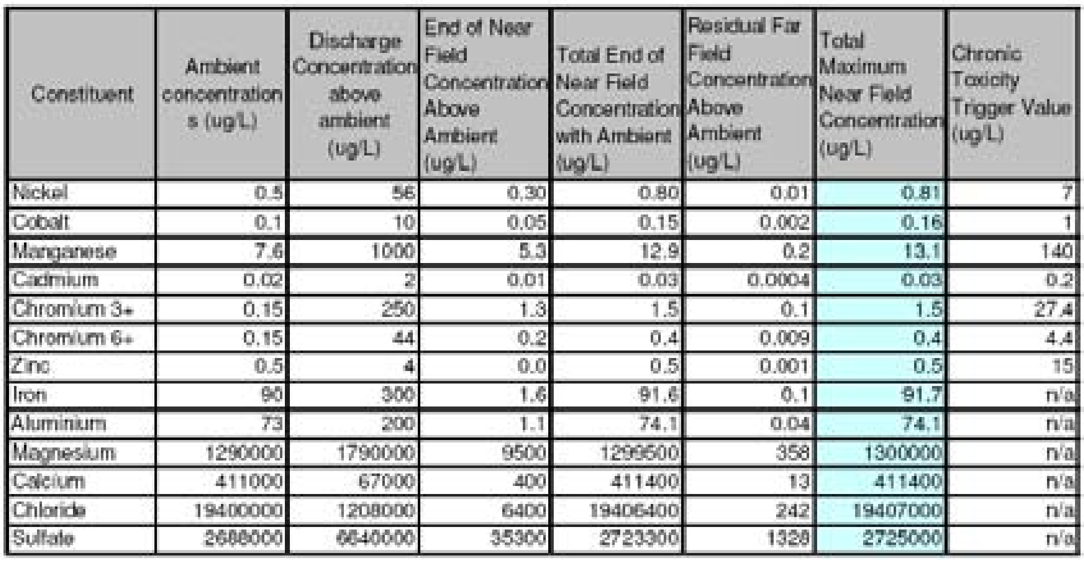
Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	End of Near Field Concentration Above Ambient (ug/L)	Total End of Near Field Concentration with Ambient (ug/L)	Residual Far Field Concentration Above Ambient (ug/L)	Total Maximum Near Field Concentration (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.67	1.17	0.01	1.18	7
Cobalt	0.1	10	0.12	0.22	0.002	0.22	1
Manganese	7.6	1000	11.9	19.5	0.2	19.7	140
Cadmium	0.02	2	0.02	0.04	0.0004	0.04	0.2
Chromium 3+	0.15	250	3.0	3.1	0.1	3.2	27.4
Chromium 6+	0.15	44	0.5	0.7	0.009	0.7	4.4
Zinc	0.5	4	0.0	0.5	0.001	0.5	15
Iron	90	300	3.6	93.6	0.1	93.6	n/a
Aluminium	73	200	2.4	75.4	0.04	75.4	n/a
Magnesium	1290000	1790000	21400	1311400	358	1312000	n/a
Calcium	411000	67000	800	411800	13	411800	n/a
Chloride	19400000	1208000	14400	19414400	242	19415000	n/a
Sulfate	2688000	6640000	79200	2767200	1328	2769000	n/a

Table 6-2 Near-field Pollutant Concentrations (End of Near-field Region) - Stage 1 Ambient Velocity of 0.25 m/s



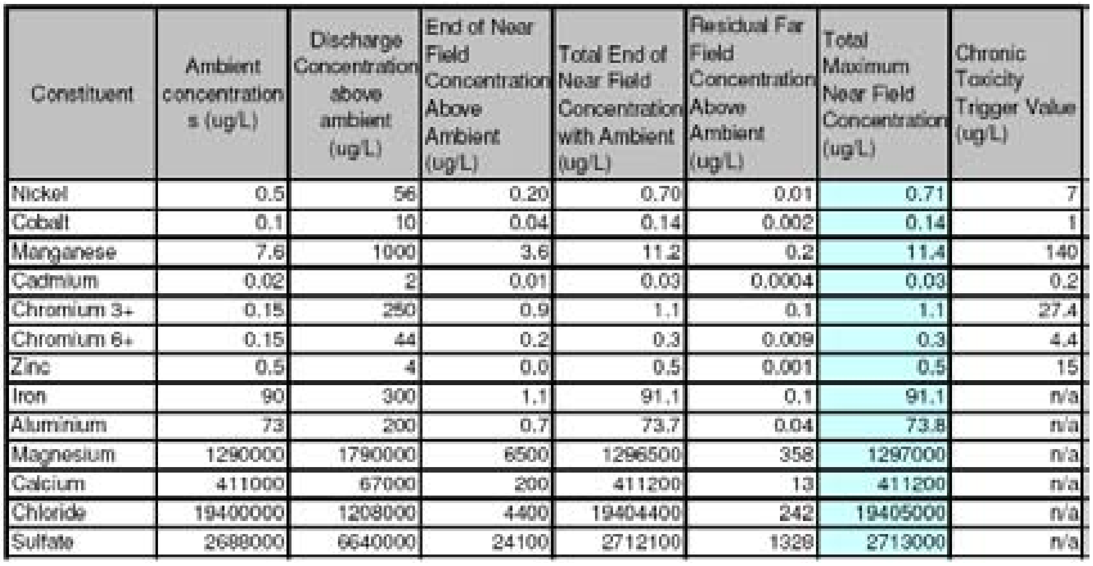
Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	End of Near Field Concentration Above Ambient (ug/L)	Total End of Near Field Concentration with Ambient (ug/L)	Residual Far Field Concentration Above Ambient (ug/L)	Total Maximum Near Field Concentration (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.54	1.04	0.01	1.05	7
Cobalt	0.1	10	0.10	0.20	0.002	0.20	1
Manganese	7.6	1000	9.6	17.2	0.2	17.3	140
Cadmium	0.02	2	0.02	0.04	0.0004	0.04	0.2
Chromium 3+	0.15	250	2.4	2.5	0.1	2.6	27.4
Chromium 6+	0.15	44	0.4	0.6	0.009	0.6	4.4
Zinc	0.5	4	0.0	0.5	0.001	0.5	15
Iron	90	300	2.9	92.9	0.1	92.9	n/a
Aluminium	73	200	1.9	74.9	0.04	75.0	n/a
Magnesium	1290000	1790000	17200	1307200	358	1307600	n/a
Calcium	411000	67000	600	411600	13	411600	n/a
Chloride	19400000	1208000	11600	19411600	242	19412000	n/a
Sulfate	2688000	6640000	63700	2751700	1328	2753000	n/a

Table 6-3 Near-field Pollutant Concentrations (End of Near-field Region) - Stage 1 Ambient Velocity of 0.50 m/s



Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	End of Near Field Concentration Above Ambient (ug/L)	Total End of Near Field Concentration with Ambient (ug/L)	Residual Far Field Concentration Above Ambient (ug/L)	Total Maximum Near Field Concentration (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.30	0.80	0.01	0.81	7
Cobalt	0.1	10	0.05	0.15	0.002	0.16	1
Manganese	7.6	1000	5.3	12.9	0.2	13.1	140
Cadmium	0.02	2	0.01	0.03	0.0004	0.03	0.2
Chromium 3+	0.15	250	1.3	1.5	0.1	1.5	27.4
Chromium 6+	0.15	44	0.2	0.4	0.009	0.4	4.4
Zinc	0.5	4	0.0	0.5	0.001	0.5	15
Iron	90	300	1.6	91.6	0.1	91.7	n/a
Aluminium	73	200	1.1	74.1	0.04	74.1	n/a
Magnesium	1290000	1790000	9500	1299500	358	1300000	n/a
Calcium	411000	67000	400	411400	13	411400	n/a
Chloride	19400000	1208000	6400	19406400	242	19407000	n/a
Sulfate	2688000	6640000	35300	2723300	1328	2725000	n/a

Table 6-4 Near-field Pollutant Concentrations (End of Near-field Region) - Stage 1 Ambient Velocity of 0.75 m/s



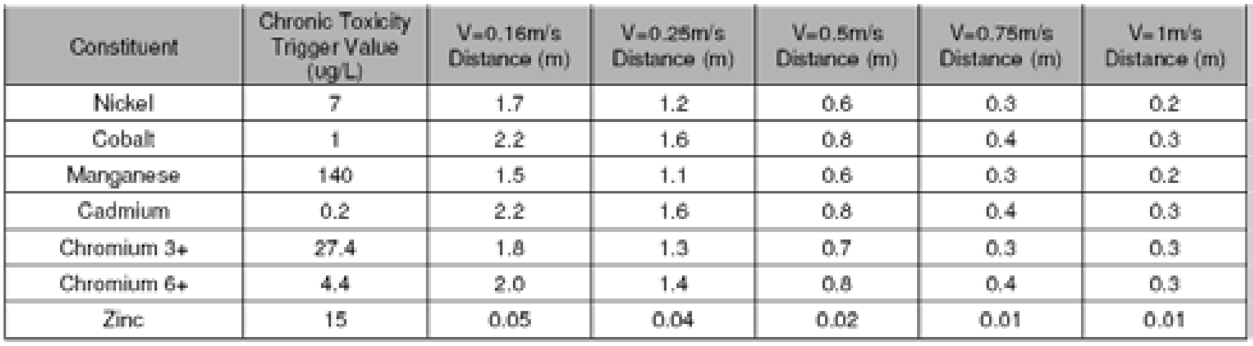
Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	End of Near Field Concentration Above Ambient (ug/L)	Total End of Near Field Concentration with Ambient (ug/L)	Residual Far Field Concentration Above Ambient (ug/L)	Total Maximum Near Field Concentration (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.20	0.70	0.01	0.71	7
Cobalt	0.1	10	0.04	0.14	0.002	0.14	1
Manganese	7.6	1000	3.6	11.2	0.2	11.4	140
Cadmium	0.02	2	0.01	0.03	0.0004	0.03	0.2
Chromium 3+	0.15	250	0.9	1.1	0.1	1.1	27.4
Chromium 6+	0.15	44	0.2	0.3	0.009	0.3	4.4
Zinc	0.5	4	0.0	0.5	0.001	0.5	15
Iron	90	300	1.1	91.1	0.1	91.1	n/a
Aluminium	73	200	0.7	73.7	0.04	73.8	n/a
Magnesium	1290000	1790000	6500	1296500	358	1297000	n/a
Calcium	411000	67000	200	411200	13	411200	n/a
Chloride	19400000	1208000	4400	19404400	242	19405000	n/a
Sulfate	2688000	6640000	24100	2712100	1328	2713000	n/a

Table 6-5 Near-field Pollutant Concentrations (End of Near-field Region) - Stage 1 Ambient Velocity of 1.0 m/s

Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	End of Near Field Concentration Above Ambient (ug/L)	Total End of Near Field Concentration with Ambient (ug/L)	Residual Far Field Concentration Above Ambient (ug/L)	Total Maximum Near Field Concentration (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.15	0.65	0.01	0.66	7
Cobalt	0.1	10	0.03	0.13	0.002	0.13	1
Manganese	7.6	1000	2.7	10.3	0.2	10.5	140
Cadmium	0.02	2	0.01	0.03	0.0004	0.03	0.2
Chromium 3+	0.15	250	0.7	0.8	0.1	0.9	27.4
Chromium 6+	0.15	44	0.1	0.3	0.009	0.3	4.4
Zinc	0.5	4	0.0	0.5	0.001	0.5	15
Iron	90	300	0.8	90.8	0.1	90.9	n/a
Aluminium	73	200	0.5	73.5	0.04	73.6	n/a
Magnesium	1290000	1790000	4900	1294900	358	1295000	n/a
Calcium	411000	67000	200	411200	13	411200	n/a
Chloride	19400000	1208000	3300	19403300	242	19404000	n/a
Sulfate	2688000	6640000	18200	2706200	1328	2707000	n/a

The distances downstream of the diffuser line where the WQOs are predicted to be met are tabulated in Table 6-6 for all considered ambient velocities.

Table 6-6 Compliance with Chronic Toxicity Trigger Values Downstream of Diffuser- Stage 1



Constituent	Chronic Toxicity Trigger Value (ug/L)	V=0.16m/s Distance (m)	V=0.25m/s Distance (m)	V=0.5m/s Distance (m)	V=0.75m/s Distance (m)	V=1m/s Distance (m)
Nickel	7	1.7	1.2	0.6	0.3	0.2
Cobalt	1	2.2	1.6	0.8	0.4	0.3
Manganese	140	1.5	1.1	0.6	0.3	0.2
Cadmium	0.2	2.2	1.6	0.8	0.4	0.3
Chromium 3+	27.4	1.8	1.3	0.7	0.3	0.3
Chromium 6+	4.4	2.0	1.4	0.8	0.4	0.3
Zinc	15	0.05	0.04	0.02	0.01	0.01

6.3.3 CFD Analysis

The OpenFOAM model explicitly simulates the plume evolution from exiting the diffuser hole to interacting with the ambient flow. Figure 6-6 shows the existing cross section at the proposed Diffuser 1 location.

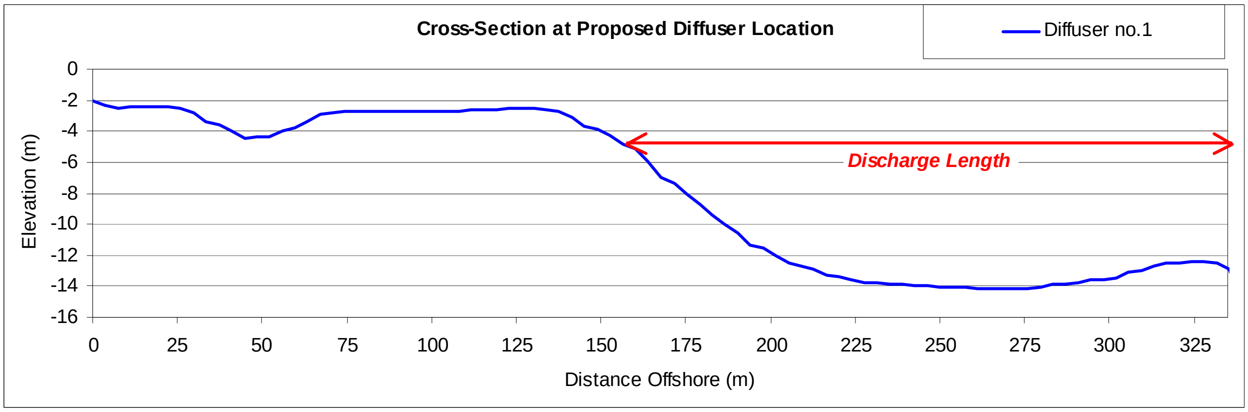


Figure 6-6 Cross Section of the Water Depth for Diffuser Pipeline – Stage 1

Steady State Longitudinal Cross Sections

Following is a series of figures showing the plume evolution downstream of the diffuser exit point for the steady state simulation. The ambient velocity is always from left to right, and plume colours represent a tracer concentration, as per the colourbar. The injection concentration was 1.0, so for example, a plume concentration of 0.1 represents a dilution of 10:1. Figures are presented in order of decreasing ambient velocity, and the total length of each figure downstream of the exit point is 50 m.

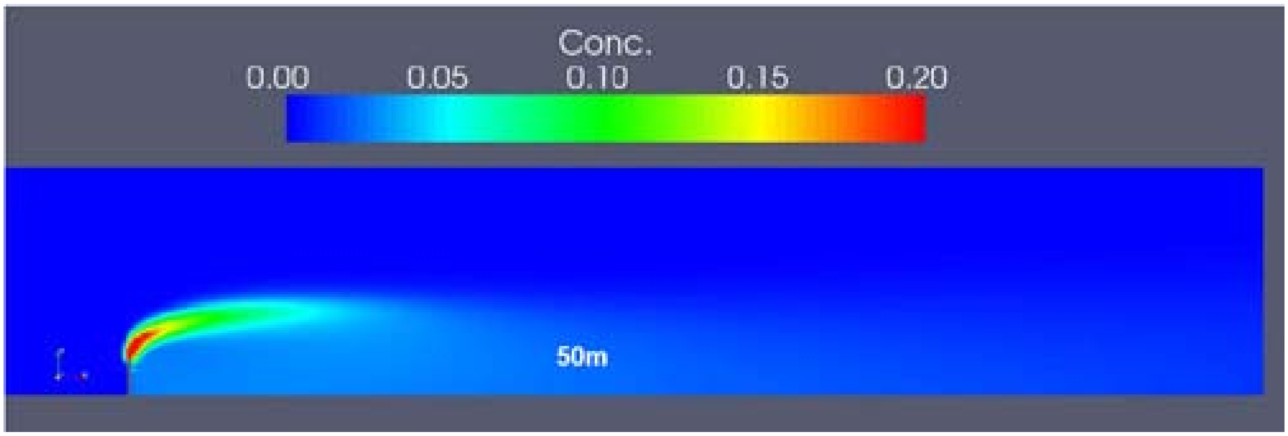


Figure 6-7 Longitudinal Plume Evolution: 1.0 m/s Ambient Velocity

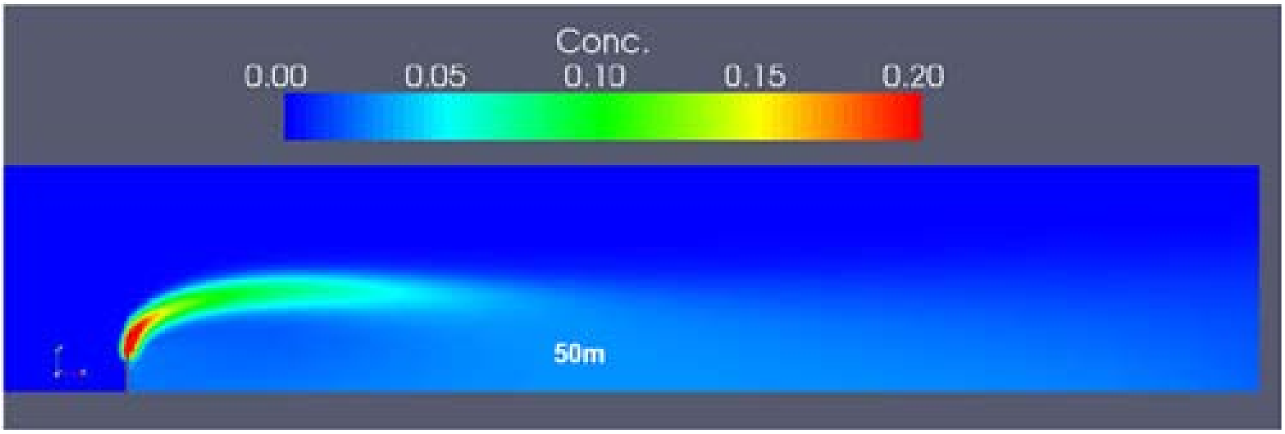


Figure 6-8 Longitudinal Plume Evolution: 0.5 m/s Ambient Velocity

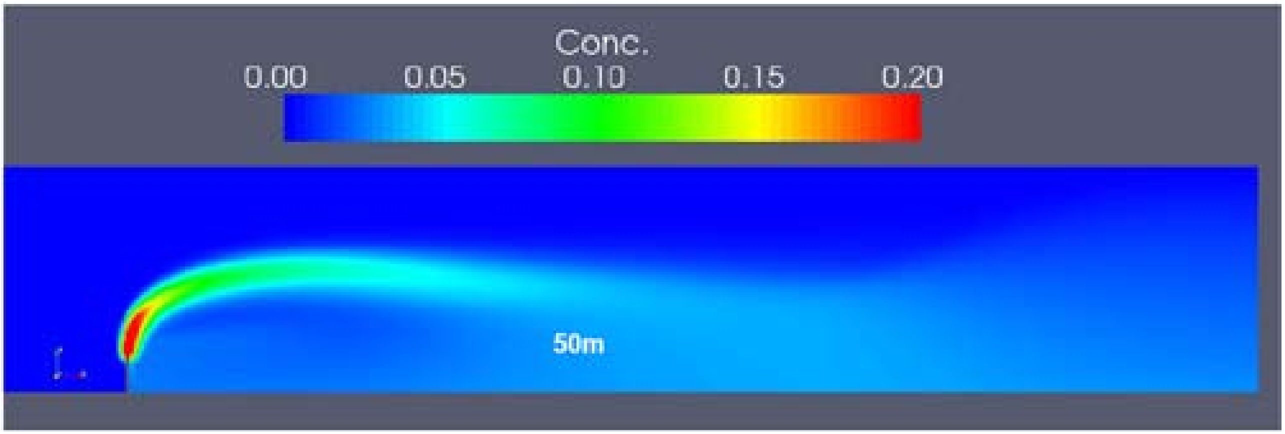


Figure 6-9 Longitudinal Plume Evolution: 0.3 m/s Ambient Velocity

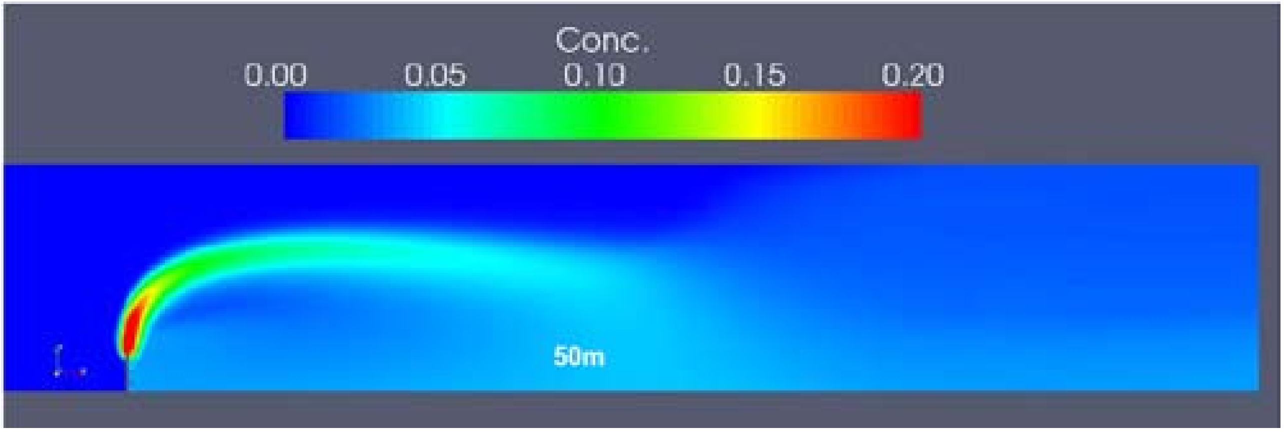


Figure 6-10 Longitudinal Plume Evolution: 0.2 m/s Ambient Velocity

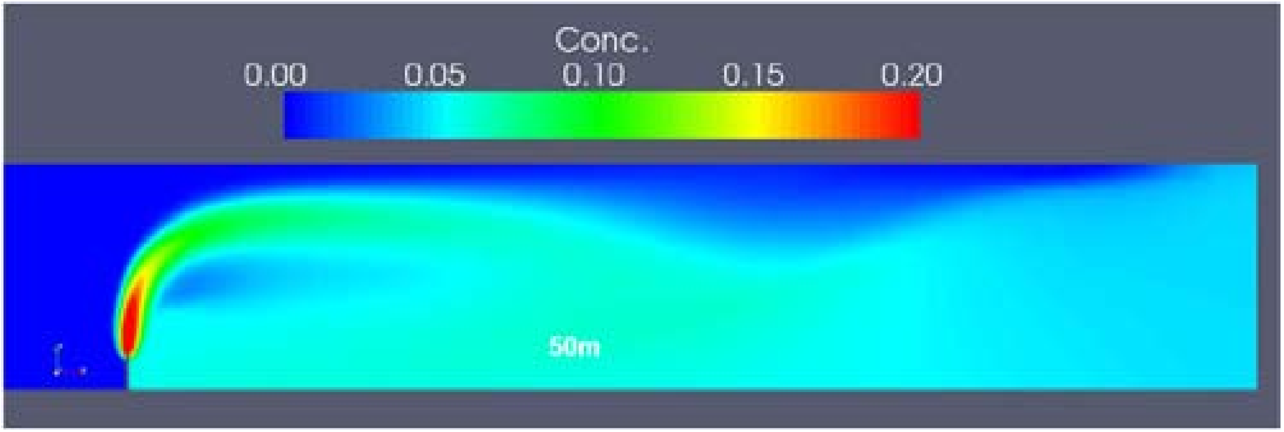


Figure 6-11 Longitudinal Plume Evolution: 0.1 m/s Ambient Velocity

The figures show several key features:

- As ambient velocity decreases, the plumes reach progressively higher into the water column following discharge, with an ambient velocity of 0.1 m/s eventually hitting the water surface. This is shown graphically in Figure 6-11 and Figure 6-12;

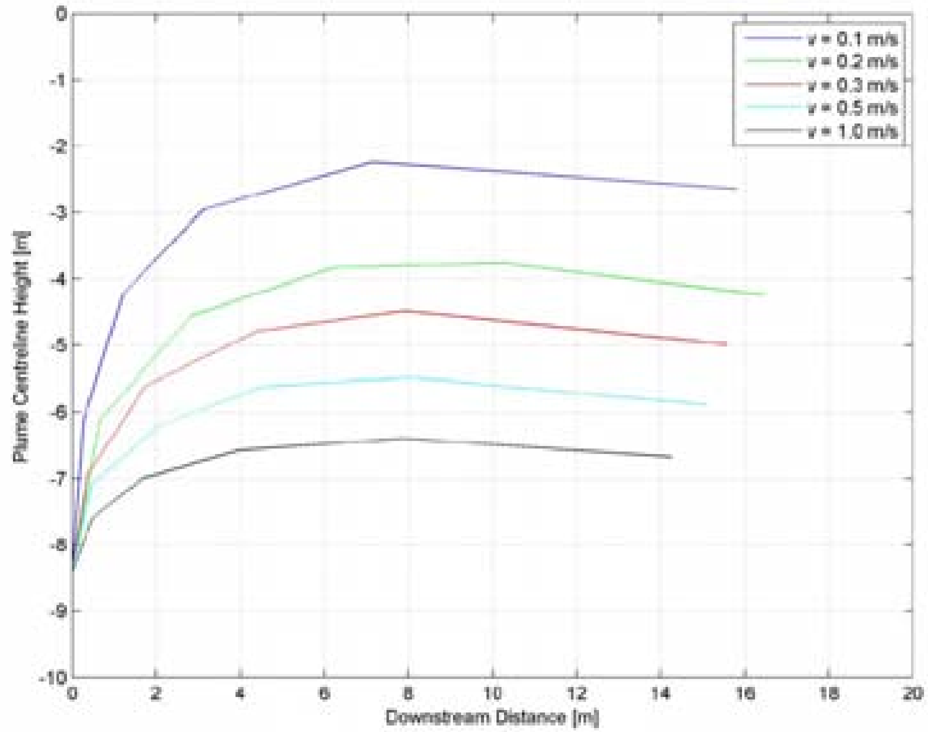


Figure 6-12 Longitudinal Plume Centreline Heights

- Complete mixing over the plume downwards from its peak height, or a close approximation to it, generally occurs by about 25 m downstream of the exit point, for all velocities; and
- Generally the highest concentrations are within the core of the plume, and do not reach across the entire plume vertical extents.

Some unstable vertical recirculation 40 m downstream of the diffuser was qualitatively predicted by CORMIX for the low ambient velocities and no details of pollutant concentrations were able to be predicted, hence the move to CFD modelling. Figure 6-13 which shows the CFD velocity field at 0.1 m/s, is consistent with this prediction.

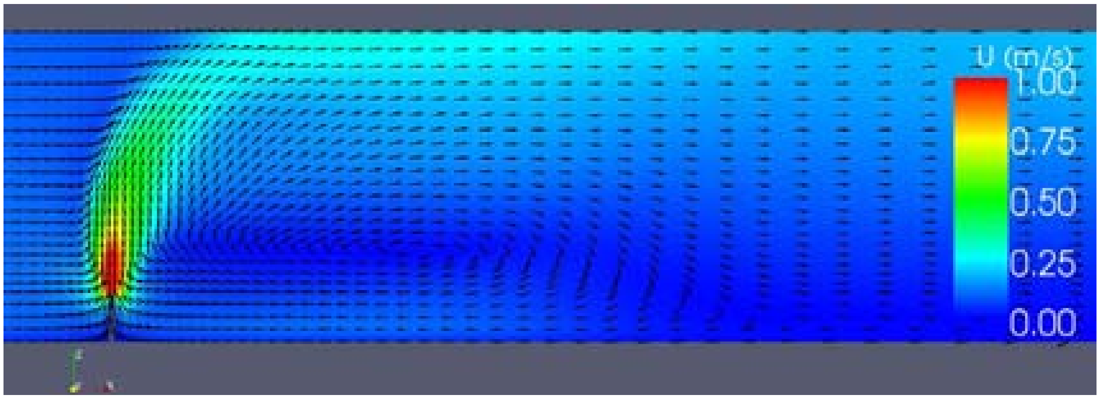


Figure 6-13 Longitudinal Plume Velocity Evolution: 0.1 m/s Ambient Velocity

Figure 6-13 clearly demonstrates a degree of recirculation, which is a quantitative confirmation of the qualitative CORMIX prediction.

Steady State Transverse Cross Sections

Because the CFD modelling is three dimensional, the transverse behaviour of the plumes can be examined. Following is a series of figures that show, as an example, vertical slices through the plume as it evolves downstream for the 0.5 m/s ambient velocity case. The colours again correspond to the tracer concentration, as per the colourbar. The figures are presented in increasing distance downstream of the exit point (as shown in the top left hand corner), and the top of the water column has been truncated for clarity of presentation.

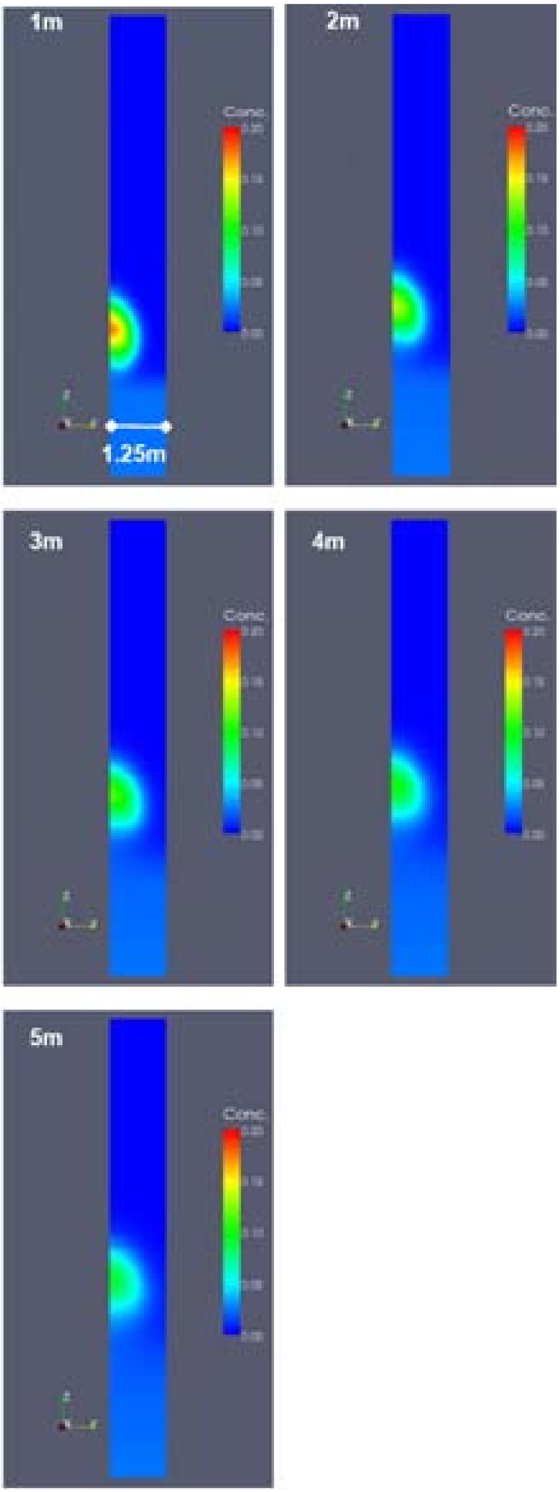


Figure 6-14 Transverse Plume Evolution: 0.5 m/s Ambient Velocity

Figure 6-14 demonstrates that the plume does not occupy the entire water column width or depth. From the results, it is estimated that the cross-sectional area of the water column that contains the 0.1 concentration at 2 m downstream is (at most) 1.0 m by 1.0 m. This is approximately 1.0 m^2 of 25 m^2, i.e. 4% of the flow area. In other words, the higher concentrations potentially above the WQOs are confined to the core of the plume, i.e. the plume centreline and are not spread throughout the entire water column. This is a key finding of the CFD modelling study.

Steady State Centreline Concentrations

The steady state CFD results allowed extraction of the centreline concentration for all computational cells downstream of the exit point. These have been plotted below for illustrative purposes only – quantitative analysis is presented with regards to the dynamics simulations in subsequent sections. The figure is a log-linear plot, and it is stressed that it presents distance downstream of the exit point on the x axis, rather than distance along the plume centreline.

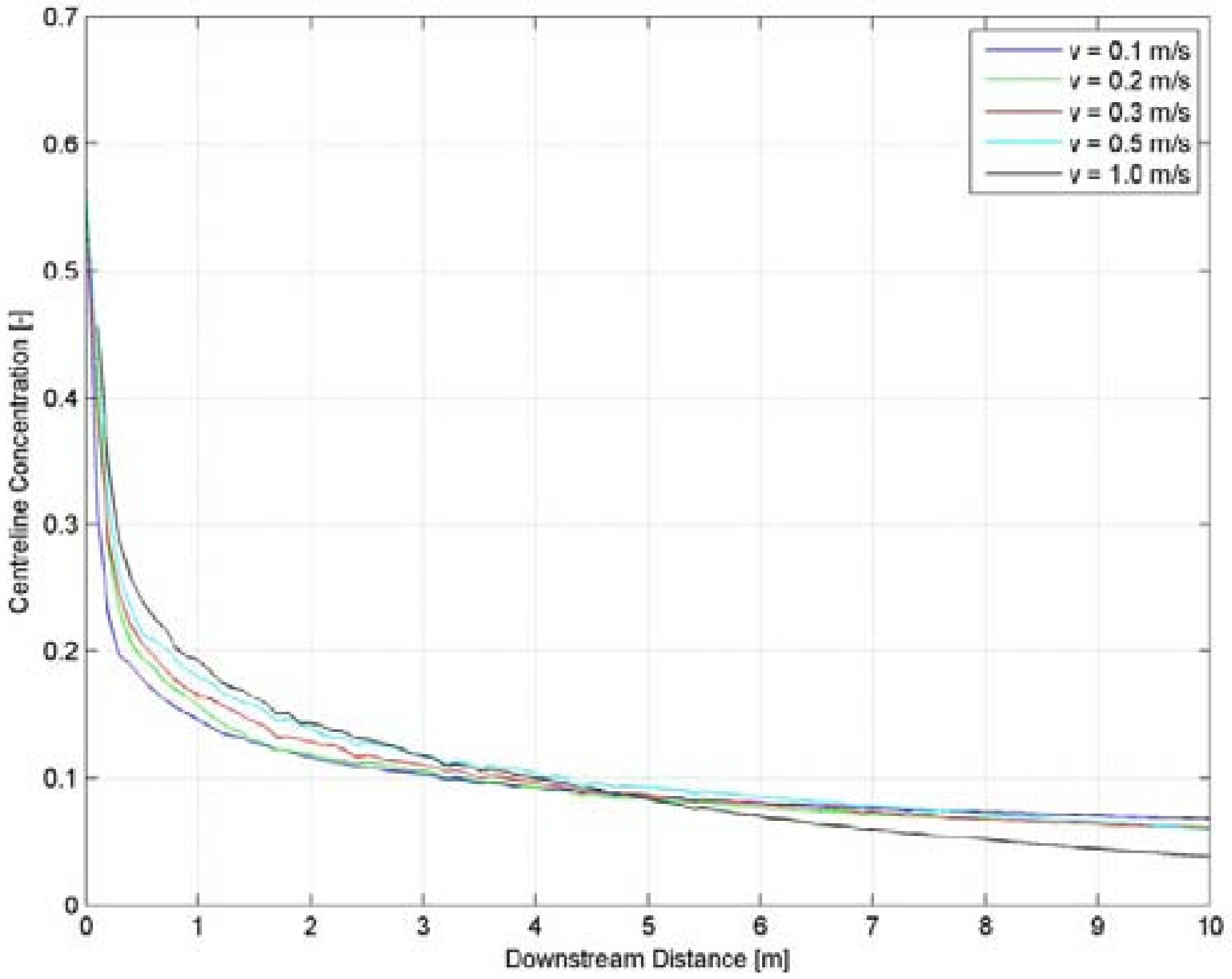


Figure 6-15 Centreline Concentrations with Downstream Distance

Figure 6-15 shows a rapid decrease in centreline concentration with distance downstream for all ambient velocities, with all cases behaving similarly in this regard. Importantly, the 0.1 m/s case shows excellent performance in this regard, primarily because the ejected effluent has an opportunity to mix with the entire water column without travelling far downstream away from the diffuser line. Because the ambient velocity is low, this opportunity allows the plume to mix relatively quickly (in the vertical) using the momentum of the jet, rather than the advection induced mixing mechanism that is predicted in the higher ambient velocity cases.

As a guide, all cases show that a centreline dilution of 10:1 is reached in approximately 5 to 6 metres downstream of the exit point, in the core of the plume.

The centreline dilutions 50m downstream of the diffuser are reported in Table 6-7 for the five ambient velocity cases considered.

Table 6-7 Near-field Predicted Dilutions – Stage 1

Ambient Velocity	Dilution at 50 m Downstream
0.1 m/s	15.9
0.2 m/s	24.9
0.3 m/s	34.7
0.5 m/s	43.3
1.0 m/s	63.9

6.4 Stage 2 Results

6.4.1 RMA-11 Modelling

Within the model each diffuser line was assigned an inflow accompanied by a tracer. The total discharge through the two diffuser lines was 34,200 m^3/hr (i.e. 17,100 m^3/hr per diffuser line). The tracer was assigned a half-life transformation rate of 10 days for manganese, and a zero decay rate for all other parameters. The resulting water quality model simulation covered approximately 10 months, which allowed the tracer to approximate steady state within Port Curtis.

The results are documented below. As for Stage 1, concentration contours, averages and time series are presented only for the zero decay rate simulation results. These results do not apply for manganese, as it is subject to a 10 day half life rate. The results for manganese are reported in the tables.

Spatial and Temporal Concentrations at Steady State

The spatial extent of the tracer covers a large proportion of Port Curtis. The 6-hourly maximum concentration (approximately 0.1%) was found in the immediate vicinity of the diffusers. The 12-hourly maximums were slightly smaller than the 6-hourly concentrations, with a value of approximately 0.07% close to the diffusers. The extent was similar in both cases. Concentrations of less than 0.02% extend across the wider receiving waters in Stage 2.

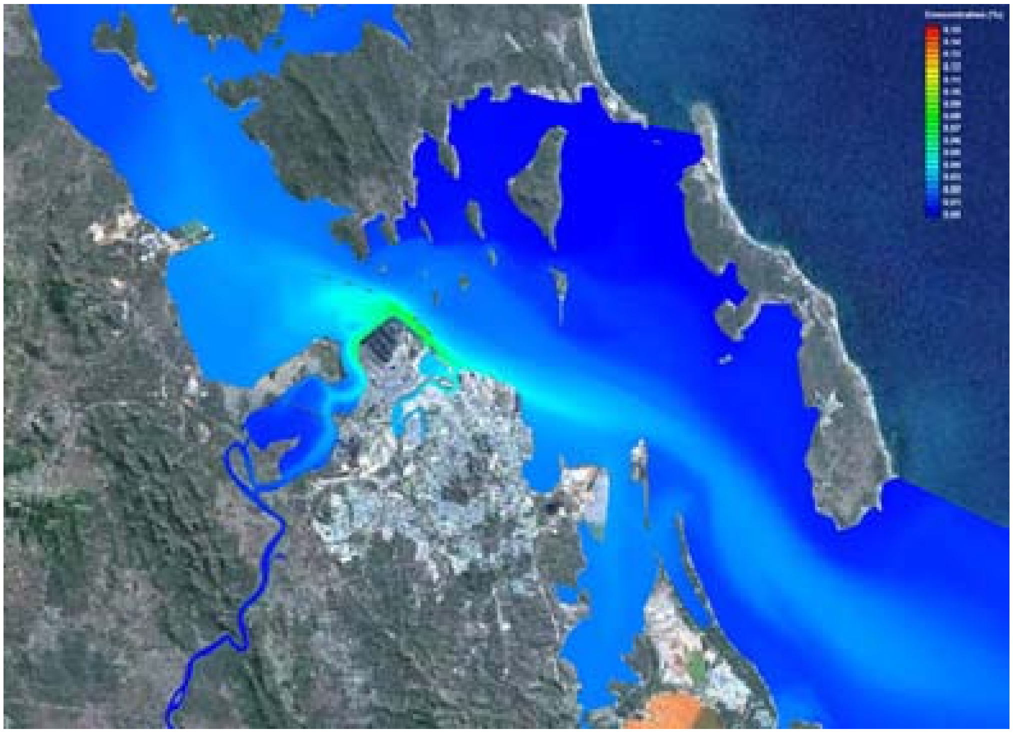


Figure 6-16 6-hourly Maximum Concentrations of the Tracer in Port Curtis – Stage 2

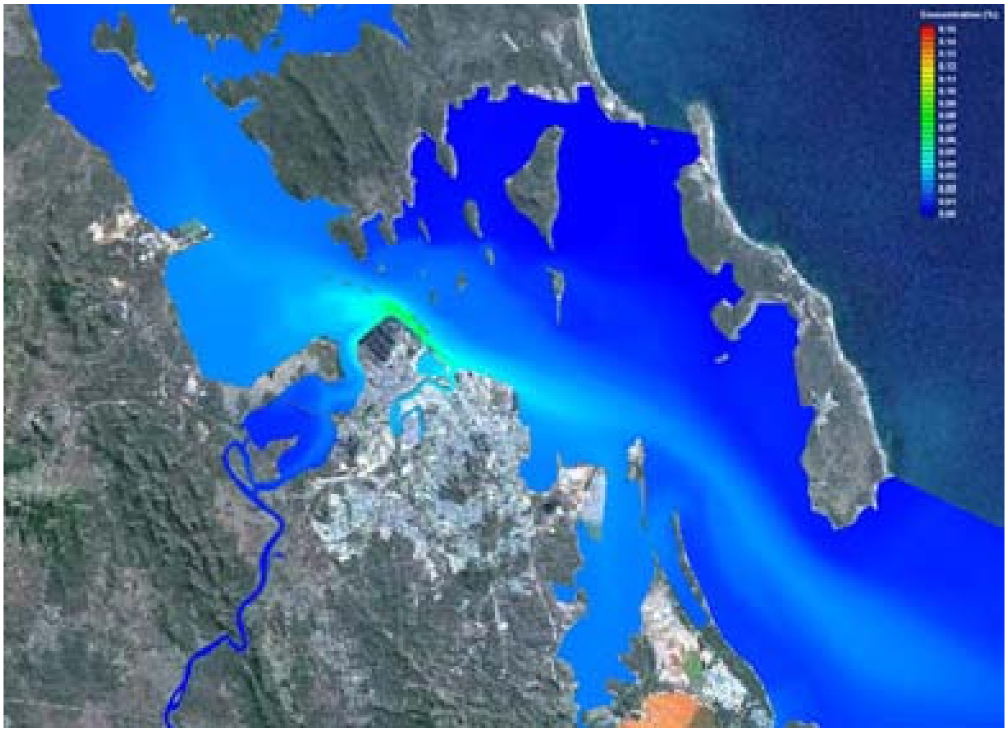


Figure 6-17 12-hourly Maximum Concentrations of the Tracer in Port Curtis – Stage 2

The time series data (Figure 6-18) show the temporal variation in the concentrations, with peaks and troughs occurring due to the flood - ebb tidal cycle and the spring neap cycle.

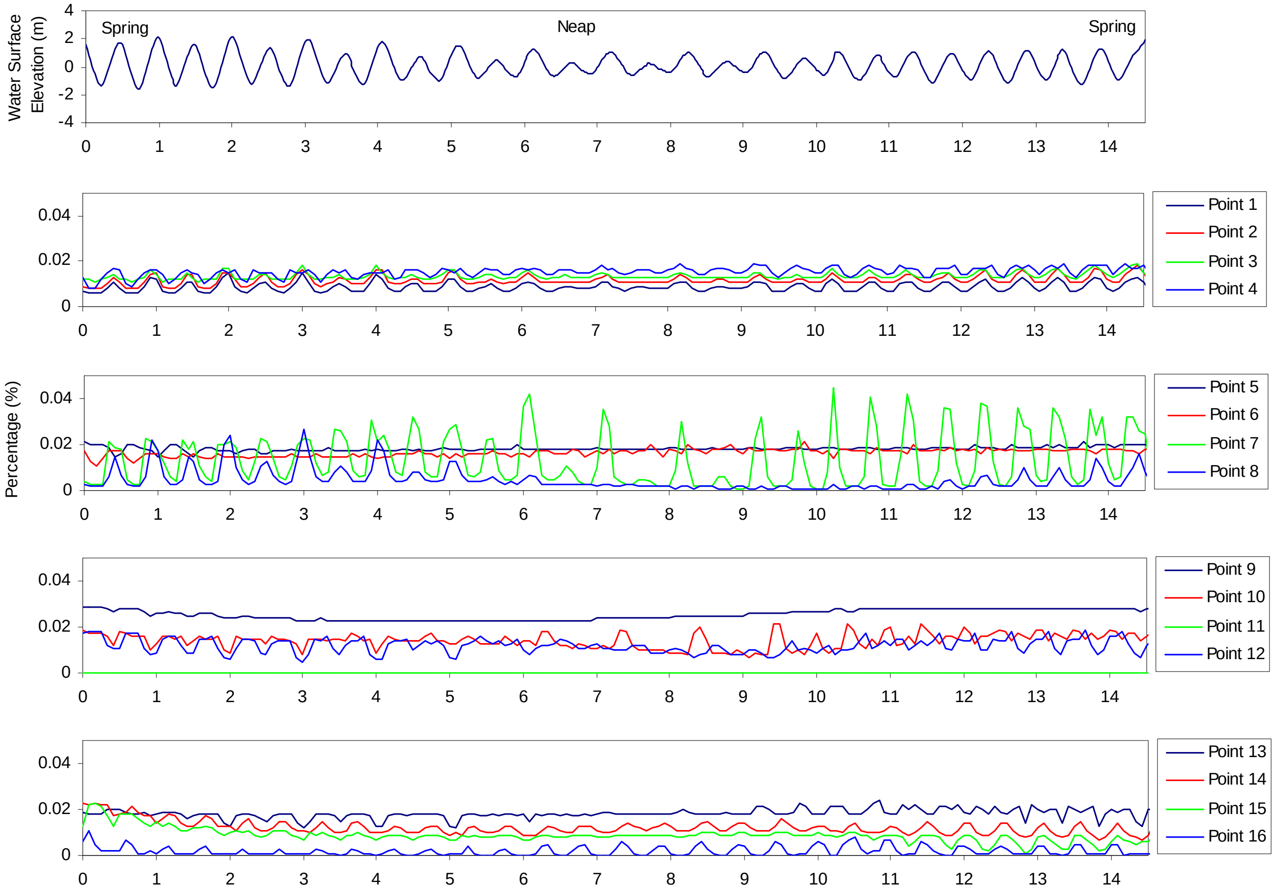


Figure 6-18 Time series of Concentrations at 16 Locations Within Port Curtis – Stage 2

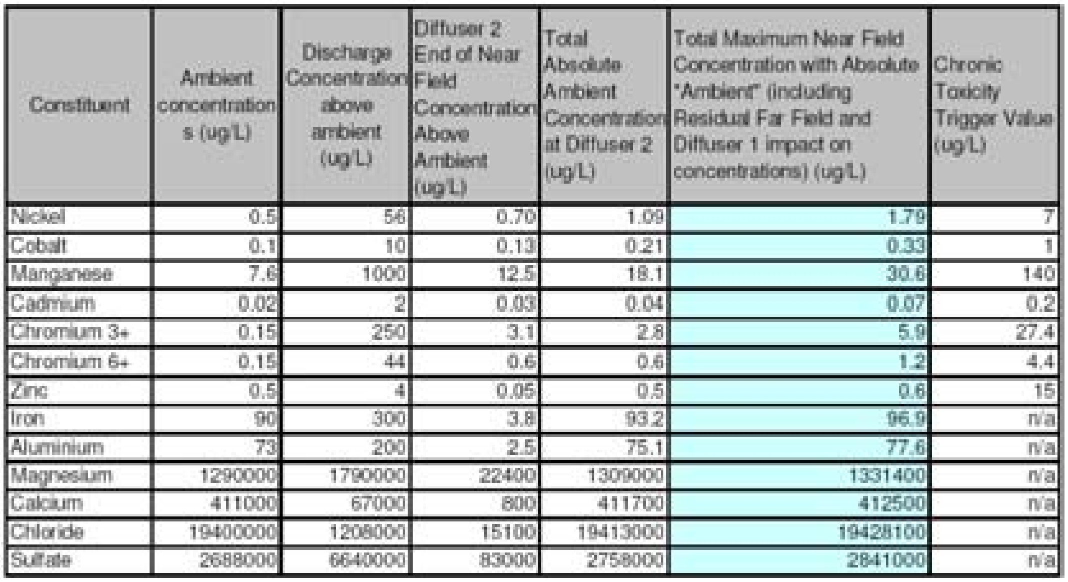
Figure 6-19 Location of Tracer Concentrations Time Series Data at Steady State

6.4.2 CORMIX Modelling

Stage 2 pollutant concentrations were estimated at the end of the mixing zone (as defined by CORMIX) of Diffuser 2. As discussed previously, they take into account long term background concentrations increases in the vicinity of the diffuser (computed with the far-field modelling results) and the residual near-field concentrations from Diffuser 1, 600 m distant from Diffuser 2).

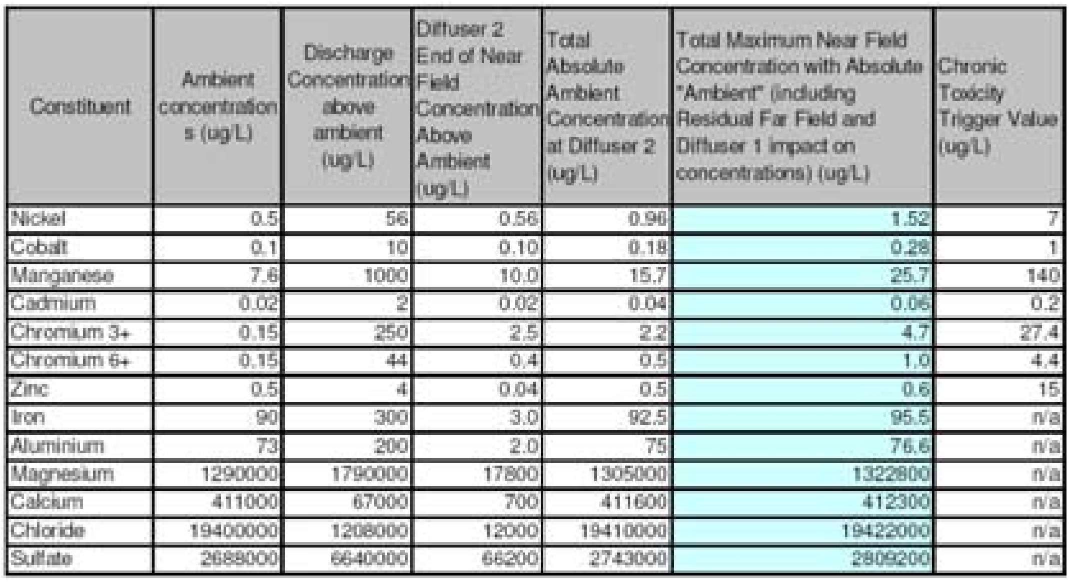
Stage 2 pollutant concentration results are reported in Table 6-8 to Table 6-12 for the five considered ambient velocities.

Table 6-8 Near-field Pollutant Concentrations (End of Diffuser 2 Near-field Region) –Stage 2 – Ambient Velocity of 0.16 m/s



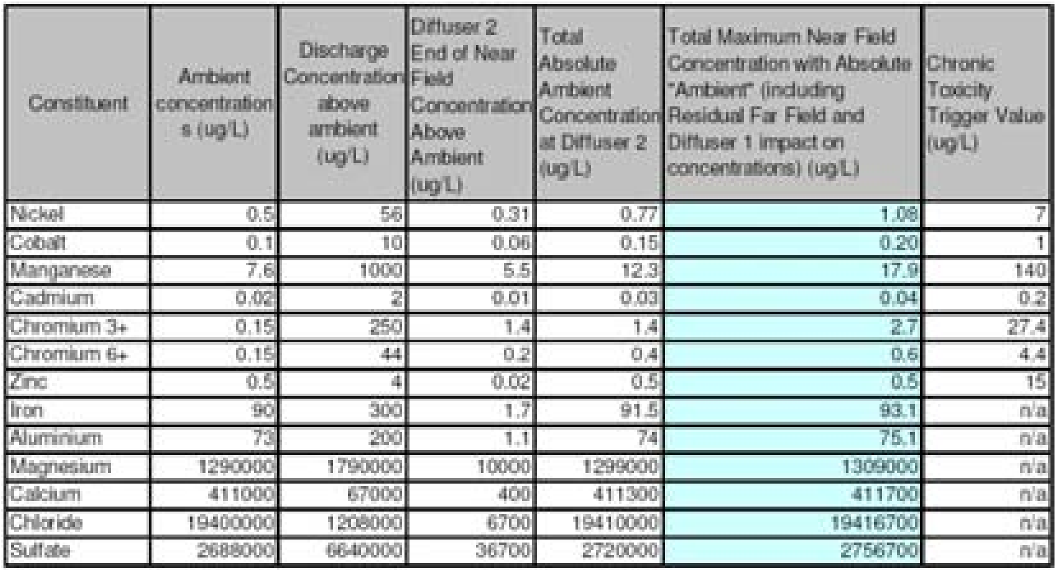
Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	Diffuser 2 End of Near Field Concentration Above Ambient (ug/L)	Total Absolute Ambient Concentration at Diffuser 2 (ug/L)	Total Maximum Near Field Concentration with Absolute "Ambient" (including Residual Far Field and Diffuser 1 impact on concentrations) (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.70	1.09	1.79	7
Cobalt	0.1	10	0.13	0.21	0.33	1
Manganese	7.6	1000	12.5	18.1	30.6	140
Cadmium	0.02	2	0.03	0.04	0.07	0.2
Chromium 3+	0.15	250	3.1	2.8	5.9	27.4
Chromium 6+	0.15	44	0.6	0.6	1.2	4.4
Zinc	0.5	4	0.05	0.5	0.6	15
Iron	90	300	3.8	93.2	96.9	n/a
Aluminium	73	200	2.5	75.1	77.6	n/a
Magnesium	1290000	1790000	22400	1309000	1331400	n/a
Calcium	411000	67000	800	411700	412500	n/a
Chloride	19400000	1208000	15100	19413000	19428100	n/a
Sulfate	2688000	6640000	83000	2758000	2841000	n/a

Table 6-9 Near-field Pollutant Concentrations (End of Diffuser 2 Near-field Region) –Stage 2 – Ambient Velocity of 0.25 m/s



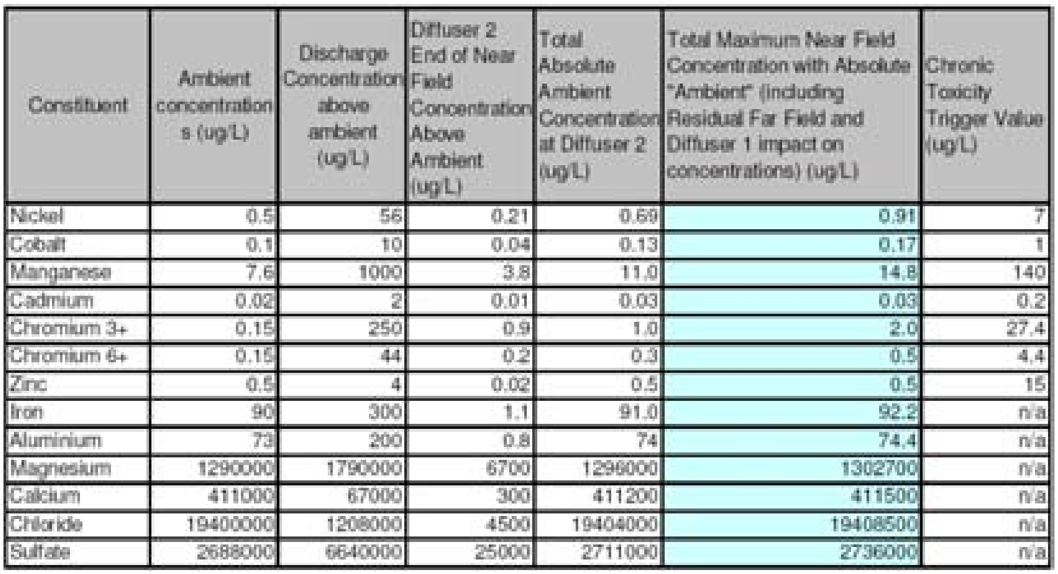
Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	Diffuser 2 End of Near Field Concentration Above Ambient (ug/L)	Total Absolute Ambient Concentration at Diffuser 2 (ug/L)	Total Maximum Near Field Concentration with Absolute "Ambient" (including Residual Far Field and Diffuser 1 impact on concentrations) (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.56	0.96	1.52	7
Cobalt	0.1	10	0.10	0.18	0.28	1
Manganese	7.6	1000	10.0	15.7	25.7	140
Cadmium	0.02	2	0.02	0.04	0.06	0.2
Chromium 3+	0.15	250	2.5	2.2	4.7	27.4
Chromium 6+	0.15	44	0.4	0.5	1.0	4.4
Zinc	0.5	4	0.04	0.5	0.6	15
Iron	90	300	3.0	92.5	95.5	n/a
Aluminium	73	200	2.0	75	76.6	n/a
Magnesium	1290000	1790000	17800	1305000	1322800	n/a
Calcium	411000	67000	700	411600	412300	n/a
Chloride	19400000	1208000	12000	19410000	19422000	n/a
Sulfate	2688000	6640000	66200	2743000	2809200	n/a

Table 6-10 Near-field Pollutant Concentrations (End of Diffuser 2 Near-field Region) – Stage 2 – Ambient Velocity of 0.50 m/s



Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	Diffuser 2 End of Near Field Concentration Above Ambient (ug/L)	Total Absolute Ambient Concentration at Diffuser 2 (ug/L)	Total Maximum Near Field Concentration with Absolute "Ambient" (including Residual Far Field and Diffuser 1 impact on concentrations) (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.31	0.77	1.08	7
Cobalt	0.1	10	0.06	0.15	0.20	1
Manganese	7.6	1000	5.5	12.3	17.9	140
Cadmium	0.02	2	0.01	0.03	0.04	0.2
Chromium 3+	0.15	250	1.4	1.4	2.7	27.4
Chromium 6+	0.15	44	0.2	0.4	0.6	4.4
Zinc	0.5	4	0.02	0.5	0.5	15
Iron	90	300	1.7	91.5	93.1	n/a
Aluminium	73	200	1.1	74	75.1	n/a
Magnesium	1290000	1790000	10000	1299000	1309000	n/a
Calcium	411000	67000	400	411300	411700	n/a
Chloride	19400000	1208000	6700	19410000	19416700	n/a
Sulfate	2688000	6640000	36700	2720000	2756700	n/a

Table 6-11 Near-field Pollutant Concentrations (End of Diffuser 2 Near-field Region) – Stage 2 – Ambient Velocity of 0.75 m/s



Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	Diffuser 2 End of Near Field Concentration Above Ambient (ug/L)	Total Absolute Ambient Concentration at Diffuser 2 (ug/L)	Total Maximum Near Field Concentration with Absolute "Ambient" (including Residual Far Field and Diffuser 1 impact on concentrations) (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.21	0.69	0.91	7
Cobalt	0.1	10	0.04	0.13	0.17	1
Manganese	7.6	1000	3.8	11.0	14.8	140
Cadmium	0.02	2	0.01	0.03	0.03	0.2
Chromium 3+	0.15	250	0.9	1.0	2.0	27.4
Chromium 6+	0.15	44	0.2	0.3	0.5	4.4
Zinc	0.5	4	0.02	0.5	0.5	15
Iron	90	300	1.1	91.0	92.2	n/a
Aluminium	73	200	0.8	74	74.4	n/a
Magnesium	1290000	1790000	6700	1296000	1302700	n/a
Calcium	411000	67000	300	411200	411500	n/a
Chloride	19400000	1208000	4500	19404000	19408500	n/a
Sulfate	2688000	6640000	25000	2711000	2736000	n/a

Table 6-12 Near-field Pollutant Concentrations (End of Diffuser 2 Near-field Region) – Stage 2 – Ambient Velocity of 1.0 m/s

Constituent	Ambient concentrations (ug/L)	Discharge Concentration above ambient (ug/L)	Diffuser 2 End of Near Field Concentration Above Ambient (ug/L)	Total Absolute Ambient Concentration at Diffuser 2 (ug/L)	Total Maximum Near Field Concentration with Absolute "Ambient" (including Residual Far Field and Diffuser 1 impact on concentrations) (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	56	0.16	0.65	0.81	7
Cobalt	0.1	10	0.03	0.13	0.16	1
Manganese	7.6	1000	2.8	10.3	13.1	140
Cadmium	0.02	2	0.01	0.03	0.03	0.2
Chromium 3+	0.15	250	0.7	0.8	1.5	27.4
Chromium 6+	0.15	44	0.1	0.3	0.4	4.4
Zinc	0.5	4	0.01	0.5	0.5	15
Iron	90	300	0.9	90.8	91.7	n/a
Aluminium	73	200	0.6	74	74.1	n/a
Magnesium	1290000	1790000	5000	1295000	1300000	n/a
Calcium	411000	67000	200	411200	411400	n/a
Chloride	19400000	1208000	3400	19403000	19406400	n/a
Sulfate	2688000	6640000	18800	2706000	2724800	n/a

The following table reports the distance downstream of Diffuser 2 where the WQOs are predicted to be met.

Table 6-13 Compliance with Chronic Toxicity Trigger Values Downstream of Diffuser – Stage 2

Constituent	Chronic Toxicity Trigger Value (ug/L)	V=0.16m/s Distance (m)	V=0.25m/s Distance (m)	V=0.5m/s Distance (m)	V=0.75m/s Distance (m)	V=1m/s Distance (m)
Nickel	7	4.5	2.7	1.4	0.3	0.2
Cobalt	1	5.9	3.6	1.9	0.3	0.2
Manganese	140	3.9	2.4	1.2	0.2	0.2
Cadmium	0.2	5.9	3.6	1.9	0.3	0.2
Chromium 3+	27.4	4.8	2.9	1.5	0.3	0.2
Chromium 6+	4.4	5.5	3.3	1.7	0.3	0.2
Zinc	15	0.1	0.1	0.1	0.1	0.1

6.4.3 CFD Analysis

No additional CFD simulations were executed for Stage 2 as the two proposed diffusers are the same the near-field dynamics will be similar for both. Figure 6-20 shows the existing cross section at the proposed Diffuser 2 location.

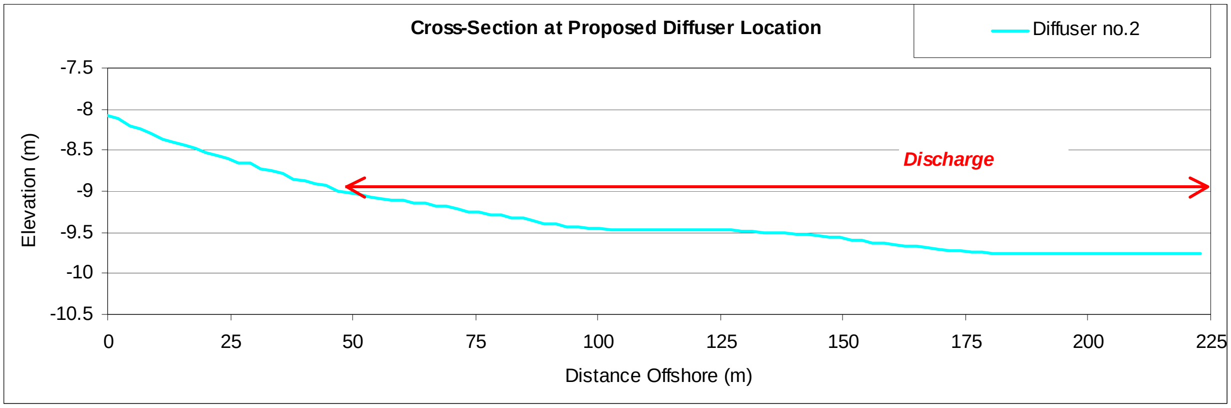


Figure 6-20 Cross Section of the Water Depth for Diffuser Pipeline – Stage 2

Discharge water quality, existing ambient concentrations and water quality objectives were the same as for Stage 1. The steady state plume characteristics described in Section 6.3.3 for Stage 1 will also apply for Stage 2.

7.1 Marine Water Quality

7.1.1 Far-Field Effects

Based on the results of the modelling (far-field and near-field), the following table summaries the predicted total maximum pollutant concentrations for Stage 1. It can be seen from these results that all WQOs will be met.

Table 7-1 Maximum Far-field (Only) Pollutant Concentrations Over Entire Domain – Stage 1

Constituent	Ambient Concentration (ug/L)	Barren Liquor (ug/L)	Discharge Concentration (ug/L)	Maximum Additional Far Field Concentration (ug/L)	Total Maximum Far Field Concentration (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	560	56	0.015	0.52	7
Cobalt	0.1	100	10	0.003	0.10	1
Manganese	7.6	10000	1007	0.272	7.9	140
Cadmium	0.02	20	2	0.001	0.02	0.2
Chromium 3+	0.15	2500	250	0.068	0.22	27.4
Chromium 6+	0.15	440	44	0.012	0.16	4.4
Zinc	0.5	40	4	0.001	0.50	15
Iron	90	3000	381	0.103	90.1	n/a
Aluminium	73	2000	266	0.072	73.1	n/a
Magnesium	1290000	17900000	2951717	797	1290797	n/a
Calcium	411000	670000	437006	118	411118	n/a
Chloride	19400000	12080000	see note 1			n/a
Sulfate	2688000	66400000	9061402	2447	2690447	n/a

Note 1: The chloride discharge concentration is below the background receiving water concentration. This means that the discharge and dilution of this constituent into Port Curtis will, to a certain extent, reduce ambient salinity. In addition, no chronic trigger value was provided for this constituent. Hence, the chloride maximum concentrations downstream of the diffusers have not been reported in the results tables.

For Stage 2, the results of the modelling again show that all water quality objectives will be met. The following table summarises the total maximum pollutant concentrations for Stage 2 and the water quality objectives.

Table 7-2 Maximum Far-field (Only) Pollutant Concentrations Over Entire Domain – Stage 2

Constituent	Ambient Concentration (ug/L)	Barren Liquor (ug/L)	Discharge Concentration (ug/L)	Maximum Additional Far Field Concentration (ug/L)	Total Maximum Far Field Concentration (ug/L)	Chronic Toxicity Trigger Value (ug/L)
Nickel	0.5	560	56	0.027	0.53	7
Cobalt	0.1	100	10	0.005	0.10	1
Manganese	7.6	10000	1007	0.473	8.1	140
Cadmium	0.02	20	2	0.001	0.02	0.2
Chromium 3+	0.15	2500	250	0.118	0.27	27.4
Chromium 6+	0.15	440	44	0.021	0.17	4.4
Zinc	0.5	40	4	0.002	0.50	15
Iron	90	3000	381	0.179	90.2	n/a
Aluminium	73	2000	266	0.125	73.1	n/a
Magnesium	1290000	17900000	2952249	1388	1291388	n/a
Calcium	411000	670000	437085	205	411205	n/a
Chloride	19400000	12080000	see note 1			n/a
Sulfate	2688000	66400000	9063033	4260	2692260	n/a

Note 1: The chloride discharge concentration is below the background receiving water concentration. This means that the discharge and dilution of this constituent into Port Curtis will, to a certain extent, reduce ambient salinity. In addition, no chronic trigger value was provided for this constituent. Hence, the chloride maximum concentrations downstream of the diffusers have not been reported in the results tables.

7.1.2 Near-Field Effects

Two modelling packages were used to investigate the near-field plume behaviour. The first model used was the 1-dimensional CORMIX model, but due to limitations becoming apparent in the latter stages of this study, a second, more detailed 3-dimensional CFD model was used to provide a more robust assessment of the near-field plume dynamics particularly at low ambient tidal velocities. Limitations of CORMIX which CFD modelling can overcome included:

- No specific investigation of the potential for local recirculation within each eductor could be undertaken.
- The near field modelling of CORMIX was essentially a steady state analysis that could not take into account the influence of the dynamic ambient tidal conditions on plume evolution.
- CORMIX could compute resultant pollutant concentrations for five selected ambient velocities, however modelling of small velocities (< 0.15 m/s) presented limitations with model stability.

For these reasons, the near-field results presented in the follow section are those that were developed using the CFD modelling.

Stage 1

Based on the above far-field concentrations, resultant target dilutions for the near-field simulations have been computed, with these dilutions (and greater) indicating compliance with water quality objectives. These target dilutions are presented below to the nearest integer value, with the corresponding tracer concentrations included. Note that these required dilutions are based on a ten-fold dilution of the refinery effluent before discharge.

Table 7-3 Target Dilutions and Tracer Concentrations – Stage 1

Constituent	Water Quality Objective (μg/L)	Dilution Required	Target Tracer Concentration
Nickel	7	9	0.12
Cobalt	1	11	0.09
Manganese	140	8	0.13
Cadmium	0.2	11	0.09
Chromium 3+	27.4	9	0.11
Chromium 6+	4.4	10	0.10
Zinc	15	0	3.67

Based on the results in Table 7-3, once a dilution of 11:1 has been achieved downstream of the diffuser, all relevant WQOs will have been met.

Near-field results are presented in two ways:

- Colour contour plots of tracer dilution across all depths and all times at each profile location. Each colour contour figure has four panels. The first presents a line plot of the background ambient velocity with time, as applied at the model boundaries. This came from a typical tidal cycle from the far-field model. The vertical red lines bound the period of tidal velocity less than 0.1 m/s^{-1} when the discharge concentration drops to half the normal, (i.e. 20:1 dilution in the dilution pump pit prior to discharge rather than 10:1 when the tidal velocity is greater than 0.1 ms^{-1} (Section 3.0)). The subsequent three panels show the evolution of tracer dilution (as per the colour bar at the bottom of the figure) at a fixed distance away from the port, depending on the figure, with these distances being 0, 3 and 5 m for Figure 7-1, Figure 7-2 and Figure 7-3, respectively.

  Given the dynamic nature of the simulations, each profile location is initially upstream of the diffuser, with the obvious exception of the 0 m downstream case which is over the diffuser line itself. In particular, the vertical profile of tracer dilution is plotted at every timestep, with increasing time along the X axis, and depth on the Y axis, over the simulation duration. As such, it is akin to a prediction for the time variation of results of a field monitoring program that involves taking vertical profiling casts at a set distance (either 0, 3 or 5 m) away from the diffuser, and converting measurements to dilutions. The three panels within each figure differ in their lateral location relative to the diffuser port. The first is midway between ports (i.e. 1.25 m along the diffuser axis from the port), the last is at the port, and the second last panel is at the midpoint between the second and last panels (i.e. 0.625 m along the diffuser axis from the port). The colour contours at 0 m from the diffuser extend only to a depth of 8.4 m as the diffuser pipe occupies 1.6 m vertical extents in the 10 m domain.

- Timeseries of dilutions at 1 m height intervals for each profile location, and correspond to the colour contour figures. These timeseries are grouped into three figures: one each for the location across the diffuser line, i.e. parallel to the discharge port, and 0.625 and 1.25 m along the diffuser away from the port. These correspond to Figure 7-4, Figure 7-5 and Figure 7-6, respectively. Each figure consists of 12 panels. The top two contain the same data: the time variation of ambient tidal velocity, with the vertical red lines encompassing the period over which the tidal velocity magnitude is less than 0.1 ms^{-1}. The remaining 10 panels show the timeseries of tracer dilution at 1 m height increments from the surface downwards. Each of the 10 panels has three timeseries lines, with the blue, green and magenta line colours corresponding to 0, 3 and 5 m downstream of the diffuser pipe, respectively. The horizontal red line on each dilution timeseries plot shows the 11:1 dilution as a reference marker. Data at 9 m below the surface cannot be presented for the 0 m downstream case as this depth is inside the diffuser pipe. Green and magenta (3 and 5 m downstream data) are still presented at that depth.

These figures allow direct visual comparison with the target dilution values for each discharge constituent presented in Table 7-3. The reason that 0, 3 and 5 m data have been presented here is that the draft Queensland EPA (QEPA) licence conditions were targeted towards WQO compliance at locations 3 m downstream of the diffuser (for Stage 1). These locations, in turn, came from the best estimates of the CORMIX modelling at the time the conditions were released. Subsequent investigation gave rise to the need to move to the CFD model for near-field modelling, with the view to then reporting relative to the initial licence conditions. As part of the ongoing discussions around the CFD modelling results, QEPA subsequently requested data at 0 and 5 m from the diffuser to be presented, and as such, this report is a summary of all QEPA data requests regarding the CFD results.

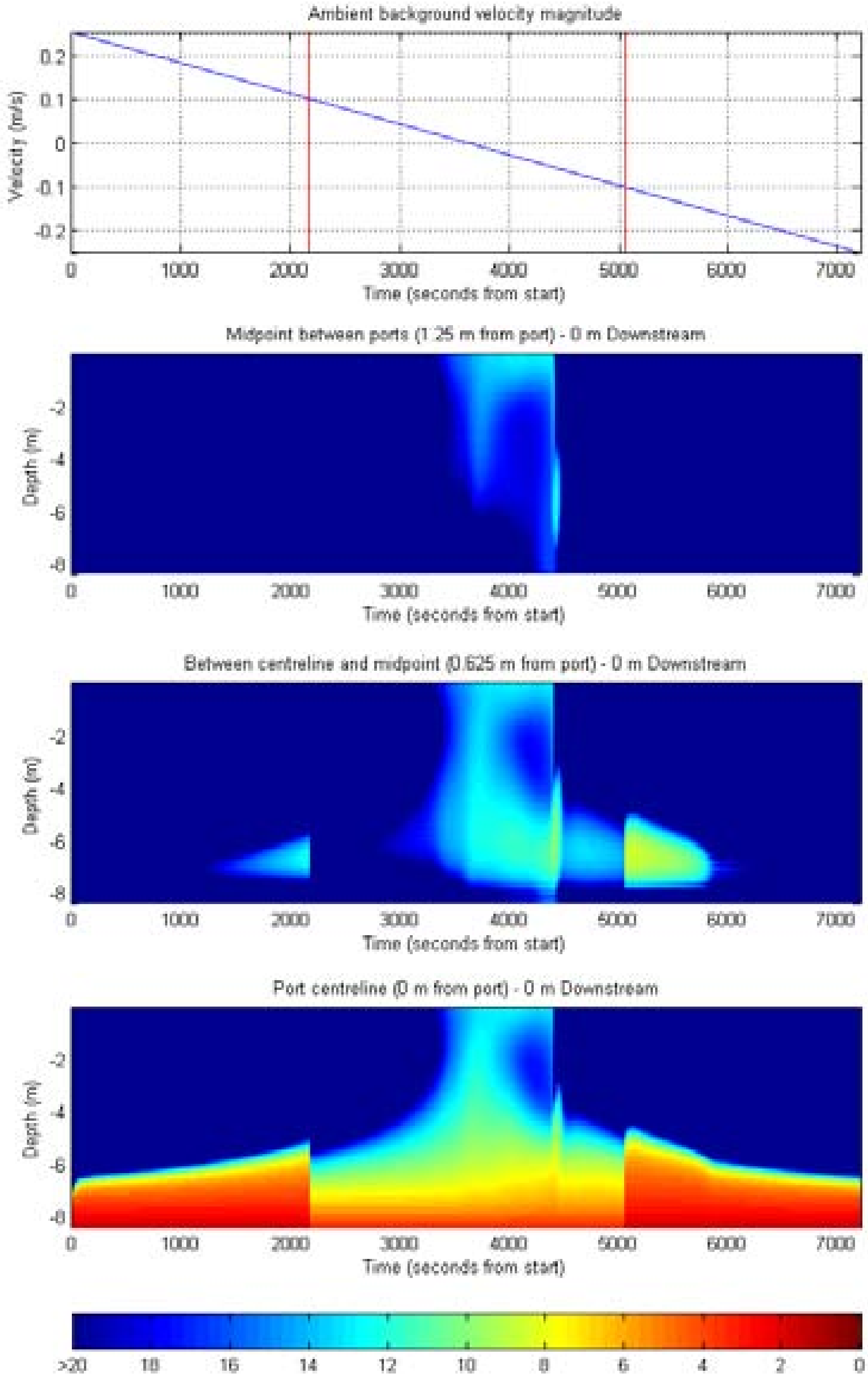


Figure 7-1 Tracer Dilutions – 0 m Downstream Of Diffuser

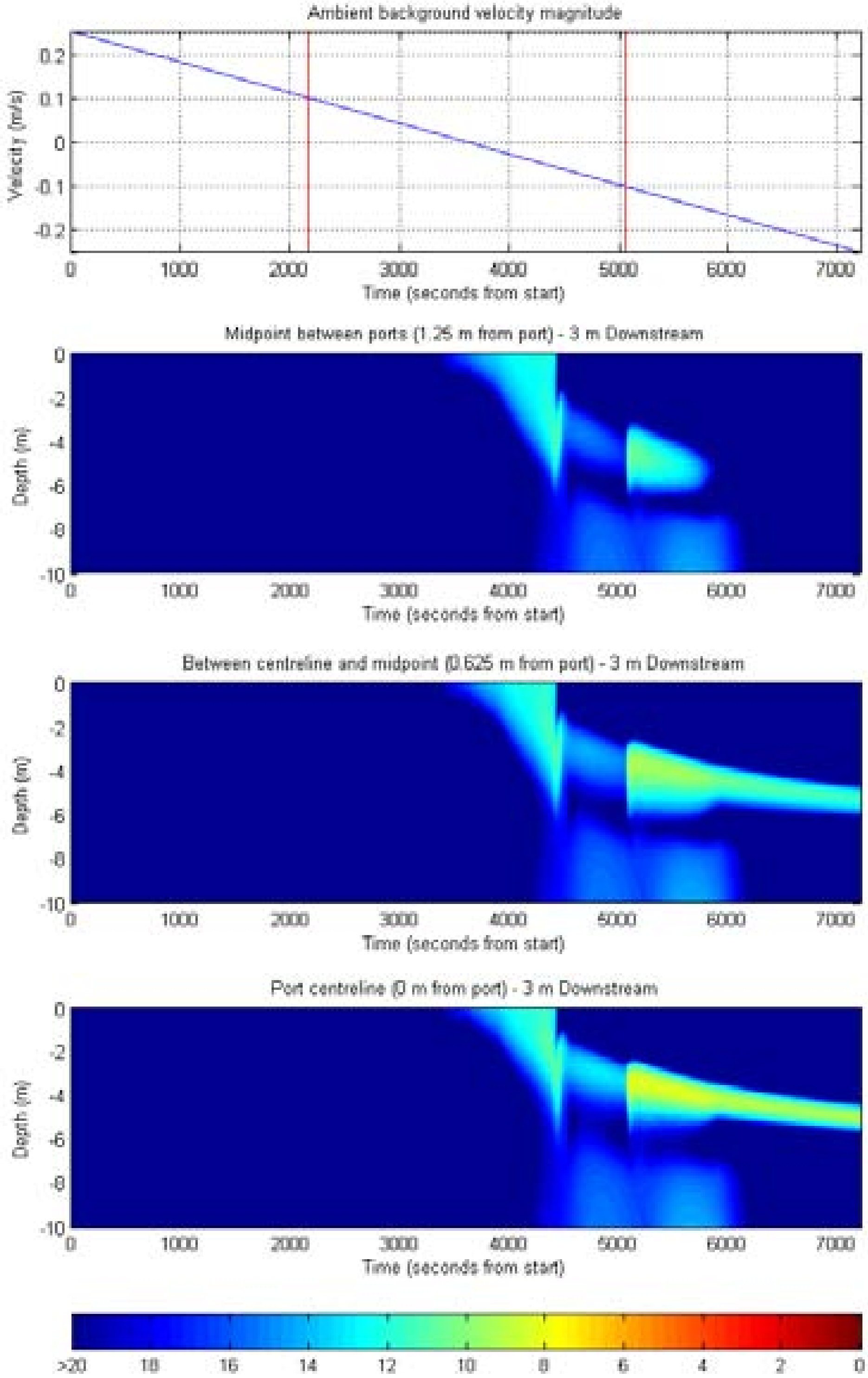


Figure 7-2 Tracer Dilutions – 3 m Downstream Of Diffuser

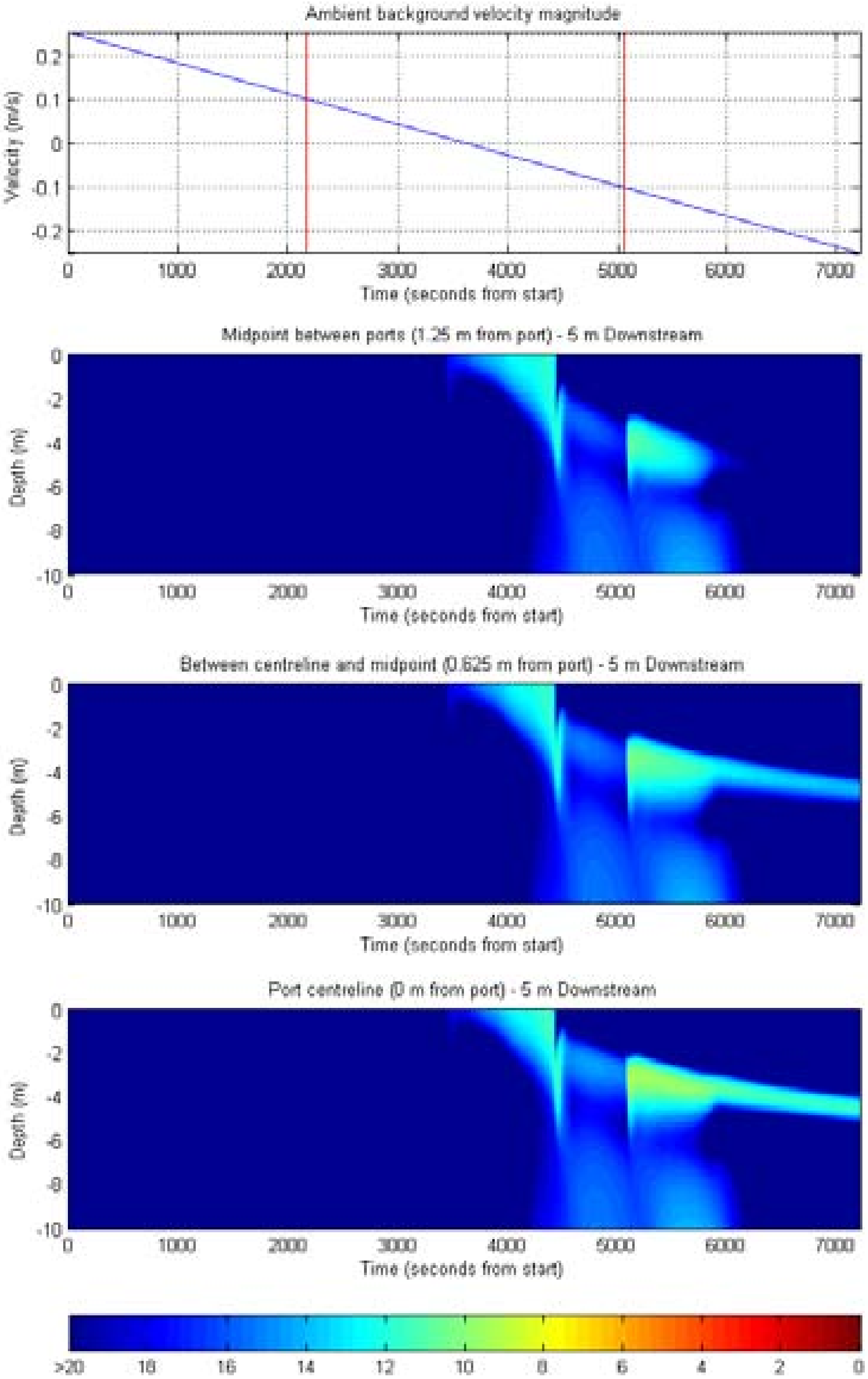


Figure 7-3 Tracer Dilutions – 5 m Downstream Of Diffuser

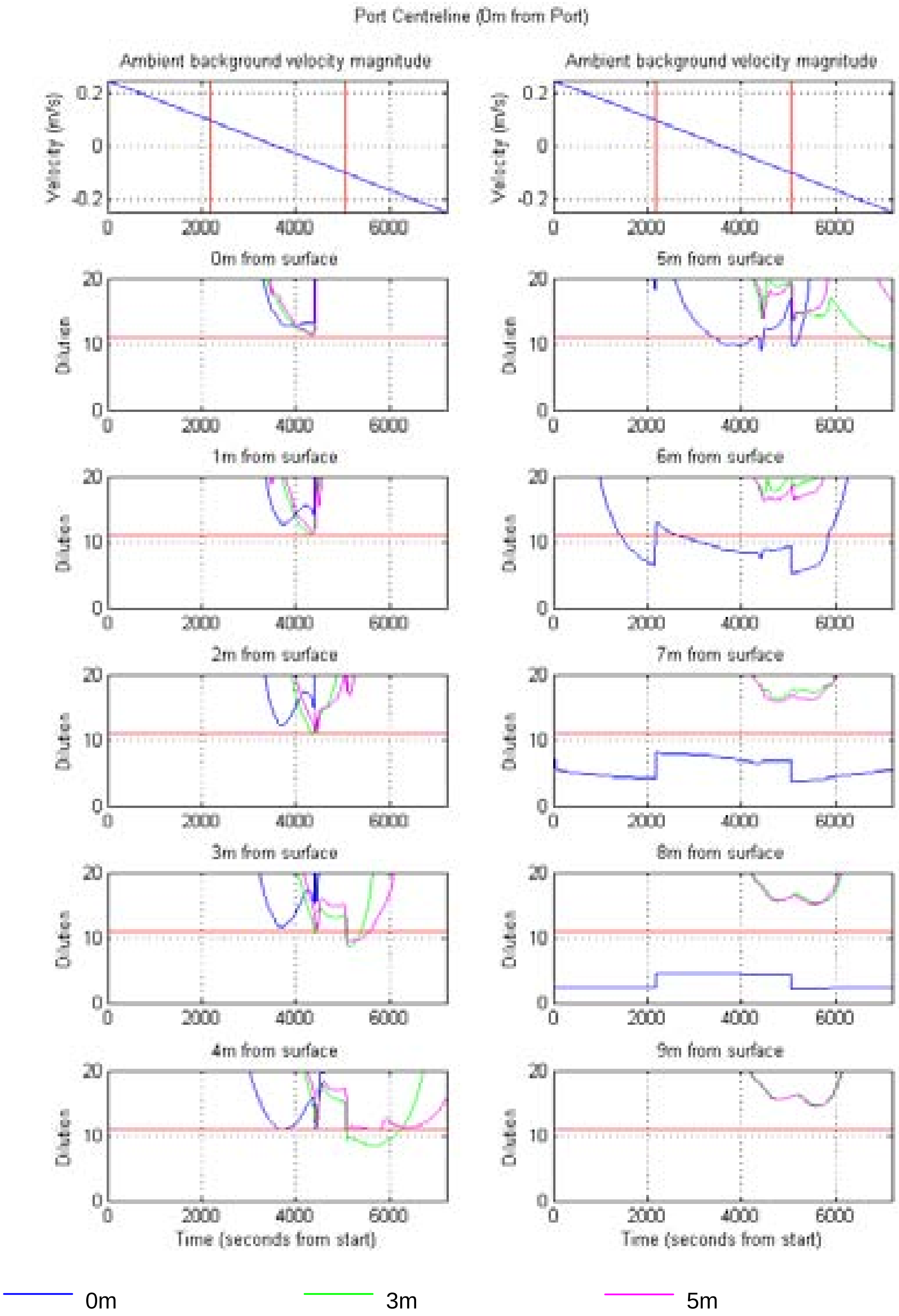


Figure 7-4 Tracer Dilutions – Port Centreline

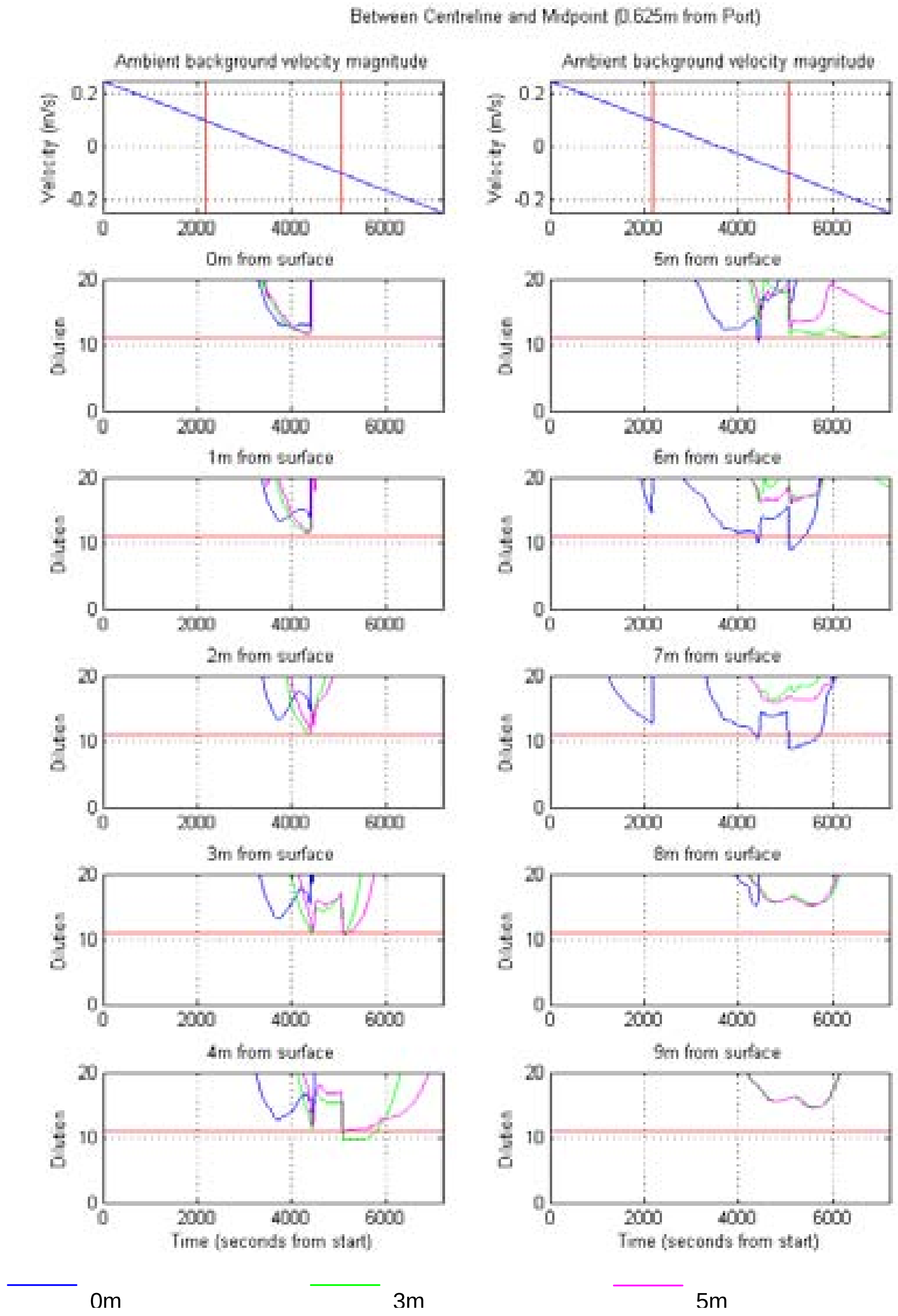


Figure 7-5 Tracer Dilutions – 0.625 m from Port

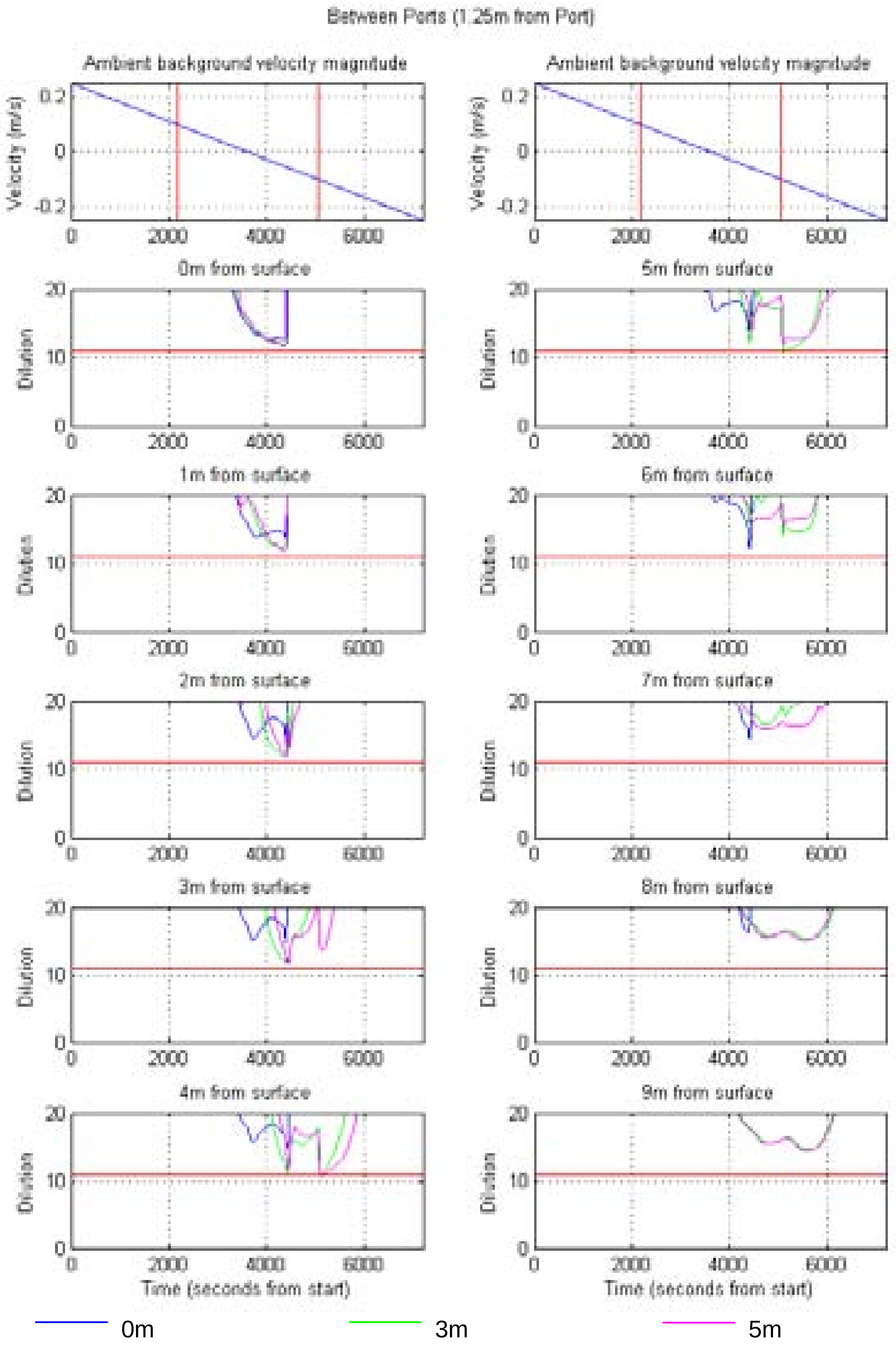


Figure 7-6 Tracer Dilutions – 1.25 m from Port

Stage 2

Based on the far-field concentrations predicted for Stage 2, resultant target dilutions for the near-field simulations have been computed, with these dilutions (and greater) indicating compliance with water quality objectives. These target dilutions are presented below to the nearest integer value, with the corresponding tracer concentrations included. Note that these required dilutions are based on a ten-fold dilution of the refinery effluent before discharge.

Table 7-4 Target Dilutions and Tracer Concentrations – Stage 2

Constituent	Water Quality Objective (µg/L)	Dilution Required	Target Tracer Concentration
Nickel	7	10	0.10
Cobalt	1	13	0.08
Manganese	140	8	0.12
Cadmium	0.2	13	0.08
Chromium 3+	27.4	10	0.10
Chromium 6+	4.4	12	0.08
Zinc	15	0	3.71

Figure 7-7, Figure 7-8 and Figure 7-9 are timeseries of dilutions at 1 m height intervals for each profile location, and correspond to the colour contour figures. These timeseries are grouped into three figures: one each for the location across the diffuser line, i.e. parallel to the discharge port, and 0.625 m and 1.25 m along the diffuser away from the port. Each figure consists of 12 panels. The top two contain the same data: the time variation of ambient tidal velocity, with the vertical red lines encompassing the period over which the tidal velocity magnitude is less than 0.1 ms^{-1} (low tidal flow periods). The remaining 10 panels show the timeseries of tracer dilution at 1 m height increments from the surface downwards. Each of the 10 panels has three timeseries lines, with the blue, green and magenta line colours corresponding to 0, 3 and 5 m downstream of the diffuser pipe, respectively. The horizontal red line on each dilution timeseries plot shows the 20:1 dilution as a reference marker. Data at 9 m below the surface cannot be presented for the 0 m downstream case as this depth is inside the diffuser pipe. Green and magenta (3 and 5 m downstream data) are still presented at that depth.

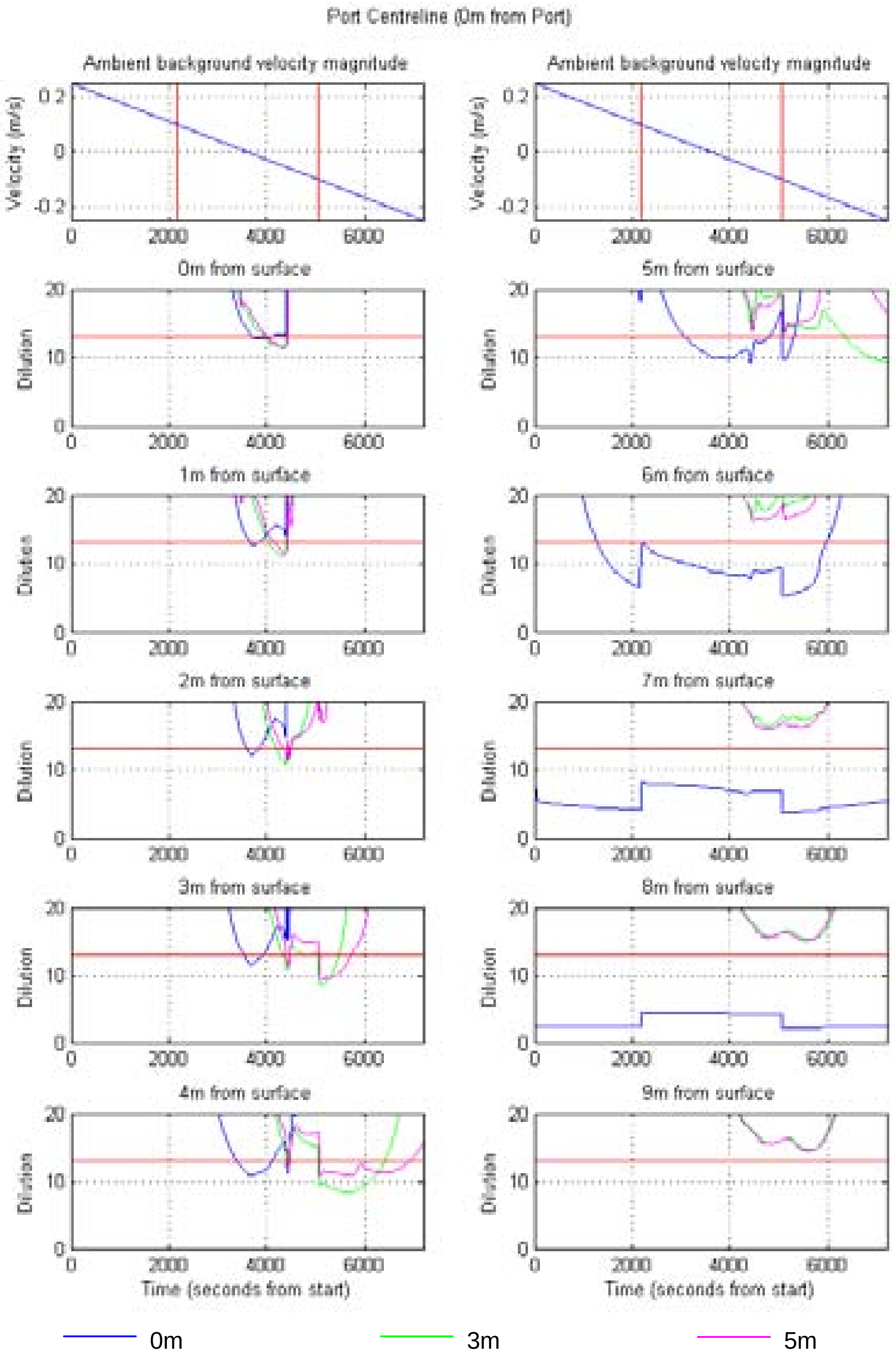


Figure 7-7 Tracer Dilutions – 0 m from Port

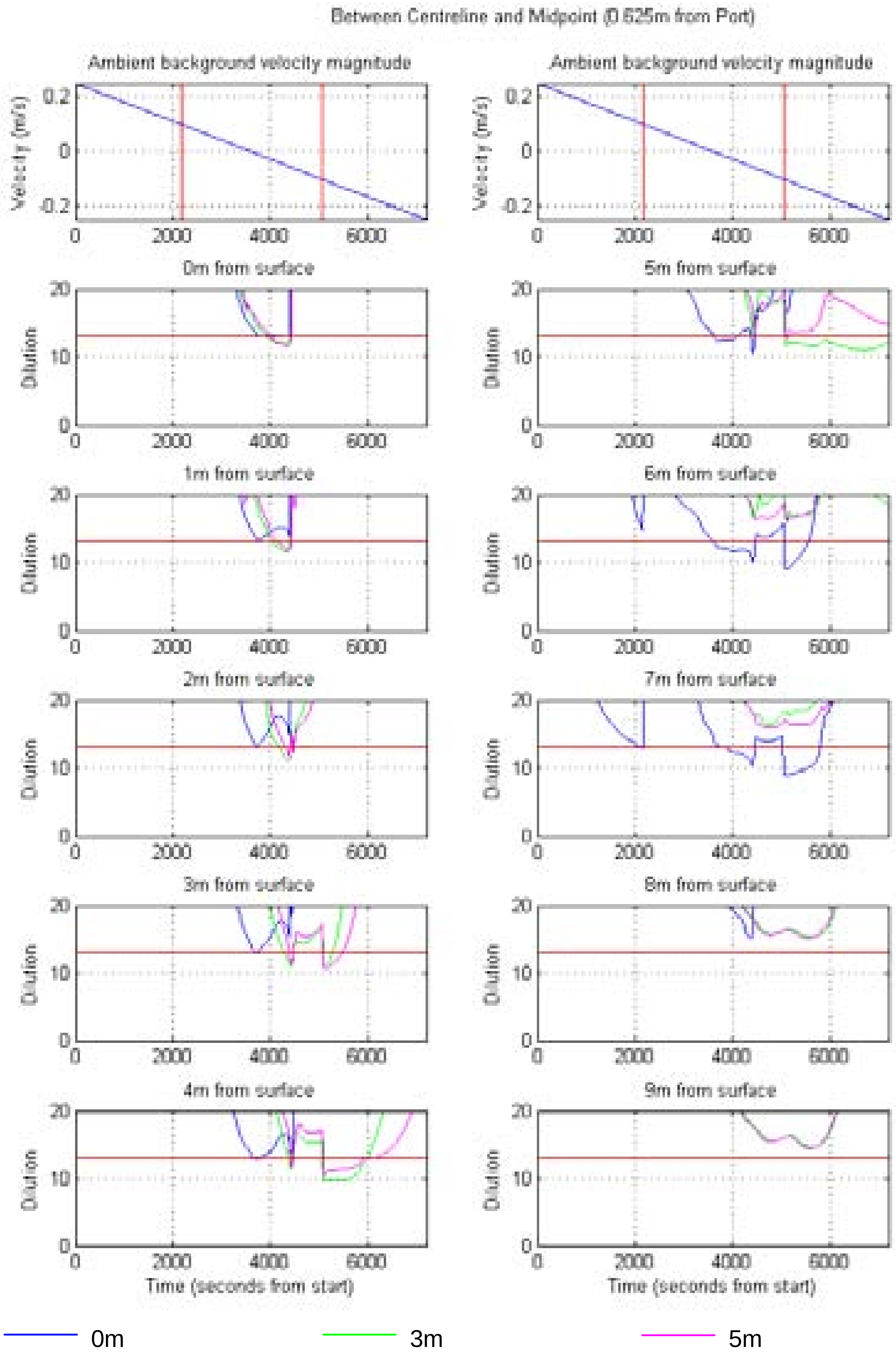


Figure 7-8 Tracer Dilutions – 0.625 m from Port

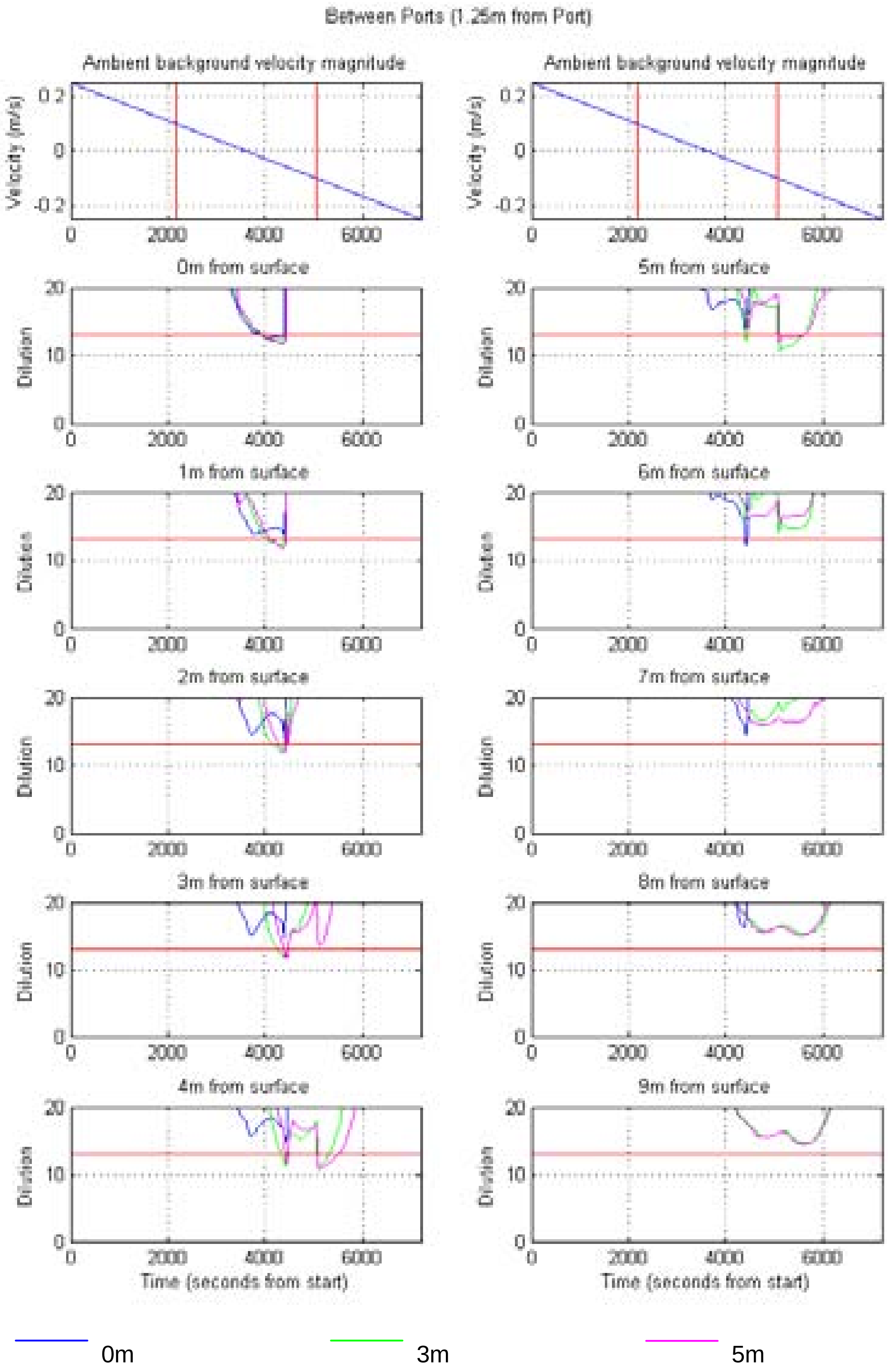


Figure 7-9 Tracer Dilutions – 1.25 m from Port

Discussion

Key points arising from analysis of the modelling results are as follows.

- Peak concentrations (minimum dilutions) predicted by the CFD modelling occur primarily in the core of the effluent plume. Importantly, these lower dilutions are not representative of bulk (or even 'typical') downstream concentrations: they are the highest expected concentrations at any time, and only occupy the very central core of each diffuser port plume. As such, they should not be interpreted as characteristic concentrations, and the corresponding computed distances downstream to achieve WQOs do not apply to the entire diffuser length, or water depth.
- For Stage 1, dilutions below 11:1 occur at specific heights in the water column, and persist for very short periods of time. For example, the longest time for which the dilution falls below this level at 3 m from the diffuser (and directly downstream of the port as per Figure 7-4) is approximately 1,000 seconds, or 16 minutes, and this occurs only at 4 m from the water surface. Typically, these lower dilutions are short lived and are not generally reflective of typical downstream dilutions.
- For Stage 2, dilutions below 13:1 occur at specific heights in the water column, and persist for very short periods of time. For example, the longest time for which the dilution falls below this level at 3 m from the diffuser (and directly downstream of the port as per Figure 7-7) is approximately 1,250 seconds, or 21 minutes, and this occurs only at 4 m from the water surface.
- Extending the above, the CFD modelling has shown that the individual plumes (of which the central cores are a subset) occupy a small fraction of the total cross-sectional flow area, even at very short distances downstream of the exit point.
- Concentration peaks do not occur during slack flow periods, at least at 3 m away from the diffuser. The highest tracer concentration observed at the plume centreline location during discharge at 20:1 dilution is 0.093, i.e. almost 11:1 dilution, and this occurs only for a few minutes at a specific height in the water column. Referring to Table 7-3, this dilution is in the vicinity of the maximum required to meet WQOs for Stage 1. The reason for this high dilution is that at these low background velocities, the jet from the port mixes well with the entire water column under the influence of the ejected plume momentum. The results show also that some large scale recirculation occurs during these times as tracer signals appear 3 m from the diffuser at the time when the ambient velocity approximates 0 ms^{-1}. This large scale eddying was predicted qualitatively by CORMIX.
- Overall concentration peaks occur only in the core of the effluent plumes following increase in ambient velocities and discharge concentrations (10:1 dilution instead of 20:1). These core concentrations occupy a very small fraction of the water column cross-sectional area.
- The recommencement of discharge at 10:1 dilution following slack water is clearly visible in the results at approximately t=5,000 seconds.
- The CFD modelling was set to have almost zero background (ambient flow) turbulence, with a relatively smooth bottom surface. In reality, there will be considerable background turbulence generated both naturally and as a result of flow interaction with existing infrastructure such as the RG Tanner approach wharf piles. As such, the CFD modelling has, if anything, under-predicted the capability of the background flow to further mix the plume and dilute the discharged effluent, and as such has overestimated centreline concentrations.

Recirculation

In addition to the CFD simulations, the far-field RMA-11 results have been re-interrogated to qualitatively assess the likelihood of water that initially flows over the diffuser returning at subsequent tidal states. This return flow of all waters is an implicit assumption of the CFD modelling. This investigation has been undertaken by inserting numerical drogues into the RMA-11 hydrodynamic results, and allowing these drogues to be advected by the ambient velocity field over several tidal cycles. Figures 7-10 and 7-11 show the eventual paths of the numerical drogues. The drogues leave a trail indicating their paths. The first panel is the initial condition (i.e. drogues released over and between the diffusers), and the second panel shows the drogue paths after several tidal cycles.

Figure 7-10 RMA-11 Drogue Path Initial Condition

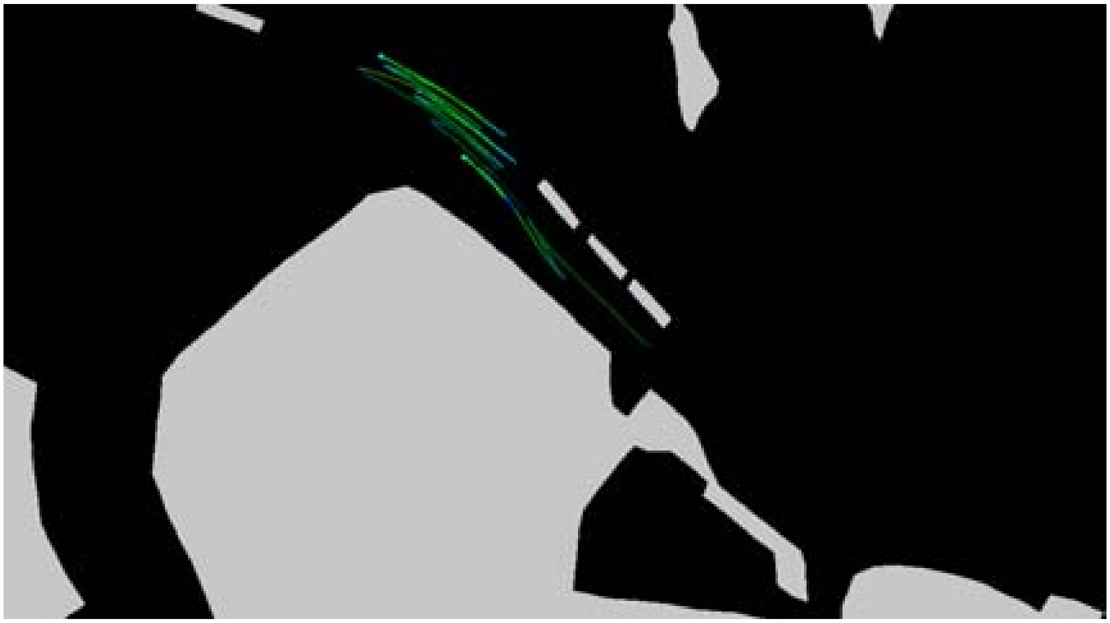


Figure 7-11 RMA-11 Drogue Paths over Several Tidal Cycles

The figure shows that, at least over the period considered, the drogues generally leave the vicinity of the diffusers, and move out to more open waters at the entrance of the Calliope River, where they move back and forth. As such, the potential for return flow is limited to the extent that assuming 100% return flows of waters over each diffuser (as is the case in the CFD modelling) is likely to be a conservative assumption. It is also noted that by the time these drogues (and associated waters) reach this location, it is expected that the high 'core' concentrations from the discharged plumes will have dissipated.

As can be seen by each of the models, the water quality objectives are met close to the diffusers.

7.1.3 Temperature

With the proposed 10:1 dilution of the refinery effluent prior to discharge a temperature differential of 3°C above ambient will be achieved.

The dilution by 10:1 of the treated water brings the temperature of the water down to 3°C above ambient from initial temperatures of between 50-65°C. The release of the treated and diluted water along the diffuser pipe will lead to very quick dilution close to the port exit points. Modelling that has been undertaken for a discharge of 5°C above ambient indicated that within 2 m of the exit ports a temperature differential of 0.5°C would be achieved. It is expected that for a discharge of 3°C above ambient this distance would be even less.

A 3°C differential between discharge and ambient is not expected to impact significantly the marine environment in and around RG Tanna in Port Curtis.

7.2 Marine Sediments

Contaminants in the discharge are in dissolved form and will not settle out to contaminate the sediment of Port Curtis.

The possible exception to this is manganese which may oxidise after some time and form insoluble particles of MnO_2.

An initial experimental program was undertaken in a joint study by CSIRO and the Central Queensland University to confirm an oxidation rate (Appendix B1). Oxidation rates were determined in the laboratory under controlled incubation conditions over a seven-day period. In situ incubations at a moored site in Port Curtis were conducted as a confirmatory check on the laboratory experiment. In addition, laboratory incubation experiments were conducted with both inorganic manganese (II) and a synthetic liquor typical of the proposed discharge[4]. This comparative experiment was included in order to check for enhanced oxidation in the presence of other chemical components of the proposed discharge. The experiments used waters from Port Curtis containing ambient suspended sediment concentrations. The potential scenario of enhanced biological oxidation at the sediment-water interface in mangrove-lined tidal mudflats was also examined by using benthic-corer reactors[5]. The findings of the study were as follows:

- In both laboratory and field incubations tests conducted at a total suspended sediment concentration of 35 mg/L and water temperature of 26°C, the oxidation of dissolved manganese was slow. Less than 6% of the added manganese was lost from solution over the 7-day time period of the experiments. This indicates that the half-life of dissolved manganese originating from the proposed discharge is likely to be of the order of weeks to months.
- Over the 7-day timescale of the laboratory experiment, there was no observable difference between the oxidation behaviour of dissolved manganese added as part of a synthetic liquor or as an inorganic manganese solution.
- Rapid oxidation of manganese (II) was observed in the benthic-corer reactor experiments using sediments collected from a mangrove-lined tidal mudflats in Port Curtis. Half lives of 19 and 32 hours were measured in the two reactors. These experiments illustrate the important role of bacterial communities residing at the sediment water interface in accelerating the oxidation of manganese in estuarine systems.

Simple mass chemical calculations indicate that the oxidation of dissolved manganese present in the 1-10 mg/L concentration range is unlikely to cause any significant depletion of dissolved oxygen in coastal seawaters where there is efficient mixing (Apte, 2006 (b)) such as in Port Curtis. Tidal mixing and the slow oxidation of Mn(II) will reduce the impact on dissolved oxygen concentrations. This has been confirmed by the experimental program of Adams et. al. (2007) where measured dissolved oxygen concentrations showed no significant reductions during the 7-day program.

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[4] The experimental program used a manganese concentration in the synthetic discharge liquor of 29 mg/L. Since then, further manganese reduction is proposed within the refinery prior to discharge. The proposed manganese concentration in the discharge will now be 1 mg/L.

[5] The experimental program used a dissolved manganese concentration of 150-200 µg/L based on the results of initial modelling of a discharge with a manganese concentration of 29 mg/L. Subsequent modelling of the proposed discharge with a manganese concentration of 1 mg/L predicts concentrations in the tidal mudflats of 7–9 µg/L.

Any manganese oxides formed from the refinery discharge to Port Curtis are considered a less toxic form of manganese than dissolved manganese. The oxides may adsorb other metals in the seawater and may therefore have a beneficial effect on marine organisms in the water column due to reduced bioavailability of these metals. Should any formed manganese oxides which have adsorbed other metals settle to the bed, these compounds may be re-released into the water column under reducing conditions or be ingested by bottom-dwelling biota (and subsequently by re-released in the gut).

7.3 Marine Ecosystems

As discussed in Section 7.1, the predicted water quality concentrations will remain below the established WQOs. The objectives have been set on the basis of ensuring that there will be no detrimental effects to marine species and habitats. These include:

- Marine Habitats:
  - Supratidal and Hetertidal Habitat, and
  - Benthic Habitat;
- Species associated with Marine Conservation Areas:
  - Great Barrier Reef World Heritage Area and Marine Park,
  - Port Curtis Wetland,
  - Habitat Protection Zones, and
  - Dugong Protection Zones;
- Threatened and Migratory Species including Matters of National Environmental Significance; and
- Species of interest to the commercial and recreational fishing industries in Port Curtis.

7.3.1 Great Barrier Reef World Heritage Area

As discussed in Section 4, Port Curtis is located in the Great Barrier Reef World Heritage Area. The following table discusses the potential impact of the project on each of the criterion applicable to this area.

Table 7-5 Impact on World Heritage Criterion

Criterion	Project Impact
Outstanding example representing a major stage of the earth's evolutionary history	Examples given of the values of the Great Barrier Reef which relate to this criterion include its coral reefs; coral cays; geological processes linking reefs, cays, islands, sand barriers and dunes; and its record of sea level changes and climatic history. There are no coral reefs or cays in the vicinity of the refinery site. The nearest significant coral communities are between Curtis and Facing Islands, approximately 8 km to the east of the proposed discharge point. While parts of Port Curtis may exhibit geological processes linking the various elements of the coastal environment (e.g. estuaries, intertidal flats, mangroves and embayments) the project will not result in any additional disturbance to any of these elements. The project will be using land that will be filled and wharfs that will be constructed by the Central Queensland Ports Authority which has obtained or is seeking separate approvals for these activities. There will be no other project components which will interfere with the listed examples of the earth's evolutionary history.

Criterion	Project Impact
An outstanding example representing significant ongoing geological processes, biological evolution and man's interaction with his natural environment.	Examples given of the values of the Great Barrier Reef which relate to this criterion include its size and morphological diversity; the process of accretion and erosion of coral reefs; extensive Halimeda beds; dispersion and evolution of hard corals; diversity of flora and fauna; coral colonies and communities; floristic regions; and morphological and genetic changes in mangroves and seagrass. The project area is located in Port Curtis which contains one of Queensland's busiest ports. In 2004/05 the Port of Gladstone had a throughput of over 60 million tonnes of cargo and in 2005/06 it was visited by over 1,100 commercial ships. The GNP will reinforce this existing commercial nature of Port Curtis. As discussed above, the project will not result in any further physical disturbance to the area's marine features beyond those which already exist or have been approved. While there are no coral reefs or cays in the project vicinity, the diversity of marine flora and fauna has been described and the only potential disturbance to this will be from the discharge of the refinery's waste water. The assessment described in Section 7.1 shows that all relevant water quality objectives will be met and that no significant impacts on Port Curtis are expected.
Contains unique, rare and superlative natural phenomena, formations and features and areas of exceptional natural beauty.	Examples given of the values of the Great Barrier Reef which relate to this criterion include its vast extent and variety of reefs and islands; coastal mangrove systems of exceptional beauty; rich variety of landscapes and seascapes; spectacular breeding colonies of seabirds and butterflies; and migrating mammals. The project does not interfere with any reefs or islands. While there is a coastal mangrove system in the vicinity of the refinery, there will be no disturbance to these mangroves. The project is located in a port and industrial landscape and will add further to this landscape character. There will be no disturbance to breeding colonies of seabirds nor to migrating mammals as a result of this project.
Provides habitats where populations of rare and endangered plants and animals still survive	Examples given of the values of the Great Barrier Reef which relate to this criterion include structurally and ecologically complex coral reefs; large number of islands providing extensive habitats; mangroves and seagrass beds; inter-reefal and lagoonal benthos; and plants and animals of conservation significance. As discussed, in the project vicinity there are no reefs or islands that will be affected by the project. Nor are there any inter-reefal or lagoonal areas within Port Curtis. While there are mangrove and seagrass areas in the vicinity of the refinery, these are not predicted to be significantly disturbed by the project. There are no threatened or significant species that have key or important habitats in Port Curtis that will be lost or damaged due to the GNP.