

Appendix J

Blacktip Produced Formation Water
Assessment prepared by International Risk
Consultants Environment



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Blacktip Produced Formation Water Assessment

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Abstract: Woodside Energy Ltd (WEL) is planning to develop the Blacktip Gas Field in the Joseph Bonaparte Gulf. This report provides an assessment of the environmental risk associated with disposing of produced formation water (PFW) from the development. The preferred disposal option is onshore treatment followed by discharge to the ocean through a long sea outfall.			
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ABBREVIATIONS

ADCIRC	Advanced Circulation Model
AGSO	Australian Geological Survey Office
ANZECC	Australian and New Zealand Environment and Conservation Council
ASTM	American Society for Testing Materials
BAF	Bioaccumulation Factor
BCF	Bio-concentration Factor
BF	Biomagnification Factor
BOD	Biochemical Oxygen Demand
BTEX	Benzene, Toluene, Ethyl benzene and Xylene
CHARM	Chemical Hazard Assessment and Risk Management
CORJET	Cornell Buoyant Jet Integral Model
CORMIX	Cornell Mixing Zone Expert System
CP	Cossack Pioneer
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DO	Dissolved Oxygen
DREAM	Dose related Risk and Effect Assessment Model
EC50	The Median Effect Concentration
EIF	Environmental Impact Factor
EPBC	Environment Protection and Biodiversity Conservation
FE	Finite Element
FEED	Front End Engineering Design
FID	Flame Ionisation Detection
GC-MS	Gas Chromatography – Mass Spectrometry
GWA	Goodwyn 'A'
HAT	Highest Astronomical Tide
Hs	Significant Wave Height
HQ	Hazard Quotient
IC50	Median Inhibition Concentration
IR	Infra-Red
IRCE	IRC Environment

IUCN	International Union for the Conservation of Nature and Natural Resources
K _{oc}	Organic carbon/water partition coefficient
K _{ow}	Octanol/water partition coefficient
K	Diffusion coefficient
LAT	Lowest Astronomic Tide
LC50	Median Lethal Concentration
LTS	Low Temperature Separator
MAH	Monocyclic Aromatic Hydrocarbon
MFO	Mixed Function Oxygenase
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MHWS	Mean High Water Springs
MHWN	Mean High Water Neaps
MSL	Mean Sea Level
ND	Not Detected
NE	Northern Endeavour
NOAA	National Oceanic and Atmospheric Administration
NOEC	No Observed-Effect Concentration
NORM	Naturally Occurring Radioactive Material
NNE	North Northeast
NV	No Value
NPD	Naphthalene, Phenanthrene and Dibenzothiophene
NRA	North Rankin 'A'
OGP	International Association of Oil and Gas Producers
OL	Ocean Legend
OSPAR	Oslo and Paris Commission
PAH	Polycyclic Aromatic Hydrocarbons
PSU	Practical Salinity Unit
PEC	Predicted Environmental Concentration
PFW	Produced Formation Water
PID	Photoionisation detection

PNEC	Predicted No Effect Concentration
P(SL)A	Petroleum (Submerged Land) Act
P(SL)(ME)R	Petroleum (Submerged Land)(Management of the Environment) Regulations
PWCNT	Parks and Wildlife Commission of the Northern Territory
SDH	Sorbital Dehydrogenase
SE	Southeast
Tm	Mean Spectral Period
TOC	Total Organic Carbon
UKOOA	United Kingdom Offshore Operators Association
USEPA	United States Environmental Pollution Authority
WA	Western Australia
WEL	Woodside Energy Ltd.
WET	Whole Effluent Toxicity
°C	Degree Celsius

EXECUTIVE SUMMARY

This report assesses the environmental risk associated with disposing of produced formation water (PFW) from Woodside Energy Limited's (WEL's) Blacktip Gas development. The preferred disposal option is onshore treatment followed by discharge to the marine environment of the Joseph Bonaparte Gulf through a long sea outfall.

PFW discharge rates are projected to increase from 200 bbl/day at start-up to a maximum of 7,000 bbl/day five years into production. The actual toxicity of the PFW is presently unknown, however, WEL's previous ecotoxicology studies on PFW from all its other offshore assets indicate that the lowest threshold concentration for potential environmental impact is 0.1% concentration of PFW. Blacktip PFW will be treated onshore to a higher standard than the offshore facilities and the toxic threshold is expected to be higher, ie, the PFW is likely to be less toxic.

The favoured offshore release point is in the vicinity of the Swamp Mooring, which lies three kilometres offshore in a water depth of 15m. Tidal currents in the Joseph Bonaparte Gulf are large and the assimilative capacity of the receiving waters high. Initial dilution from the discharge can be further enhanced through use of an end-of-pipe diffuser.

Pipeline hydraulics were reviewed and, based on preliminary information, a four port diffuser configuration was proposed. Dispersion modelling for this configuration predicted that at least 700 initial dilutions would be achieved for the maximum future discharge rate, reducing the PFW concentrations to 0.14%.

Far field modelling showed that the receiving waters are well flushed due to the large tidal currents. Maximum PFW concentrations occurred at slack waters with values building up to just over the 0.1% PFW threshold within 400m from the near field mixing zone. As the modelling was undertaken for worst case conditions of maximum discharge rate combined with a neap tide and low wind speed, 400m is likely to be the maximum extent of the impact. At all other stages of tide, this zone of impact would reduce substantially.

PFW also has an oxygen demand. This can be controlled by treatment prior to discharge. It was predicted that to maintain oxygen levels to within 90% of saturation levels, the biochemical oxygen demand of the effluent should be kept below $2,500\text{mgL}^{-1}$ for the maximum discharge rate.

The overall conclusion is that the proposed discharge should have minimal impact on the marine environment. This is based on the Blacktip PFW being no more toxic than those from other WEL assets. It is recommended that ecotoxicology studies be undertaken once PFW becomes available to verify this assumption. As well as reducing the concentration of dispersed oil, treatment should focus on removing polycyclic aromatic hydrocarbons and reducing the toxicity of process chemicals, the compounds of most concern in PFW.

1 INTRODUCTION

1.1 Background

Blacktip is an offshore gas development located 300km South West of Darwin, Australia. The development comprises of an unmanned wellhead platform in 50m of water and a 16 inch, 120km long pipeline through which well fluids will be transported to an onshore gas treatment station (Figure 1.1 and Figure 1.2). The wet gas will be conditioned at the treatment station and then exported to Gove through the trans-territory pipeline. The favoured option for disposal of the Produced Formation Water (PFW) is treatment prior to offshore discharge to the Joseph Bonaparte Gulf through a long sea outfall.

As part of the Front End Engineering Design (FEED) for the project, IRC Environment (IRCE) was commissioned by Woodside Energy Limited (WEL) to devise an effective ocean disposal scheme and to assess the environmental risks associated with discharging PFW to the ocean.

1.2 Objective

The objective of the study is to devise an effective PFW disposal scheme for the Blacktip development and to gain a full understanding of the environmental impact associated with it.

1.3 Scope of Work

The scope of work included:

- describing the typical composition of PFW, its fate and toxicity in the marine environment;
- describing the meteorological and oceanographic conditions for the Joseph Bonaparte Gulf;
- developing a discharge model and using it to derive an effective PFW disposal scheme for the Blacktip PFW; and
- predicting the fate and effect of the PFW once it has been discharged.

1.4 IRC

IRC is an independent consultancy providing a variety of services to the mining, oil and gas exploration, production and financial industries. IRC's methods and tools have been developed to enable rapid, confident decision making, and to recognise the key decision criteria necessary to minimise risk and maximise value. IRC has an overall objective of assisting our clients improve their performance and increase the value of their assets. This is achieved by improving:

- safety performance through reducing the risk/cost associated with injury/fatality;
- environmental performance through reducing environmental damage and clean up costs;
- production performance through optimising production uptime and availability;
- health performance through implementation of organisation cultural assessment and change programs, including the Peak Performance Program; and
- information system performance through development, integration, implementation and support of stable and secure business systems.

Figure 1.1 Location of the Blacktip Gas Field and associated infrastructure (from WEL)

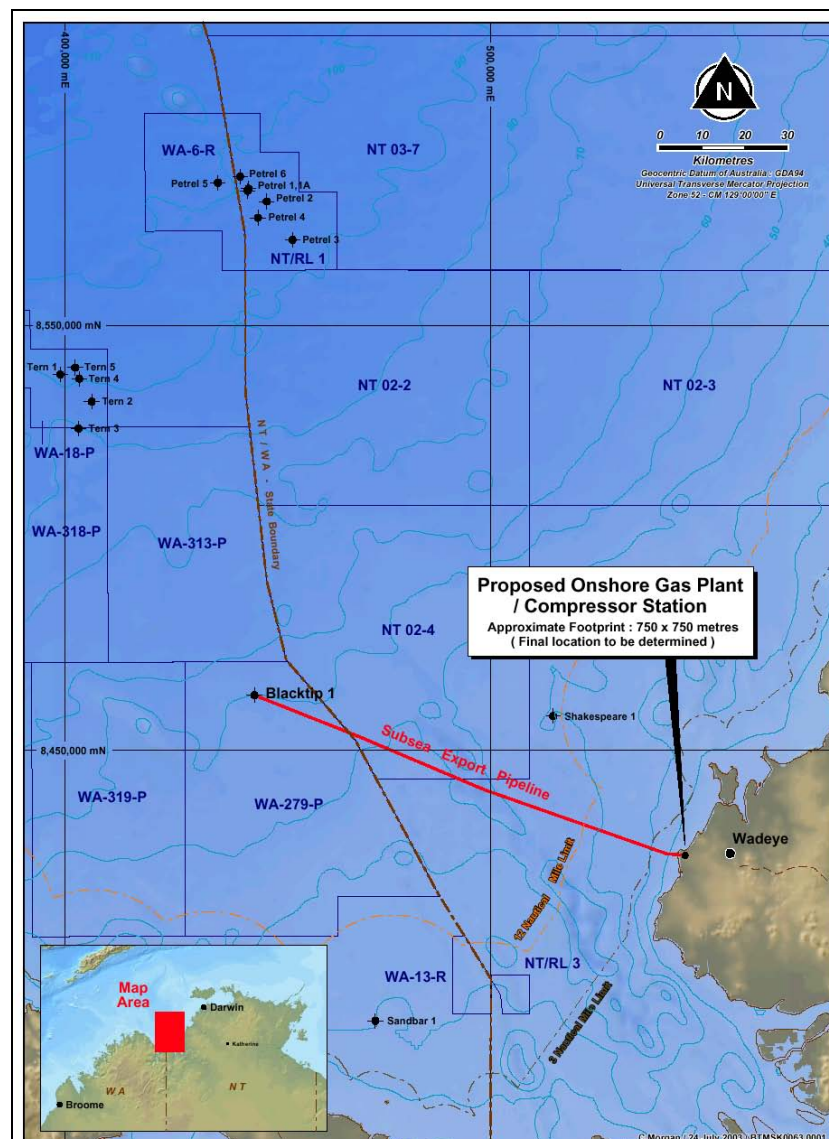
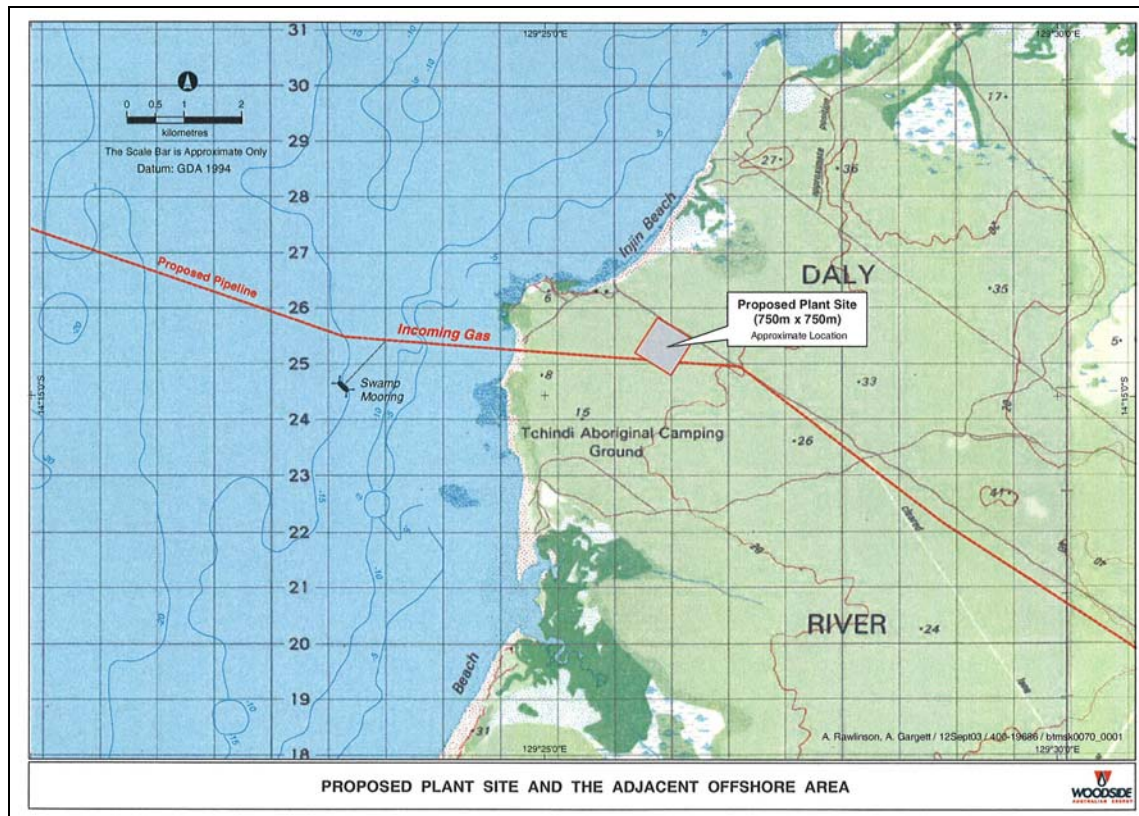


Figure 1.2 Shoreline crossing and proposed plant site (from WEL)

2 PRODUCED FORMATION WATER CHARACTERISTICS

2.1 Introduction

2.1.1 Overview

PFW (also referred to as produced water or formation water) is the waste water that is separated from the production stream during oil and gas production operations. For oil production fields the largest constituent is typically fossil water, the water found with the oil and gas inside the geological reservoir. However in gas and condensate wells, it is generally associated with saturation water that condenses due to the pressure drop between the reservoir and surface. As the reservoir matures, fossil water may be introduced and volumes of PFW tend to increase.

It is common practice throughout the offshore industry to physically separate the water from the well fluids and then dispose of the water directly to the ocean. This separation is not 100% effective and the PFW often contains small amounts of naturally occurring contaminants including dispersed oil, dissolved organic compounds (aliphatic and aromatic hydrocarbons, organic acids and phenols), inorganic compounds and residual process chemicals. Although only small concentrations of these compounds are released, the continuous discharge of large PFW volumes gives rise to environmental concern. Accordingly, most of the world's national or regional regulatory authorities set limits on the concentration of petroleum hydrocarbons (or total oil and grease) that can remain in PFW for ocean disposal. Many regulators also require that environmental impact assessments be undertaken to fully evaluate the risk.

The chemical composition of PFW varies over a wide range and depends mainly on attributes of the reservoir geology. The composition of PFW may also change slightly through the production lifetime of the reservoir. Compared to oil production fields, PFW from gas/condensate fields generally have higher hydrocarbon contents due to technical difficulties in separating condensate and water and also due to the higher aromatic content of condensate. However, the total volume of water produced from gas fields is much smaller than from oil production fields. Many gas fields discharge less than 10m³ of PFW per day whilst most oil fields discharge hundreds or even thousands of cubic metres per day.

2.1.2 Previous Studies

In 2002 WEL undertook a comprehensive study of PFW discharges from their assets on the North West Shelf and Timor Sea (IRCE, 2003a-e). These assets included:

- North Rankin 'A' (NRA);
- Goodwyn 'A' (GWA);
- Cossack Pioneer (CP);

- Ocean Legend (OL); and
- Northern Endeavour (NE).

The study consisted of:

- characterising the chemical composition of the PFW;
- ecotoxicology; and
- dispersion and risk assessment modelling.

The results from these studies will be applied here. There are numerous other studies in the scientific literature and excellent reviews of these are given in Swan *et al.* (1994) and, more recently, in Neff (2002).

2.2 Chemical Composition of PFW

2.2.1 Introduction

The chemical composition of PFW has been described extensively by several authors (see for example Neff, 2002; OGP, 2002; DK, 2001; Roe Utvik, 1999 and Flynn *et al.*, 1996) and operators in the North Sea report regularly on the composition and volumes of their discharges (see UKOOA, 2002; OGP, 2002 and DK, 2001).

Prior to production, it is difficult to predict the exact composition or toxicity of Blacktip PW, however, based on knowledge of other PW in the region and also worldwide, it is likely to contain trace concentrations of:

- petroleum hydrocarbons;
- phenols;
- organic acids;
- metals;
- radioisotopes; and
- residual process chemicals.

This Section introduces the chemical characteristics of each of these constituents and presents typical concentrations from oil and gas production facilities around the world.

2.2.2 Petroleum hydrocarbons

Petroleum hydrocarbons are the organic components of greatest environmental concern in PFW. These compounds contain only carbon and hydrogen atoms, with the carbon atoms linked by single or double covalent bonds to form linear branched and cyclic hydrocarbons. In aliphatic hydrocarbons all carbon-carbon bonds are single. Aromatic hydrocarbons are composed of six carbon rings in which six carbon atoms equally share nine covalent bonds.

The aqueous solubility of petroleum hydrocarbons decreases as their molecular weight increases. As oil/water separator equipment is efficient in removing oil droplets from the PFW but not dissolved oil, most of the petroleum hydrocarbons remaining after treatment are low molecular weight aromatic and aliphatic hydrocarbons that are dissolved in the PFW.

Aliphatic hydrocarbons

Aliphatic hydrocarbons are carbon structures without any aromatic nucleus. They are further divided into alkanes, alkenes and alkynes. The alkanes are the major group in crude oil. Alkanes have the general formula C_nH_{2n+2} . In crude oil they cover a broad range from methane (CH_4) which is a gas at normal conditions to heavy components like n-tetracontane ($C_{40}H_{82}$) or even heavier, which are solid compounds at normal conditions. The essential characteristic of alkane hydrocarbon molecules is that only single covalent bonds are present. In these compounds, the bonds are said to be saturated thus the alkanes are also known as the saturated hydrocarbons.

Low molecular weight alkanes are volatile whilst those with more than 16 carbons have an extremely low aqueous solubility. The most abundant alkanes found in PFW are therefore in the C13 to C16 range. It is likely that the higher molecular weight alkanes are in colloidal form or associated with dispersed oil droplets not removed by the oil/water separator.

Due to technical difficulties with separating condensate from water, aliphatic hydrocarbon concentrations in PFW are generally higher from gas/condensate fields than they are from oil fields. The average concentration from North Sea gas installations was 242mgL^{-1} in 2001 (UKOOA, 2002). This compared with 52mgL^{-1} from oil installations. However, most gas installations have concentrations of less than 40mgL^{-1} and the average value is enhanced by a few installations reporting very high concentrations (up to 700mgL^{-1}).

Aromatic hydrocarbons

Aromatic hydrocarbons are carbon structures with double bonding in all positions and the carbon skeleton arranged in planar six-rings. The most typical example is benzene (C_6H_6). The structure can include more than one six-ring-structure, e.g. naphthalene which has two rings ($C_{10}H_8$), and phenanthrene, which has three rings ($C_{14}H_{10}$). In environmental investigations structures with up to six rings are included, but structures with more rings exist. The rings are often alkylated with methyl groups and in some crude oils the content of the alkylated aromatic is an order of magnitude higher than the content of the pure aromatic hydrocarbon.

The aromatic hydrocarbons are grouped into:

- monoaromatic hydrocarbons (MAHs); and
- polyaromatic hydrocarbons, (PAHs).

PAHs contain three or more aromatic rings. The two ring hydrocarbons are not included in either of these groups, however, in practice they are grouped with the PAHs.

Monocyclic aromatic hydrocarbons

MAHs have one aromatic ring that may be alkylated. The most common compounds and those of most concern in the environment are:

- benzene (C_6H_6), without any substitutes;
- toluene, ($C_6H_5-CH_3$) with one methyl substitute;
- ethyl benzene, ($C_6H_5-C_2H_5$), with one ethyl substitute; and
- xylene ($C_6H_4-(CH_3)_2$), with two methyl substitutes, which can be placed in three different positions and therefore there are three isomers.

These hydrocarbons are often named by the combined abbreviation BTEX. There are higher alkylated MAHs, with three and four carbons alkylated, but normally they are not specified or determined individually. The BTEX compounds are more soluble in water than other hydrocarbons and are generally the most abundant in PFW.

Ranges of BTEX concentrations in PFW from oil and gas facilities in the North Sea are given in Table 2.1. Concentrations may range from 0.042mgL^{-1} to as high as $2,244\text{mgL}^{-1}$. PFW from gas wells usually contain higher concentrations of BTEX than oil wells due to the higher aromatic content of the condensate and gas produced. Benzene is often the most abundant BTEX compound in effectively treated PFW, followed by toluene. Ethyl benzene and the three xylene isomers are usually present at only a small fraction of the concentrations of benzene and toluene. A large number of C3- and C4- benzene isomers may also be present, usually at low concentrations.

Table 2.1 Concentration ranges of BTEX compounds in PFW from oil and gas fields in the North Sea (1999 – 2001) (from OGP, 2002)

	Oil (mgL^{-1})	Gas (mgL^{-1})
Norway	0.7 – 24.1	1.9 – 36
UK	<0.5 - 34	0.5 – 2,244
Holland	0.042 – 4.8	0.01 – 1,164
Denmark	8.7 - 14	N/A

N/A – Not available

Table 2.2 presents the concentrations measured in the PFW from WEL's production facilities on the North West Shelf and Timor Sea. Values range from 29.4mgL^{-1} at NRA to 3.3mgL^{-1} at GWA.

Table 2.2 BTEX concentrations measured in PFW from Woodside's Assets in 2002 (from IRCE, 2003a–e)

Compound	Concentration (mgL ⁻¹)				
	NRA	GWA	CP	OL	NE
Benzene	7.3	1.2	1.3	2.3	0.7
Toluene	13.0	1.3	1.9	3.6	1.3
Ethyl Benzene	0.8	0.1	0.2	<0.2	0.3
Xylenes	8.3	0.7	1.1	3.3	1.5
Sum BTEX	29.4	3.3	4.5	9.2	3.8

Notes: Measured by PID/FID (USEPA 5030B, 8020A and 8260)

Polycyclic aromatic hydrocarbons

PAHs cover a broad range of compounds, which may be formed by a variety of mechanisms (Neff, 1979), such as:

- very rapid, high temperature (700°C) incomplete combustion or pyrolysis of organic materials (pyrogenic PAHs);
- very slow (millions of years) rearrangement and transformation of biogenic organic materials at moderate temperatures of 100-300°C to form fossil fuels (petrogenic PAHs);
- relatively rapid (days to years) transformation of certain classes of organic compounds in soils and sediments (diagenic PAHs); and
- direct biosynthesis by organisms (biogenic PAHs).

In environmental investigations it is common to measure the 16 PAH defined by the list of Priority Pollutants from the United States Environmental Pollution Authority (USEPA) (see Table 2.3). These 16 compounds are all full aromatic hydrocarbons without any substitutes. In crude oil, alkyl homologues usually are more abundant than the parent PAHs, however, this often is not so in PFW because of the decreasing aqueous solubility with increasing PAH alkylation, favouring retention in the oil phase.

Concentrations of total PAHs in PFW typically range from about 0.04mgL⁻¹ to 3.0mgL⁻¹ (Neff, 2002). Naphthalene and occasionally phenanthrene (three fused aromatic rings) and their alkyl homologues are the only PAHs that are present at higher than trace concentrations. These low molecular weight PAHs usually represent 95% of the total PAHs in PFW.

Four to six ring PAHs, some of which are phototoxic, mutagenic and carcinogenic, are rarely detected in PFWs that meet effluent standards for oil and grease. For example, the carcinogenic benzo(a)pyrene is rarely present in PFW at concentrations greater than about 0.1µgL⁻¹. The aqueous solubility of benzo(a)pyrene is so low and its affinity for the oil phase

so high that it would not be expected to be present in PFW in dissolved form. Despite the low level measurements of PAHs in PFW, there is ongoing concern about the environmental effects of such components in the marine environment.

Table 2.3 The 16 USEPA priority PAHs

Compound	No. of rings
Naphthalene	2
Phenanthrene	3
Acenaphthylene	3
Acenaphthene	3
Fluorene	3
Anthracene	3
Fluoranthene	4
Pyrene	4
Benz(a)anthracene	4
Chrysene	5
Benzo(b)fluoranthene	5
Benzo(k)fluoranthene	5
Benzo(a)pyrene	5
Indeno(1,2,3-c,d)pyrene	5
Dibenz(a,h)anthracene	5
Benzo(g,h,i)anthracene	6

The concentration ranges of naphthalene, phenanthrene and dibenzothiophene (NPD) and other PAH compounds in PFW from oil and gas facilities in the North Sea are given in Table 2.4. Concentrations of NPD range from 0.001mgL⁻¹ to 10.4 mgL⁻¹. Concentrations of other PAHs range from 0.0004mgL⁻¹ to 4.125mgL⁻¹.

Table 2.4 Concentration range of NPD and other PAH compounds in PFW from oil and gas fields in the North Sea (1999 – 2001) (from OGP, 2002)

	NPD ¹		PAH ²	
	Oil (mgL ⁻¹)	Gas (mgL ⁻¹)	Oil (mgL ⁻¹)	Gas (mgL ⁻¹)
Norway	0.8 – 10.4	0.24 – 0.8	0.001 – 0.13	0.003 – 0.05
UK	0.007 – 0.74	0.001 – 0.74	0.002 – 0.12	0.0004 – 0.23
Holland	N/A	N/A	0.0026 – 0.1545	0.002 – 4.125
Denmark	0.22 – 0.436	N/A	0.12 – 0.285	N/A

¹ including C1 – C3 alkyl homologues; ² 16 USEPA PAH other than naphthalene and phenanthrene; N/A – not available

Studies of one specific field over a period of one week show that there is little variation in composition of aromatic hydrocarbons over that time span (OGP, 2002). Results from the Norwegian database also show that composition of PFW is relatively constant from one year to another at individual fields (OGP, 2002).

Table 2.5 presents the concentrations measured in the PFW from WEL's production facilities on the North West Shelf and Timor Sea in 2002. Values of NPD range from 0.67mgL^{-1} at NRA to 0.15mgL^{-1} at GWA. Of the other PAHs, only fluorene was detected in OL and NE PFW at 0.021mgL^{-1} and 0.018mgL^{-1} , respectively.

Table 2.5 PAH concentrations measured in PFW from Woodside's Assets in 2002 (from IRCE, 2003a–e)

Compound	Concentration (mgL^{-1})				
	NRA	GWA	CP	OL	NE
NPD ¹	0.670	0.150	0.304	0.568	0.537
Other PAHs ²	ND	ND	ND	0.021^3	0.018^3

Notes: Measured by GC-MS in SIM mode (USEPA 3550B, 8270); ¹ including C1 – C3 alkyl homologues; ² 16 USEPA PAH other than naphthalene and phenanthrene; ³ fluorene; ND – Not Detected;

2.2.3 Phenols

Phenol is a hydroxy derivative of benzene with the formula $\text{C}_6\text{H}_5\text{OH}$. The five aromatic carbons not bonded to the hydroxyl group readily react with methyl carbons to form methyl phenol (alkyl phenols) and with halogens to form a wide variety of halogenated phenols. Phenol, alkyl phenols and to a lesser extent halogenated phenols are natural components of the environment. Many different phenols are synthesized by a wide variety of bacteria and fungi, plants and animals. Phenols can be formed from the oxidation of benzene. The most abundant phenols in many crude oils are the C2 through C9 alkyl phenols. However, phenol solubility decreases with increasing alkylation so PFW rarely contains detectable concentrations of the more highly alkylated phenols.

The most complete analysis to date of phenols in PFW are those from three production facilities in Indonesia (Neff and Foster, 1997) and five in the Norwegian sector of the North Sea (Roe Utvik, 1999). Phenols with up to five alkyl carbons were detected and total phenols ranged from 0.36mgL^{-1} to 16.83mgL^{-1} (Table 2.6).

Table 2.7 presents the concentrations measured in the PFW from WEL's production facilities on the North West Shelf and Timor Sea in 2002. Phenols with up to three alkyl carbons were detected. Both NRA and GWA had relatively high total concentrations at 15.4mgL^{-1} and 17.3mgL^{-1} , respectively. Concentrations at CP, OL and NE were much lower at less than 2.1mgL^{-1} .

Table 2.6 Concentration of phenol and different alkylphenol groups in PFW from three production facilities in Indonesia and five production facilities in the Norwegian Sector of the North Sea (from Neff, 2002)

Chemical	Indonesian PFW (mgL ⁻¹)	North Sea PFW (mgL ⁻¹)
Phenol	0.67 – 2.49	0.007 – 7.0
C ₁ -Phenols	0.77 – 1.69	0.011 – 6.78
C ₂ -Phenols	0.58 – 1.10	0.19 – 2.51
C ₃ -Phenols	0.30 – 0.59	0.064 – 0.60
C ₄ -Phenols	0.13 – 0.37	0.077 – 0.43
C ₅ -Phenols	0.04 – 0.09	0.007 – 0.02
C ₆ -Phenols	ND	ND
C ₇ -Phenols	ND	ND
C ₈ -Phenols	ND	ND
C ₉ -Phenols	ND	ND
Total Phenols	2.49 – 6.33	0.36 – 16.83

ND – Not Detected

Table 2.7 Concentration of phenol and different alkylphenol groups measured in PFW from Woodside's assets in 2002 (from IRCE, 2003a–e)

Chemical	NRA	GWA	CP	OL	NE
Phenol	4.00	2.90	0.73	0.03	0.25
C ₁ -Phenols	7.70	6.60	0.94	0.17	0.21
C ₂ -Phenols	3.33	6.34	0.36	0.17	0.06
C ₃ -Phenols	0.37	1.49	0.03	ND	ND
C ₄ -Phenols	ND	ND	ND	ND	ND
C ₅ -Phenols	ND	ND	ND	ND	ND
C ₆ -Phenols	ND	ND	ND	ND	ND
C ₇ -Phenols	ND	ND	ND	ND	ND
C ₈ -Phenols	ND	ND	ND	ND	ND
C ₉ -Phenols	ND	ND	ND	ND	ND
Total Phenols	15.40	17.33	2.06	0.36	0.51

Notes: Measured by GC-MS (USEPA 8270 modified); ND – Not Detected

2.2.4 Organic acids

Much of the total organic carbon (TOC) in PFW consists of organic acids. These are thought to have been produced by hydrous pyrolysis of kerogen and hydrocarbons in the source rocks and hydrocarbon-bearing formation (Neff, 2002). Most of the organic acids are short chain aliphatic monocarboxylic acids, such as acetic (C₂), propionic (C₃), butyric (C₄) and valeric (C₅) acids. Concentrations tend to decrease with molecular weight with the most abundant acid usually being acetic acid.

2.2.5 Metals

PFW may contain several metals in solution. The metals present and their concentrations are extremely variable, depending on the age and geology of the formation from which the oil and gas are produced. There is usually a poor correlation between concentrations of metals in crude oil and the water produced with it (Neff, 2002).

Metals are classified as alkali and alkaline earth metals (sodium, potassium, magnesium, calcium, strontium and barium) and heavy metals (arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, silver and zinc). The alkali and, to a lesser degree, the alkaline earth metals are very reactive. Hence they never occur in elemental form and are found combined with halide, sulphate, carbonate or silicate ions. In this form they are not considered toxic and water quality guideline values for these metals do not exist. The heavy metals are considered toxic and, with the exception of iron and silver, USEPA marine quality criteria and Australian and New Zealand Environment and Conservation Council (ANZECC) guideline trigger values exist.

Generally, heavy metal concentrations in PFW are very low (typically <0.5mgL⁻¹ – 1.0mgL⁻¹ (UKOOA, 2002). The metals most frequently present in PFW at elevated concentrations include: barium, chromium, copper, iron, lead, nickel and zinc. Usually only a few of these metals are present at elevated concentrations in a particular PFW sample. Table 2.8 shows the concentration ranges of heavy metals from North Sea samples taken between 1999 and 2001 (UKOOA, 2002). These are average ranges and higher concentrations at individual facilities were detected.

Table 2.9 presents the concentrations measured in the PFW from WEL's production facilities on the North West Shelf and Timor Sea in 2002. In general heavy metal concentrations were low and not considered to be an environmental hazard.

Table 2.8 Concentration range of heavy metals in PFW from oil and gas fields in the North Sea (1999 – 2001) (from UKOOA, 2002)

	Heavy metal Concentrations	
	Oil (mgL ⁻¹)	Gas (mgL ⁻¹) ¹
Arsenic	0.679 – 1.300	0.030 – 0.414
Cadmium	0.145 – 0.313	0.033 – 0.097
Chromium	15.4 – 20.1	0.005 – 0.140
Copper	0.072 – 2.620	0.020 – 0.164
Lead	1.959 – 3.524	0.890 – 3.865
Mercury	0.045 – 0.157	0.008 – 2.630
Nickel	21.0 – 24.6	0.016 – 0.120
Zinc	16.0 – 26.0	11.002 – 14.640

¹ annual average concentrations from 35, 27 and 21 North Sea gas platforms in 1999, 2000 and 2001, respectively.

Table 2.9 Concentration range of heavy metals in PFW from WEL's Assets (IRCE, 2003a-e)

	Heavy metal Concentrations (mgL ⁻¹)				
	NRA	GWA	CP	OL	NE
Arsenic	<0.005	<0.005	<0.005	<0.005	<0.005
Cadmium	<0.005	<0.005	<0.005	<0.005	<0.005
Chromium	0.0080	0.0200	0.0260	0.0270	0.0200
Copper	<0.005	<0.005	0.0060	0.0100	<0.005
Lead	<0.005	<0.005	<0.005	<0.005	<0.005
Mercury	<0.0001	0.0001	<0.0001	<0.0001	0.0002
Nickel	<0.005	0.0110	<0.005	<0.005	<0.005
Zinc	0.0230	0.0100	0.0110	0.0320	0.0270

Notes: Measured by Atomic Absorption Spectrometry.

2.2.6 Radioisotopes

Several naturally occurring radioactive materials (NORMs) occur in PFW. The most abundant, because of their relatively long half lives, are radium-226 and radium-228 (²²⁶Ra and ²²⁸Ra). Radium is derived from the radioactive decay of uranium and thorium associated with certain rocks and clays in the hydrocarbon reservoir. The half-lives for ²²⁶Ra and ²²⁸Ra are 1,620 and 5.76 years, respectively. They decay through several intermediates to stable ²⁰⁷Pb and ²⁰⁸Pb, respectively. Typical total radium concentrations in PFW range from 0BqL⁻¹ to 190BqL⁻¹ (Neff, 2002).

2.2.7 Process Chemicals

Large numbers of speciality additives are available for use in the production system of a well to aid in recovery and pumping of hydrocarbons, protect the production system from corrosion and facilitate separation of oil, gas and water. The number of additives used in a particular production system is usually low and depends on the particular production problems encountered in the well. They could include:

- biocides;
- corrosion inhibitors;
- scale inhibitors;
- oxygen scavengers;
- demulsifiers;
- emulsifiers;
- coagulant/deoiler;
- flocculant;
- antifoam agent;
- dispersants;
- thinners;
- viscosifiers;
- surfactants/detergents; and
- hydrate inhibitors.

Three process chemicals will be added to the Blacktip system. These are:

- Corrosion Inhibitor;
- Methanol/Mono Ethylene Glycol; and
- Demulsifier/coagulant.

2.3 Fate of PFW in the Marine Environment

2.3.1 General

An understanding of the processes involved in changing the nature and behaviour of the individual compounds in PW is essential to predict their fate and impact. This section describes some of the processes that PFW undergoes when discharged to the ocean and introduces the mechanisms by which marine organisms bioaccumulate contaminants.

2.3.2 Degradation processes

Upon discharge contaminants in the PFW undergo a number of degradation or weathering processes, including:

- dilution;
- evaporation of volatile components;
- adsorption to particles and sedimentation;
- biodegradation; and
- photodegradation.

Collectively, these processes tend to decrease the concentration of chemicals in the PFW plume and thereby decrease its toxicity to marine organisms. However, weathering is a complex process and difficult to predict with accuracy. It may produce new chemicals or

result in speciation of chemicals in the mixture to forms that are more bioavailable and toxic than the original chemicals. Therefore, it is possible that PFW may not lose toxicity and could even increase in toxicity during the weathering process (Neff, 2002). Furuholt (1996) suggests that these transformation processes are more likely to cancel each other out for mixtures with more than five toxicants.

Plume behaviour is unique to each platform, however, Burns, *et al.* (1999) provide an estimated mass balance (within 900m) for petroleum hydrocarbons discharged daily from Harriet 'A', a shallow water platform in 22m of water on the North West Shelf of Australia. They estimate that 37% of hydrocarbons are dissolved and 36% become attached to suspended particles (11% of which settle and 25% remain suspended). Dispersion, photodegradation and biodegradation accounts for 24% and evaporation just 3%.

For Blacktip, dilution is likely to be the most effective process for reducing the inorganic and organic contaminants. Evaporation will also be important for removing volatile components. In experiments, Flynn *et al.* (1996) demonstrated that sparging had little effects on volatile fatty acids, however, it removed some of the phenols (<50%) and over 90% of BTEX and PAH compounds. Toxicity did not reduce significantly, suggesting, for that particular sample, volatile compounds were not necessarily the most important in determining the overall toxicity of the PFW. Adsorption of dispersed oil and heavier chemical components onto particles is not likely to be an issue for Blacktip as the PFW should contain mainly low molecular weight compounds. Sedimentation of hydrocarbon compounds from PFW is not generally thought to be a problem as suspended particles would be spread over a wide area meaning that concentration build up in the sediments is likely to be extremely low and probably of no significance (Furuholt, 1996). Biodegradation will occur over longer time scales (greater than one day) and is important for reducing possible chronic toxicity effects. As dilution and biodegradation are the most important processes for Blacktip they are described in more detail in the following two subsections.

2.3.3 Dilution

Dilution is divided into two phases: the jet phase which is the initial, rapid dilution; and, the ambient phase which is the slower, far-field dilution (North Sea PFW and Effect Task Force 1994). PFW discharges are generally less dense than seawater. Unless there is adequate dilution at the point of discharge, a surface slick will form providing visual evidence of the discharge. Slicks may also be discoloured and give rise to odour problems. The presence of petroleum hydrocarbons in the effluent can enhance slick formation. Once a dense slick has formed, mixing is inhibited and advection can transport the poorly diluted effluent to environmentally sensitive areas where it can exert an undesirable effect.

Slick prevention requires adequate dilution for the discharge and initial dilution standards apply to marine outfalls. Initial dilution is defined as the number of dilutions received by an effluent from the time it leaves the diffuser port to the time it makes impact with either a submerged or surface field. Two forces are responsible for the enhanced dilution in the near field:

- the momentum of the discharge; and
- the buoyancy resulting from the density difference between the effluent and the receiving waters.

Studies have shown that slick formation can be prevented with an initial dilution of 100:1. Saline PFWs dilute rapidly upon discharge to well-mixed marine waters. Smith (1993), Terrens and Tait (1993), Stromgren *et al.* (1995) and Brandsma and Smith (1996) all predict a rapid initial dilution of discharges by 30- to 100-fold within the first few tens of metres of the outfall, followed by a slower rate of dilution at greater distances. Mixing is less rapid for positively buoyant or for high volume discharges (see for example Smith *et al.*, 1996).

In most marine environments, current speeds and directions are not constant as they are driven by a variety of forces such as tide, wind and regional circulations. Under these conditions, the distribution and concentration of a PFW plume is observed to be highly variable over time and space (see Smith *et al.*, 1996; Terrens and Tait, 1996; King and McAllister, 1998).

2.3.4 Biodegradation

A wide range of marine micro-organisms are able to utilise organic matter as an energy source in the natural environment. Low molecular weight, soluble hydrocarbons and organic acids are utilised particularly rapidly, as these classes of compounds occur ubiquitously in the environment and micro-organisms have evolved to degrade them efficiently. The importance of biodegradation in the destruction of organic chemicals in PFW plumes depends primarily on the persistence of elevated concentrations of the organic chemicals in the plume and the pre-adaptation of the local microbial community for resistance to and biodegradation of PFW chemicals (Neff, 2002). As a general rule, linear hydrocarbons are more easily biodegraded than aromatic hydrocarbons (Neff, 2002).

Biodegradation experiments performed by Stromgren *et al.* (1995) and Roe Utvik (1996) with PFW from the North Sea have provided valuable information about the marine environmental fate of some organic components of PFW. They showed that whilst low molecular weight aliphatic and aromatic hydrocarbons tend to evaporate rapidly from the PFW mixtures, many of the medium molecular weight aromatic hydrocarbons and phenols are biodegraded by indigenous microbiota in seawater. Higher molecular weight organic components, as well as heterocyclic compounds may be resistant to biodegradation and persistent in the plume. In the field, these compounds are lost primarily by dilution and adsorption on to suspended particles, particularly living and dead organic matter (Neff, 2002). Due to the differential rate

of biodegradation the relative concentrations of the different hydrocarbons remaining in seawater after discharge will vary over time.

Experiments by Flynn *et al.* (1996) showed that after eight days, over 99% of phenols and PAHs were degraded, and BTEX was reduced to below detection limits. Toxicity, as measured by Microtox®, was also reduced from 8.6% PFW to 100% PFW, suggesting that the components responsible for the initial toxicity are readily biodegradable. Biodegradation rates for individual components in PFW are given in Johnsen *et al.* (2000) (see Table 2.10).

Table 2.10 Biodegradation rates for PFW compound groups (from Johnsen *et al.*, 2000)

Group	Main Group	Biodegradation rate 1/2 life (days)
1	BTEX	0.5
2	Naphthalenes	1.5
3	PAH 2-3 ring	17
4	PAH 4-ring +	350
5	Alkyl phenols C0 – C3	1.2
6	Alkyl phenols C4+	10
7	Aliphatic hydrocarbons	60
8	Metals	None
10	Organic acids	Not included
11-n	Process Chemicals	Specific data

2.3.5 Biochemical Oxygen Demand

Biological oxygen demand (BOD) is a measure of the rate at which oxygen is consumed by bacterial activity in the water and thus is an indirect measure of the organic content of wastewater. BOD concentrations in PFW can be high. However, in the ocean where dissolved oxygen is abundant, demand is met quickly. It is estimated that in any area where BOD levels deviate by $<1.5\text{mgL}^{-1}$ from background levels, the resulting impact on dissolved oxygen levels will be $<0.5\text{mgL}^{-1}$ (CSTT, 1993). A change of 0.5mgL^{-1} can be assumed to cause no adverse effect. The Australian guidelines (ANZECC, 2000) are slightly less conservative stating that that dissolved oxygen (DO) should not normally be permitted to fall below 90% saturation, this being determined over at least one diurnal cycle. For the current project a BOD value below 1.5mgL^{-1} is taken as the threshold below which there should be no adverse impact on oxygen concentrations.

2.3.6 Bioaccumulation mechanisms

Bioavailability

A contaminant can have no effect on an organism unless it is bioavailable, ie, in a form that can move through or bind to a surface coating (e.g. skin, gill epithelium, gut lining, cell membrane) to prevent it from functioning properly. As a general rule, hydrocarbons in solution are most bioavailable followed by those in tissues of marine organisms or associated with liquid oil droplets (Neff, 2002). The bioavailability of hydrocarbons decreases sharply with increasing carbon chain length and molecular weight.

Bioaccumulation

Aquatic biota do not only degrade pollutant chemicals, they may also accumulate them. Bioaccumulation is the uptake and retention of bioavailable chemicals from any one of, or all possible external sources (water, food, substrate, air). For bioaccumulation to occur, the rate of uptake from all sources must be greater than the rate of loss of the chemical from the tissues of the organism. The bioaccumulation factor (BAF) is the ratio of the concentration of the chemical in the tissues of the organism to its concentration in all ambient environmental compartments in equilibrium with the organism.

Bio-concentration

Bio-concentration is a special case of bioaccumulation as it is defined as uptake and retention of a chemical from water alone as opposed to all possible external sources. It is measured by the bio-concentration factor (BCF), which is the ratio at equilibrium of the concentration of a chemical in the tissues of the organism (C_t) to the concentration of the chemical in solution in the water (C_w) to which the organism was exposed. The BCF can also be measured as the ratio of the uptake rate constant or uptake clearance (k_1) to the release rate constant (k_2).

$$BCF = C_t/C_w = k_1/k_2$$

Non-polar (un-ionisable) organic compounds such as aromatic hydrocarbons generally have a low aqueous solubility and a high lipid solubility. According to equilibrium partitioning theory, when an animal is exposed to a non-polar organic chemical dissolved in ambient water, the chemical partitions into tissue lipids until an equilibrium, approximated by the octanol/water partition coefficient (K_{ow}), for the chemical is reached. It is possible to predict the equilibrium BCF for a particular non-polar organic compound from its log K_{ow} , (if underlying assumptions are met) as follows:

$$\text{Log BCF} = a \text{ log } K_{ow} + b$$

EPA (1991) recommends using $a = 0.79$ and $b = -0.4$, from the experiments of Veith and Kosian (1983). This provides a conservative estimate of the potential for bio-concentration of non-polar organic chemicals. The BCF for polar (ionisable) compounds, such as phenols, is generally higher if ionised, however, their behaviour will be similar to un-ionisable organic chemicals if they remain un-ionised at the pH and salinity of seawater.

Bioaccumulation of metals by marine organisms is more complex than for organic chemicals. Concentrations of heavy metals in Blacktip PFW should be low and therefore bioaccumulation of this class of chemical is not considered to be an issue.

Trophic Transfer

Marine animals are able to bioaccumulate most bioavailable forms of metals and organic contaminants from their food. Bioaccumulation of chemicals from food is called trophic transfer. Biomagnification is the process whereby a chemical, as it is passed through a food chain or food web by trophic transfer, reaches increasingly higher concentrations in the tissues of animals at each higher trophic level. The biomagnification factor (BF) can be defined as the ratio of the concentration of a contaminant in the tissues of the consumer to its concentration in the food.

2.4 Environmental Fate of Individual PFW components

2.4.1 General

This section described how the individual components described previously behave when discharged to the marine environment.

2.4.2 Oil compounds

Dissolved Oil

Dissolved oil in PFW (predominantly aliphatics, BTEX, low molecular weight PAHs and phenols) will dilute readily into the receiving water and be dispersed by the ambient currents. These compounds are bioavailable to marine organisms and will biodegrade rapidly. While they may bioaccumulate at lower trophic levels, vertebrates including fish have detoxification mechanisms that break hydrocarbon compounds down. They are also volatile and will evaporate if they reach the sea water surface and come into contact with the atmosphere. They do not adsorb strongly to suspended particles so are unlikely to be transported to the sea bed.

Dispersed Oil

Oil compounds associated with oil droplets will either follow the plume or be retained at certain depths in the water column depending upon their buoyancy and turbulence. Vertical turbulence generated by wind shear and wave action will mix oil droplets with diameters less than about 100µm into the water column. These smaller droplets tend to float back to the surface only very slowly where they are repeatedly forced back into the water column. In this case, they are considered to be permanently dispersed. Larger oil droplets remain at the sea surface where they will spread to form a thin micro-layer (sheen) that in calm water is typically less than 1µm thick. The micro layer is then splintered and dissipated through evaporation and surface turbulence. Surface turbulence breaks the micro-layer into smaller sized droplets which causes dispersal through the water column. Once hydrocarbons have

been dispersed into the water column as fine droplets they may be removed through adsorption to particles followed by sedimentation and biodegradation, as described above.

Polycyclic Aromatic Hydrocarbons

Overview

PAHs are the petroleum hydrocarbon of greatest environmental concern in PFW because of their toxicity and persistence in the marine environment (Neff, 1987). The wide range of solubilities and partition coefficients exhibited by the different PAHs means that they exhibit a wide spectrum of behaviour (Neff, 2002). The most common PAHs (naphthalene, alkyl naphthalenes, fluorene and phenanthrene) are soluble and have relatively high Henry's law constants and tend to evaporate where possible from the water. Higher molecular weight PAHs are less soluble and are expected to be associated with particulates and the oil droplets in the PFW. These will partition primarily between the aqueous and solid (particulate) or colloidal phases according to their organic carbon/water partition coefficients (K_{oc} s), which are proportional to K_{ow} s. Biodegradation half lives range from readily to poorly biodegradable and vary from 1.5 days for naphthalene, 17 days for two to three ring PAHs and 350 days for more than four ring PAHs (Johnsen, *et al.*, 2000).

Bioaccumulation

The PAHs in PFW may bioaccumulate and cause adverse biological effects in marine organisms near offshore oil and gas production platforms (Neff, 2002). Ordinarily, the concentrations of PAHs in receiving waters in deep offshore areas are low enough due to the rapidly diluting PFW plume to prevent bioaccumulation. In contrast, discharges to shallow, poorly mixed coastal waters may not dilute rapidly enough and marine organisms may bioaccumulate PAHs to potentially harmful concentrations.

Burns and Codi (1999) measured PAH concentrations in the water column around a platform in 22m of water on the North West Shelf of Australia. Concentrations were highly variable reflecting the variability of PAH concentrations in the PFW and the complex nature of the current regime in the area.

Typical water concentrations of naphthalenes and PAHs at 10m depth and at different distances from an oil production platform are shown in Table 2.11 (from OGP, 2002). These were calculated from mussel residue and converted to water concentrations as described in Roe Utvik *et al.* (1999). The results confirm the high dilution rates, however, they are point measurements and do not provide a complete description of fate and behaviour. Comparisons of these results with predictions from the DREAM (Dose related Risk and Effect Assessment Model) model are generally favourable, supporting and justifying the application of models for regional evaluation of PFW (OGP, 2002). The DREAM model is a random walk, particle tracking model based on the same principle as that used in the present study and described in Section 4.3.3.

Table 2.11 Water column concentrations of naphthalenes and PAHs at different distances from an oil production platform in the Norwegian Sector of the North Sea

	Concentrations (μgL^{-1})			
	In PFW	At 500 m	At 2,000 m	At 10,000 m
Naphthalene	1200	0.04	0.013	0.007
PAHs	33	0.004	0.001	0.0004

2.4.3 Organic acids

Organic acids biodegrade rapidly in the ambient sea water and so are unlikely to be important contributors to toxicity of PFW in the ambient environment (Neff, 2002). However, many studies attribute the acute toxicity of PFW to organic acid concentrations (eg. DK, 2001). These studies use ecotoxicology results from freshwater species which have high toxicity values. These high values are likely to be due to a pH effect rather than the actual toxic effect of the compound. Natural seawater is a buffer solution and acidity will be quickly neutralised. Organic acids are therefore not considered to be toxic in the marine environment.

2.4.4 Heavy metals

The heavy metals associated with PFW are usually present as dissolved mineral salts. Reservoir water is anoxic and the metal ions are typically in low oxidation states. However, when brought to the surface and exposed to the atmosphere they oxidise. The metal oxides then combine with anions such as sulphides, carbonates and chlorides and form insoluble precipitates. Heavy metal concentrations are generally low in PFW. Dilution in the receiving environment reduces them to background levels and well below chronic toxic thresholds. When they form precipitates, there is the potential for build up in the sediments, however, the quantity will be so low and the spread across the sea bed so wide that the environmental impact will be insignificant.

2.4.5 Radioisotopes

Upon discharge of PFW to the ocean, radium is rapidly co-precipitated with barium sulphate. Radium concentrations in ambient water near PFW discharges are rarely higher than background levels. Toxic concentrations are well above the saturation concentrations of radium in sulphate-rich seawater. Marine animals are highly tolerant to low-level radiation as might occur in the traces of radium isotopes in the vicinity of PFW discharges. Radium, because of its low concentrations in solution in seawater, has a low bioavailability to marine organisms. There is also no evidence that radium accumulates in sediments or marine animals (molluscs, crabs and fish) living in the vicinity of offshore PFW discharges (Neff, 2002).

The Brookhaven National Laboratory performed a human health risk assessment for radium in PFW discharged to the northwestern Gulf of Mexico. It concluded that radium in PFW

represents a minimal risk to even the most sensitive workers (platform crew and recreational fishermen) who consume fish from the vicinity of PFW discharges (Brookhaven National Laboratory (1992) in Neff (2002)).

2.4.6 Process Chemicals

General

The impact of process chemicals depends on the concentration at which they are discharged and the breakdown characteristics of the chemical. The initial dosage concentration range is specified by the chemical supplier and then fine-tuned by the operator to achieve optimum performance of the chemical in combination with other chemicals and the oil.

Many of these chemicals are more soluble in the oil than in PFW and remain in the oil phase. Others are water soluble and concentrate in the PFW and are disposed with it. The point in the production stream where the chemical is added influences the amount that may be discharged in the PFW. The fraction of chemical released into the water phase (f) can be estimated from the octanol/water partition coefficient (K_{ow}) as follows:

$$f = \frac{1}{(1 + K_{ow}) \left(\frac{P_o}{P_{PFW}} \right)}$$

where, P_o is the total oil production and P_{PFW} is the total PFW production. The concentration of the process chemical in the PFW (C_w) can then be expressed as:

$$C_w = (C_d f) - (C_d r)$$

where, C_d is the dosage concentration and r is the fraction that reacts during the production process.

Due to the variability in the characteristics of the oil and the production process, the Oslo and Paris Commission (OSPAR) use a conservative formula for determining the concentration of a chemical discharged with the PFW. Reaction during the production process is ignored and a safety factor of 10% is applied so that the concentration in the discharge is now given by:

$$C_w = (C_d f) + (0.1 C_d)$$

For process chemicals not on the Pollution control Authority A list, OSPAR require ecotoxicity data on the whole product. Testing should be undertaken on marine organisms, including an alga and a crustacean.

As stated in Section 2.2.7, the process chemicals that will be added to Blacktip are:

- Corrosion Inhibitor;
- Methanol/Mono Ethylene Glycol; and
- Demulsifier/coagulant.

Corrosion Inhibitor

Corrosion inhibitor will be added to the produced fluids in order to protect the production system from corrosion. Table 2.12 provides a list of corrosion inhibitors recommended from a detailed study aimed at selecting environmentally acceptable chemicals for Blacktip (de Reus, 2004).

Table 2.12 also includes their dose rate and hazard quotient (HQ) for each chemical. The hazard quotient, calculated using the CHARM model, provides an indication of the likelihood of adverse effects occurring due to the use and discharge of the chemical under a realistic worst-case scenario. An environmental effect can be expected if the HQ is greater than one. As can be seen from Table 2.12 the HQ ranges from 0.045 to 0.977. All four chemicals are therefore environmentally acceptable.

Table 2.12 Recommended Corrosion Inhibitor chemicals

Supplier	Inhibitor	Dose rate (L/day)	HQ (hazard quotient)
Baker Petrolite	CRW-85155	50	0.977
Champion-Servo	CK-981	25	0.239
Champion-Servo	CK-988	100	0.045
Nalco	EC-1440A	50	0.130

Methanol/Mono Ethylene Glycol;

Methanol will be injected upstream of the chokes on the offshore platform to prevent hydrate formation on cold start-ups. The injection rate will be around 20-40 Lhr⁻¹ for a short duration (hours).

Methanol (or possibly Mono Ethylene Glycol) may also be injected at the onshore plant in the gas processing facility for hydrate control. This would likely be injected only occasionally upstream of the Low Temperature Separator (LTS) and so some will remain in the liquid leaving the LTS and end up in the condensate processing train, and therefore the water treatment process.

Methanol is miscible in water, non-carcinogenic and poses little long term risk to the environment. It is, however, a strong reducing agent and, in the short term, has the potential for depleting oxygen in the receiving waters. This will contribute to the BOD discussed in Section 2.3.5.

Demulsifier/coagulant.

Demulsifier/coagulant will be injected in the water treatment facility to aid in the operation of the gas flotation unit. Most, if not all, of this will be removed as skimmings from the unit and will therefore not enter the PFW.

Both the corrosion inhibitor and the methanol are water soluble so the majority of these additives will end up in the PFW discharge. On discharge to the marine environment, dilution will be the main factor reducing concentrations.

2.5 Assessing Environmental Effects and Risks

2.5.1 General

An effect on an organism is a measurable biological response which reduces its survival or reproductive capacity. A sustained widespread effect may alter the ability of a population or a community to persist. The ecological significance of an effect may be considered in terms of the magnitude and nature of the change induced at individual, population, community or higher trophic levels. The social and economic significance of effect can be considered in terms of impact on recreational or commercial fishing, tourism, conservation values and the benefit to the community of the petroleum industry (Cobby, 2002).

2.5.2 Toxicity

Toxicity depends on the chemical compounds present, the exposure duration (acute or chronic), the organisms impacted and the environmental compartment. Most hydrocarbons are considered non-specific narcotic toxins and their toxicity depends on attainment of a critical volume or concentration in the tissues of aquatic organisms (Neff, 2002). The toxicity of hydrocarbons in mixtures is additive, so the toxicities of a complex mixture depends on the total concentration of bioavailable hydrocarbons and degradation products in the water to which aquatic organisms are exposed.

Acutely toxic responses have a sudden onset after or during relatively high exposure, usually for short durations: within four days for fish and macroinvertebrates and shorter times (two days) for organisms with shorter life spans. The response may be lethal or sub-lethal. Examples of sublethal effects include: impairment of feeding mechanisms, growth rates, development rates, energetics, reproductive output, recruitment rates and increased susceptibility to disease and other histopathological disorders. Early development stages can be especially vulnerable to hydrocarbon exposure, and recruitment failure in chronically contaminated habitats may be related to direct toxic effects of hydrocarbon contaminated sediment.

In contrast, chronic responses involve endpoints that are realised over a relatively long period of time, often one-tenth of the life span of an organism or more. A chronic toxic response is usually characterised by slow toxic progress and long continuance and may be

measured in terms of reduced growth, reproduction or fertilisation at different life stages, in addition to lethality.

Toxic concentrations are standardised as median lethal concentration (LC50s) for lethal responses or median effect concentration (EC50s) and median inhibition concentration (IC50s) for non-lethal response. Definitions for these terms are as follows:

- | | |
|------|--|
| LC50 | The toxicant concentration killing 50% of exposed organisms at a specific time of observation. |
| EC50 | The toxicant concentration estimated to cause a specified effect in 50% of exposed organisms at a specific time of observation. |
| IC50 | The toxicant concentration estimated to cause a specified inhibition (eg. growth) in 50% of exposed organisms at a specific time of observation. |

PFW from oil and gas wells vary widely in composition and toxicity to freshwater and marine organisms, confounding the development of generalisations about the causes of toxicity (Neff, 2002). This uniqueness makes it necessary to undertake site specific studies. In estimating the risk of PFW to marine organisms and ecosystems in the receiving water environment there are two different approaches:

- whole effluent toxicity (WET) testing; and
- individual component toxicity testing.

Whole Effluent Toxicity Testing

General

As its name suggests, WET testing involves undertaking ecotoxicological tests on the whole PFW sample. This method represents a toxicity value for the PFW prior to discharge to the ocean. It has the advantage that it is directly relevant to the effluent that is being discharged and it takes into consideration all chemicals in the PFW and any synergy or antagonism between them. The disadvantage is that degradation rates in the environment are unknown and are difficult to determine.

Worldwide toxicity data

Stephenson *et al.* (1994) have summarised marine and toxicity data for a large number of marine and freshwater organisms and PFW from throughout the world, particularly the North Sea (Table 2.13). Due to the extreme variability in chemical composition and toxicities of the PFW from different sources, no consistent trends between taxa and sensitivity to PFW emerge.

Table 2.13. Summary of the acute, sublethal and chronic toxicity of PFW from throughout the world to different taxa of marine and freshwater organisms (from Neff, 2002)

Taxon	Species	Test Endpoint	Test Duration (days)	EC50/LC50 (%PFW)
Algae	<i>Phaeodactylum tricornutum</i>	Growth	4	0.09 – 3.6
	<i>Skeletonema costatum</i>	Growth	2	4.5 – 67.6
			3	1.0 – 42.5
Coelenterates	<i>Campanularia flexuosa</i>	Growth	10	5.0
Bivalve Molluscs	<i>Crassostrea gigas</i> larvae	Mortality	2	5.0
	<i>Mytilus californianus</i> larvae	Shell formation	2	2.1
	<i>Donax faba</i> adults	Mortality	4	0.02 – 15.3
Polychaetes	<i>Neanthes arenaceodentata</i>	Mortality	4	18.1 – 28.6
Copepods	<i>Tisbe holothuriae</i>	Mortality	4	35.7 – 66.7
	<i>Calanus finmarchicus</i>	Mortality	1	10.0
	<i>Arcatia tonsa</i>	Mortality	2	2.0 – 18.0
		Reproduction	20	0.3 – 5.0
		Immobility	4	2.0
Amphipods	<i>Allorchestes compressa</i>	Mortality	4	29.4 - >100
	<i>Chaetogammarus marinus</i>	Mortality	4	0.2 – 3.2
Shrimp	<i>Penaeus aztecus</i> larvae	Mortality	2	0.8 – 1.2
	<i>Penaeus aztecus</i> juveniles	Mortality	4	6.0 – 18.3
	<i>Penaeus aztecus</i> adults	Mortality	4	7.8 – 17.8
	<i>Penaeus setiferus</i> adults	Mortality	4	7.0
	<i>Crangon crangon</i> adults	Mortality	1	2.0
Mysids	<i>Americamysis bahia</i>	Mortality	4	4.9 – 11.8
		Mortality	7	4.4 – 9.0
		Fecundity	7	0.7 – 7.0
Brine Shrimp	<i>Artemia salina</i>	Mortality	1	16.0 – 18.0
Barnacles	<i>Balanus tintinabulem</i>	Mortality	4	8.3
Echinoderms	<i>Strongylocentrotus Purpuratus</i> gametes	Fertilisation	1 hour	0.74 – 1.7
Fish	<i>Menidia beryllina</i> larvae	Mortality	4	>1.1 – 5.5
	<i>Hypleurochilus germinatus</i>	Mortality	4	15.8 – 40.8
	<i>Cyprinodon variegatus</i>	Mortality	4	7.2 – 60.0
		Mortality	7	3.7 - >28.0
	<i>Poecilia reticulata</i>	Mortality	4	0.75 – 42.3
	<i>Oncorhynchus mykiss</i>	Mortality	2	10.0

Acute and sublethal effect concentrations (as EC50 and LC50) of whole PFW ranges from 0.02% to more than 100%. Overall the most sensitive taxa appear to be marine algae, bivalve mollusc larvae, and various species of crustaceans, particularly larval forms. Among the crustaceans, mysids appear to be as or more sensitive than other crustacean species. Generally, fish are more tolerant to PFW than marine invertebrates.

North West Shelf and Timor Sea

Figure 2.1 summarises the ecotoxicology test results for NRA, GWA, CP, OL and NE (see IRCE, 2003a–e). Individual tests target toxicity of different components in the PFW, hence results, both between tests and facilities, are quite variable. For example, PFWs from NRA and CP are most toxic to the sea urchin fertilisation test whilst not so toxic to the acute prawn and chronic algae tests. In contrast, NE PFW is most toxic towards the prawn test and only moderately toxic to the sea urchin tests. GWA and OL show the most consistency across the suite of tests. In general, NRA PFW is consistently the most toxic. This is followed, in order of toxicity, by CP, OL, GWA and NE.

Both unfiltered and filtered samples from NRA and GWA were tested. The results showed little variation in toxicity. The filtered GWA sample was slightly less toxic for the sea urchin fertilisation, rock oyster larval development and algae growth inhibition tests, more toxic for the tiger prawn acute test and about the same for the sea urchin fertilisation test. These results are within experimental variability and it may be concluded that the dissolved component contributes most to the toxicity and that there would be only minor benefit in filtering the PFW prior to discharge.

Figure 2.2 summarises the Microtox® results. These tests exhibit significant sensitivity to the PFW and results correlate with the general trend shown by the more sophisticated tests, ie, NRA is the most toxic and Northern Endeavour being the least. Microtox® could therefore provide a useful and cost effective screening tool to monitor toxicity over time.

2.5.3 Risk Assessment

The ratio of the Predicted Environmental Concentration (PEC) to the Predicted No Effect Concentration (PNEC) (PEC/PNEC ratio) is an established technique to screen chemicals in offshore discharges (EC, 1996). It forms the basis of the OSPAR Harmonised Notification Scheme (OSPAR, 2000) and is used in the EIF tool (Johnsen *et al.*, 2000). The PNEC is derived from ecotoxicity data and is the concentration below which it is believed there will be no detrimental effect on the environment. It relies upon the assumption that a single value captures the concentration at which no toxic response (acute or chronic) is expected in the target population of marine biota. Dispersion models, such as that used in the present study (see Section 4.3.3), provide spatially and temporally varying PECs for either the whole effluent or individual compounds. A PFW plume with a PEC/PNEC ratio of one will generally correspond to a probability of 5% that biota will be affected. In the EIF method, the combined risk of simultaneous exposure to a mixture of chemicals like PFW, is estimated by statistical summation of the risks for individual chemicals.

Figure 2.1 Ecotoxicology results for WEL's North West Shelf and Timor Sea Assets (from IRCE, 2003a-e)

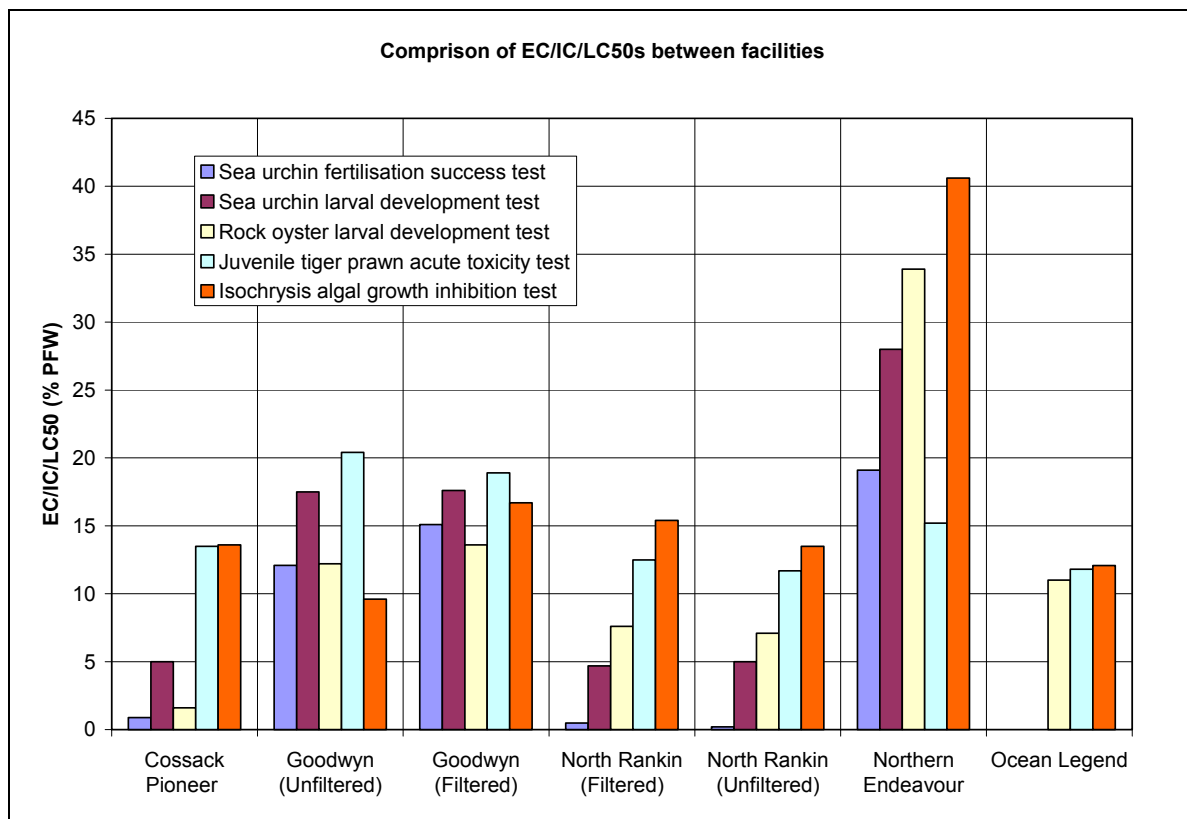
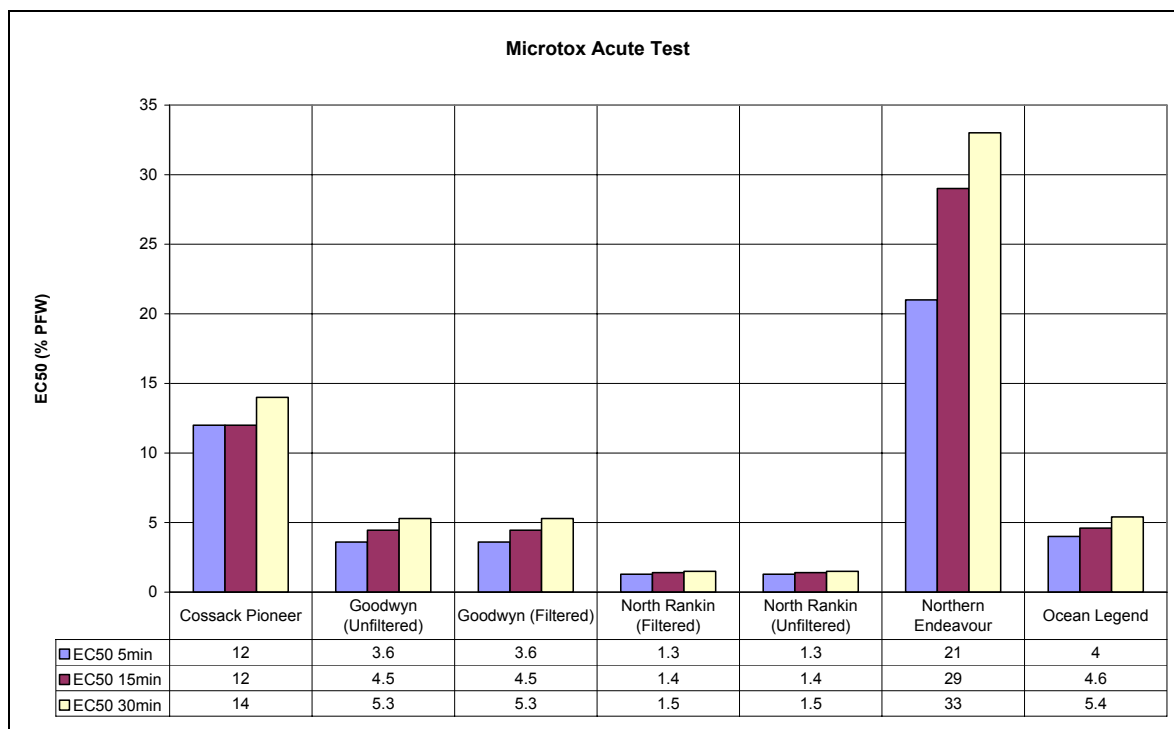


Figure 2.2 Comparison of Microtox® test results between facilities (from IRCE, 2003a-e)



If spatial scale of the effect is limited to the immediate area around an offshore facility and the significance of the effect is considered to be low, then the risk is likely to be acceptable (Terrens and Tait, 1996). Conversely, if the spatial scale of the effect is widespread and the survival or reproductive capacity of marine organisms is significantly reduced then the risk is likely to be considered unacceptable. Where there are unacceptable risks, management actions to reduce risk to acceptable levels would be required.

2.6 Observations of Exposure and Effect

Bioaccumulation studies

Any assessment of PFW effects and risks should consider acute and chronic effects as a production facility may have an operating life of up to 25 years or more. Chronic effects are notoriously difficult to measure in the natural environment. The Offshore Operators Committee (1997) reported that there have been no field observations of bioaccumulation in marine organisms living naturally in the vicinity of offshore oil and gas facilities in the Gulf of Mexico. This lead to conclusions that exposure times to PFW concentrations above chronic toxicity levels is short.

In contrast, monitoring programmes in the Norwegian sector of the North Sea using caged mussels deliberately moored in the path of a PFW plume reveal elevated (compared to background) concentrations of PAHs in mussel tissue (Johnsen *et al.*, 1998 and Roe Utvik *et al.*, 1999). Burns and Codi (1999) also present results from caged oyster studies that show bioaccumulation. It is therefore possible for marine organisms to bioaccumulate particular chemical from PFW, however, it is uncommon in freely living organisms due to the intermittent nature of their exposure (see Section 4.3.8 for a further discussion).

Biochemical Marker Studies

An alternative to measuring bioaccumulation in marine organisms is to measure the biological response induced by contaminants using biochemical markers (biomarkers) (Cobby, 2002). As suggested in Section 2.3.6, an organism may be exposed to a contaminant but it will not necessarily be adversely affected. Table 2.14 provides a summary of biomarker tools, contaminant triggers, indicator type, mechanism and ecological relevance (see Cobby (2002) for further information). These biological responses or biomarkers are direct indicators of exposure or effect and provide environmental managers with an early warning system for identifying exposure and any adverse environmental effects.

Table 2.14 Summary of biomarker tools, contaminant triggers, indicator type, mechanism and ecological relevance (from Cobby, 2002)

Biomarkers	Triggers	Indicators	Mechanism	Ecological relevance
Mixed Function Oxygenase (MFO)	Petroleum hydrocarbons	Indicator of exposure	Initial step of detoxification process to eliminate contaminant out of the body.	Correlation with reduced reproductive success. Production of PAH metabolites is related to onset of cancer in fish.
Bile metabolites	Hydrocarbons (naphthalene, pyrene)	Indicator of exposure	Final steps of the elimination of hydrocarbons. After metabolites are made water soluble they are directed to the bile for elimination.	Production of PAH metabolites is related to onset of cancer in fish. PAH metabolites may be more biologically active than parent compounds and cause genetic damage.
DNA damage	Any biological active contaminant	Indicator of effect	Contaminant integrates itself into DNA molecule causing damage to the integrity of the DNA molecule. This causes incorrect synthesis of proteins, enzymes etc.	Damaged DNA can result in no viable eggs, malformed larvae, reduced reproductive success, biochemical imbalances in living organisms, cancers etc.
Sorbital dehydrogenase (SDH)	Hydrocarbons, Solvents, Hepatotoxic agents	Indicator of effect	SDH is normally present in the liver only. Its presence in the blood of an organism indicates liver damage.	Liver damage will affect vital functions including digestion, synthesis and regulation of production hormones, production of eggs by females, detoxification by MFO's.
Stress proteins	Any sustained or chronic mechanical or chemical stress	Indicator of effect	Stress causes higher levels of transcription errors during the synthesis of biomolecules. The role of stress protein is to repair transcription errors.	Any sustained stress (heat shock, acoustic disturbance, moulting, long term handling, exposure to chemicals) can induce stress proteins.

2.7 Regulatory Framework and International Best Practice for PFW Discharges

2.7.1 Australia

In Australia, the Petroleum (Submerged Land) Act (P(SL)A) Schedule of Specific Requirements for Offshore Petroleum Exploration and Production 1995 requires that PFW shall not be discharged into the sea unless approved by the Designated Authority (Clause 602 C and 616 (4)). Where approval is granted, the concentration of petroleum in any PFW:

- shall not exceed 50mgL⁻¹ at any one time; and
- average less than 30mgL⁻¹ during each 24 hour period.

The Schedule applies to both Commonwealth and State/Territory jurisdictions.

In addition, Regulation 13(3) of the Commonwealth Petroleum (Submerged Land)(Management of the Environment) Regulations 1999 (P(SL)(ME)R) states that operators are required to assess the environmental effects and risks associated with PFW discharge, as part of a petroleum activity.

As in most countries, the definition of “petroleum” is open to interpretation but is thought to refer to dispersed aliphatic hydrocarbons. Removal of polar compounds by filtering through Florisil (silica material) and nitrogen sparging is accepted practice. Measuring techniques vary but mostly in-line analysers are used (Sigrist, Horiba, Hach and Turner). Results are reported daily.

In Australia, guidelines for water quality are provided by the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC, 2000). These guidelines provide trigger values for various chemicals.

2.7.2 USA

The USEPA requires oil and grease concentrations in produced water to be monitored by EPA Method 413.1 or 1664A. Both methods are gravimetric. Non-polar and slightly polar organic matter in produced water is extracted with Freon (Method 413.1) or n-hexane (Method 1664A). In method 1664A, the analyst has the option to treat the hexane extract with silica gel to remove polar interfering compounds. The extract is dried and weighed to derive a concentration of total extractable organic matter (total oil and grease). It should be noted that in revision A of the method N-hexane extractable material is synonymous with “oil and grease”, whilst applying silica gel (ie, Florisil) extracts the “non-polar material”.

The discharge limits in the US varies depending on law in different States. In U.S. Federal waters and state waters of Upper Cook Inlet, Alaska, the current limit for total oil and grease (defined as dispersed and dissolved oil as measured by gravimetric or infrared analysis) in treated PFW is:

- 42mgL⁻¹ daily maximum; and
- 29mgL⁻¹ monthly average.

Discharge of PFW to estuarine and coastal waters is not permitted. Permits for the Gulf of Mexico prohibit discharge of more than 4,000m³ per day of PFW from a single platform.

Since it is a generally realised fact that Infrared (IR) Absorption based methods are simpler, faster, cheaper and less labour intensive than gravimetric, the USEPA and American Society for Testing Materials (ASTM) have initiated a study with focus to develop a stand alone infrared absorption method replacing Freon as solvent.

2.7.3 OSPAR Signatory States

The OSPAR Convention is the basis for national laws governing the discharge of offshore wastes in the northeast Atlantic and covers the following countries: Belgium, Denmark, Faeroe Islands, Finland, France, Germany, Iceland, Ireland, the Netherlands, Norway,

Portugal, Spain, Sweden and the United Kingdom of Great Britain and Northern Ireland. Under OSPAR, the regulatory limit for total oil and grease in PFW discharged to the waters of the northeast Atlantic is 40mgL^{-1} averaged over a month (Ray, 1996). The United Kingdom Offshore Operators Association (UKOOA) have adopted a voluntary standard of 30mgL^{-1} .

'Oil and grease' refers to the free (liquid phase) dispersed hydrocarbons. This is indicative of the origin of concerns of oil pollution at sea. This origin is from shipping-derived oil spills where the impact is from oil as a gross, smothering, 'physical' contaminant, responsible for damage to seabirds and other wildlife and contamination of beaches and coastal amenities. In contrast, the oil in PFW is a low concentration 'chemical' pollutant (soluble as a fine stable dispersion), which rarely appears as a visible contaminant. Effects, if any, are likely to be at tissue level and not at gross physical level as in the case of oil spills (Genesis, 2000).

In recognition of this, it is likely that in the future, changes will be made to regulations to account for:

- soluble and dispersed hydrocarbons;
- polycyclic aromatic hydrocarbons (PAHs);
- heavy metals;
- process chemical residues; and
- radioactivity.

2.7.4 Other Areas

The regulatory limit for total oil and grease in PFW discharged to most offshore waters of the Mediterranean, the Arabian Gulf and Asia is 40mgL^{-1} (Ray, 1996).

2.8 International Best Practice

It is common practice throughout the offshore industry to treat the PFW to below the regulatory limit and then to dispose to the ocean. Alternatives for PFW disposal include: piping to shore for onshore disposal; reinjection and down hole separation (Johnsen *et al.*, 2000). There is also a move towards achieving zero environmentally harmful discharge. In Norway, for example, the government is requiring the oil industry operating in the Norwegian sector of the North Sea to develop a strategy for reaching this objective for PFW by 2005 (Frost *et al.* 2002). The Russian government also requires minimal discharges for the new Sakhalin Shelf oil and gas fields.

2.9 Treatment Technology

A detailed description of treatment technologies for PFW is beyond the scope of this review. The reader is referred to OGP (2002) for a useful introduction to technologies presently

available. The summary of chemical removal capabilities for each technology is reproduced here in Table 2.15.

All of the technologies are capable of removing the dispersed oil fraction, with the actual performance being dependant on the fluid properties and process conditions. As a result of the removal of the dispersed oil droplets, an associated reduction in PAH concentrations is to be expected. Physical and enhanced separation techniques do not remove dissolved BTEX, NPD or PAHs, however, the new technologies are capable of removing at least some or all of these compounds. The advantages and disadvantages of each technique are given in OGP (2002).

2.10 Summary

PFWs are known to contain a number of chemical components that have potential to cause chronic effects in the marine environment. These include heavy metals, MAHs and PAHs. Although toxic effects have been demonstrated in the laboratory, no effects on species living naturally in the environment have been observed in the field. However, most studies recognise that the measurement of sub-lethal effects in the natural environment is difficult because of the nature of the species at risk and the presence of contaminants from other sources.

Each PFW is unique in its chemical composition confounding the development of generalities about the cause of toxicity. The high dilution received by PFW is believed to reduce PFW concentrations in the receiving environment to levels below toxic thresholds very quickly. PAHs are the petroleum hydrocarbon of greatest environmental concern in PFW because of their toxicity and persistence in the marine environment.

Although only small concentrations of contaminants are released, the continuous discharge of large volumes gives rise to environmental concern. Accordingly, most of the regulatory authorities from international to regional levels set limits on the concentration of petroleum hydrocarbons that can remain in PFW for ocean disposal. Oil is not a single substance but a very wide range of hydrocarbons substances, both in solution and dispersion. The component targeted by the regulation is dictated by the method used to measure the oil-in-water content, which up until recently has been the free (liquid phase) dispersed hydrocarbons. This is not the most toxic component, which is the dissolved phase. The regulations do not tend to consider the loading to the environment either. Operators in Australia are now required to assess the environmental effects and risks of PFW discharged to the ocean as well as to meet standard regulatory limits. There are moves in OSPAR signatory states to change regulation to legislate on the more relevant toxic components of PFW.

Table 2.15 Current PFW treatment technologies

Technology	Removal Capability			
	Dispersed oil	BTEX	NPD	Other PAHs
Physical separation				
Flotation	Yes	No	No	Some
Sparging	Yes	No	No	Some
Coalescence	Yes	No	No	Some
Enhanced separation				
Hydrocyclones	Yes	No	No	Some
Hydrocyclones + coalescence (Pect-F, Mare's Tail)	Yes	No	No	Some
Centrifuges	Yes	No	No	Some
Alternative (new) technology				
Absorption (polymers, MPPE, clays)	Yes	Yes	Yes	Yes
Adsorption (carbon, natural fibres)	Yes	Yes	?	?
Hydrocyclones + solvent extraction (C-Tour)	Yes	No	Yes	Yes
Membranes	Yes	Yes	Yes	Yes
Steam stripping	No	Yes	No	No
Biological (aerobic degradation)	Yes	Yes	?	?
Produced Water Reinjection	Yes	Yes	Yes	Yes

3 JOSEPH BONAPARTE GULF RECEIVING ENVIRONMENT

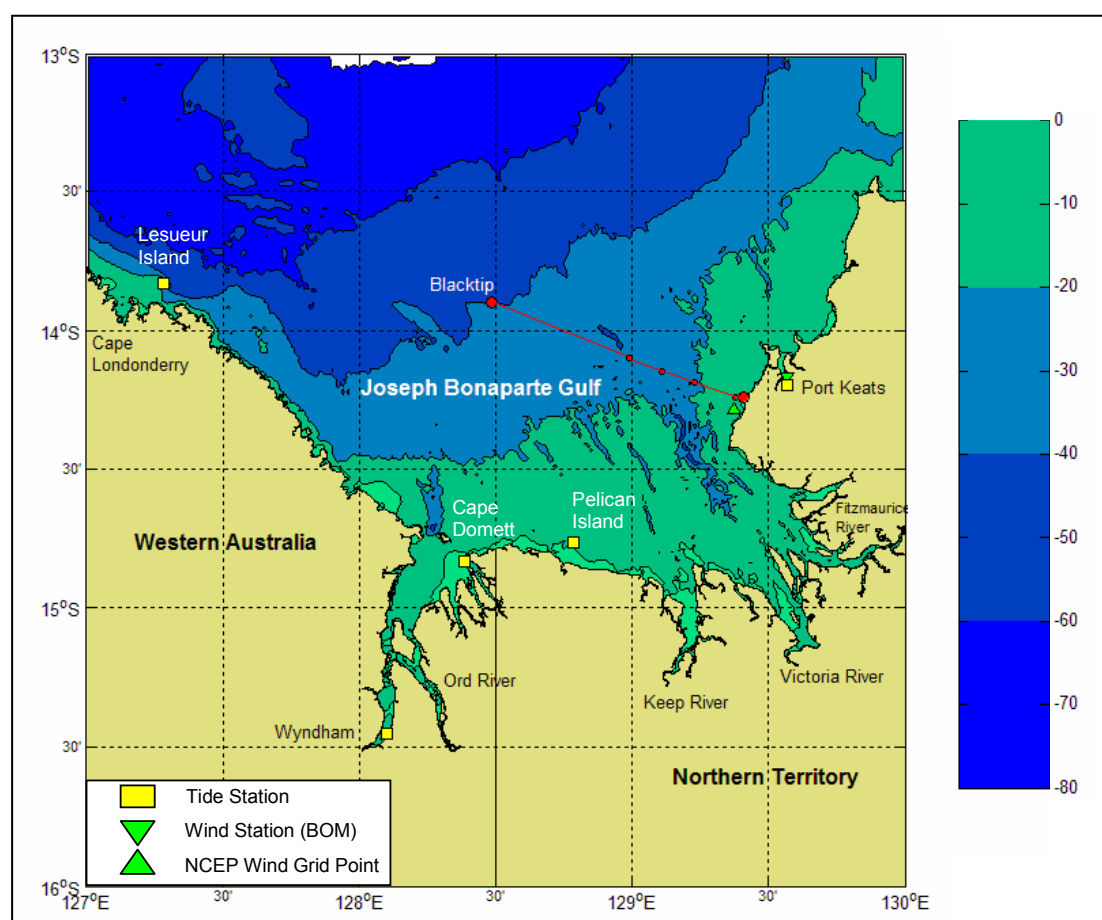
3.1 General

Joseph Bonaparte Gulf is a large embayment on the northwestern continental margin of Australia (Figure 3.1). It is approximately 300km east-west and 120km north-south with a broad continental shelf to seaward. Maximum width from the southernmost shore of Joseph Bonaparte Gulf to the edge of the continental shelf is 560km. Several large rivers enter the gulf along its shoreline.

3.2 Bathymetry

The offshore facility is located on the Sahul Shelf in 50m of water (Figure 3.1). Depths along the pipeline route generally decrease shoreward. There are no reefs or emergent banks along the pipeline route although it does pass through a dune field in the nearshore region.

Figure 3.1 The Joseph Bonaparte Gulf



3.3 Climate

The climate of the Timor Sea is monsoonal with a wet “summer” and a dry “winter”. The wet season commences between September and November as the southeast (SE) Trade winds weaken over Northern Australia and land temperatures rise. This results in two or more semi-permanent heat lows forming over central Australia, one over the Kimberley - Great Sandy Desert, and often another just south of the Gulf of Carpentaria.

The early part of the season is marked by frequent thunderstorms. As the season progresses moist ocean air from the north and northwest streams into the lows and several days of heavy rain may occur. Occasionally one of the lows may strengthen and move southeast over the interior. When this happens widespread rains follow and under exceptional circumstances the cloud may effect as far south as New South Wales. The general atmospheric circulation for the wet season is illustrated in Figure 3.2(a).

As winter approaches large highs centre over the southern part of the continent, the trade winds become re-established over Northern Australia and the monsoon retreats. The SE Trades are dry winds that bring no moisture. Figure 3.2(b) illustrates the typical atmospheric circulation for the dry season.

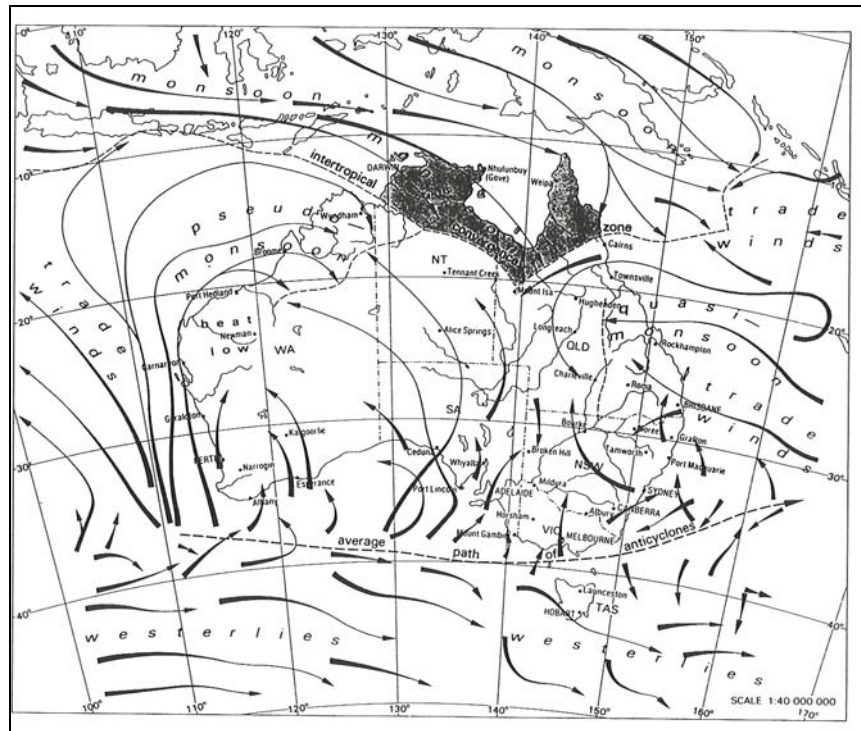
Mean daily maximum temperatures for Port Keats range from about 30 to 34°C, and minima from 14.5°C to 25°C. Annual rainfall is 750 to 900mm. Almost all rainfall occurs between November and April, the greatest falls being in January and February. The frequency and severity of the thunderstorms produce a large variation in the monthly rainfall. Rainfall during the dry months is sporadic and light.

3.4 Winds

Monthly wind roses for Port Keats are shown in Figure 3.3. Winds are predominantly from the northwest between September and February and from the southeast between April and July. During the transition periods between the two seasons in March and August, winds are more variable. Tropical cyclones can develop between November and April resulting in short lived, severe storm events often with strong but variable winds.

Figure 3.2 Generalised atmospheric circulation over Australia in Winter (July) and Summer (January) (from Swan *et al.*, 1994)

(a) Summer



(b) Winter

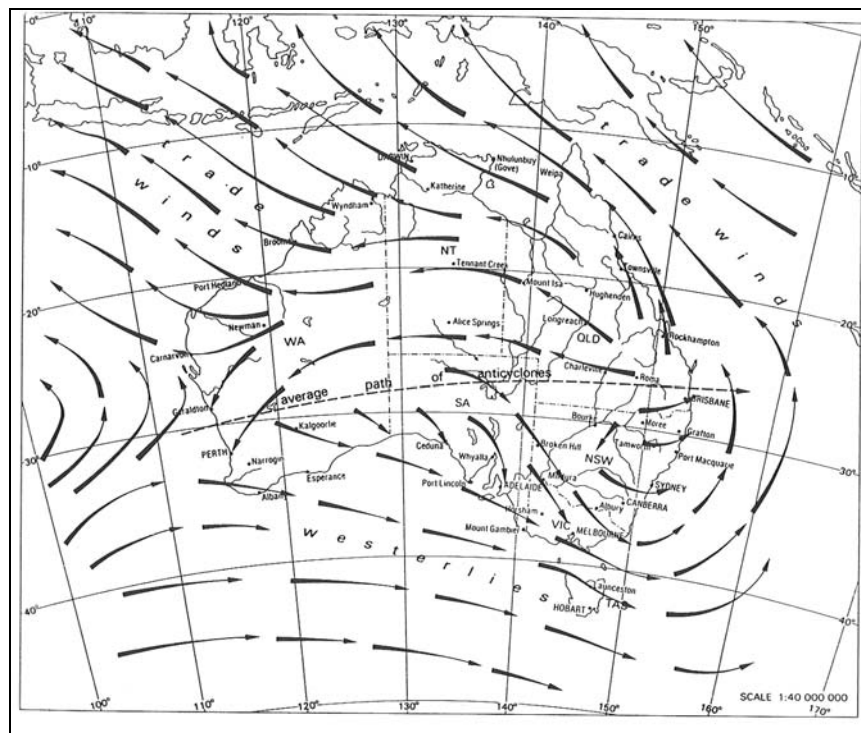


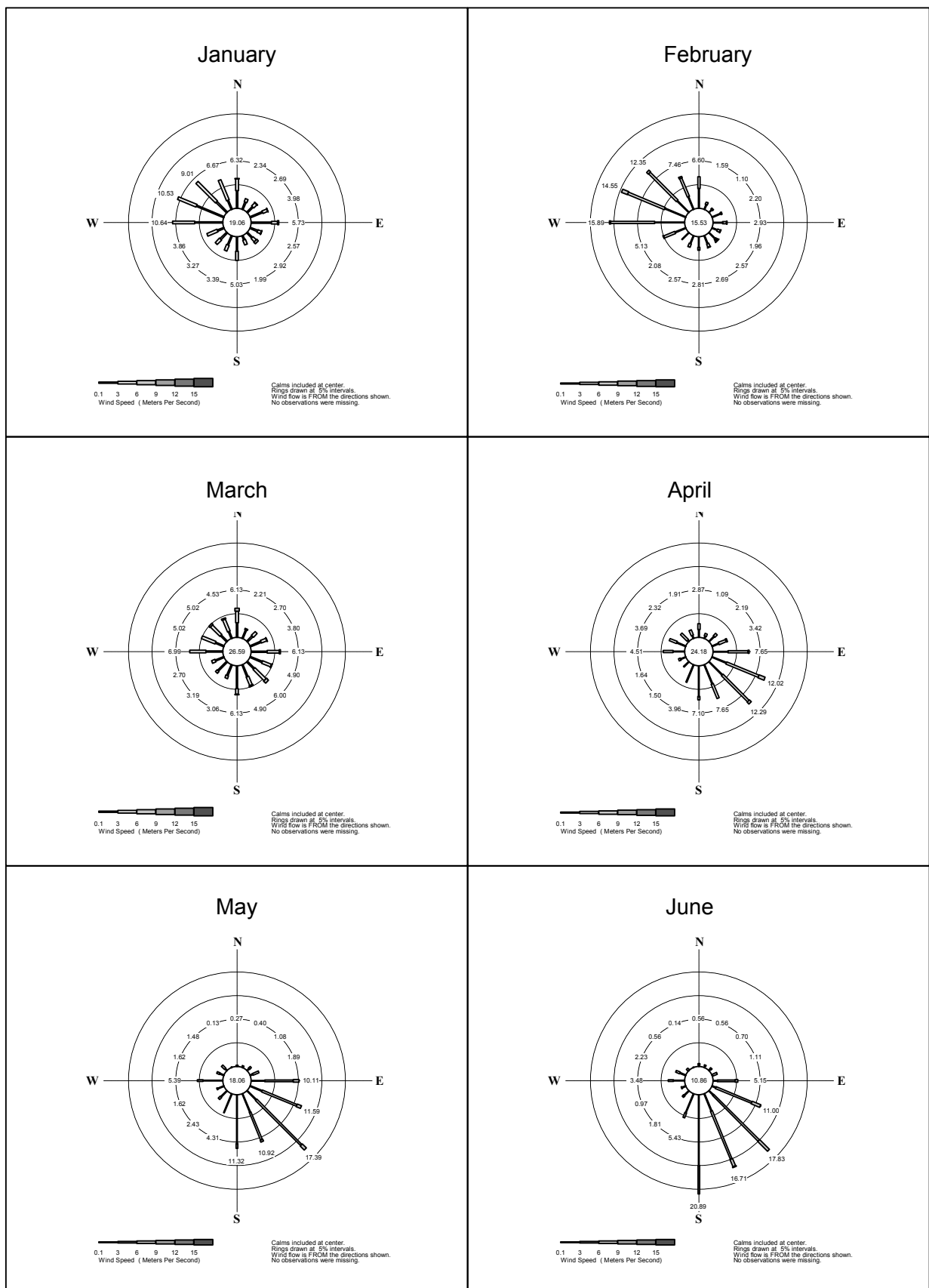
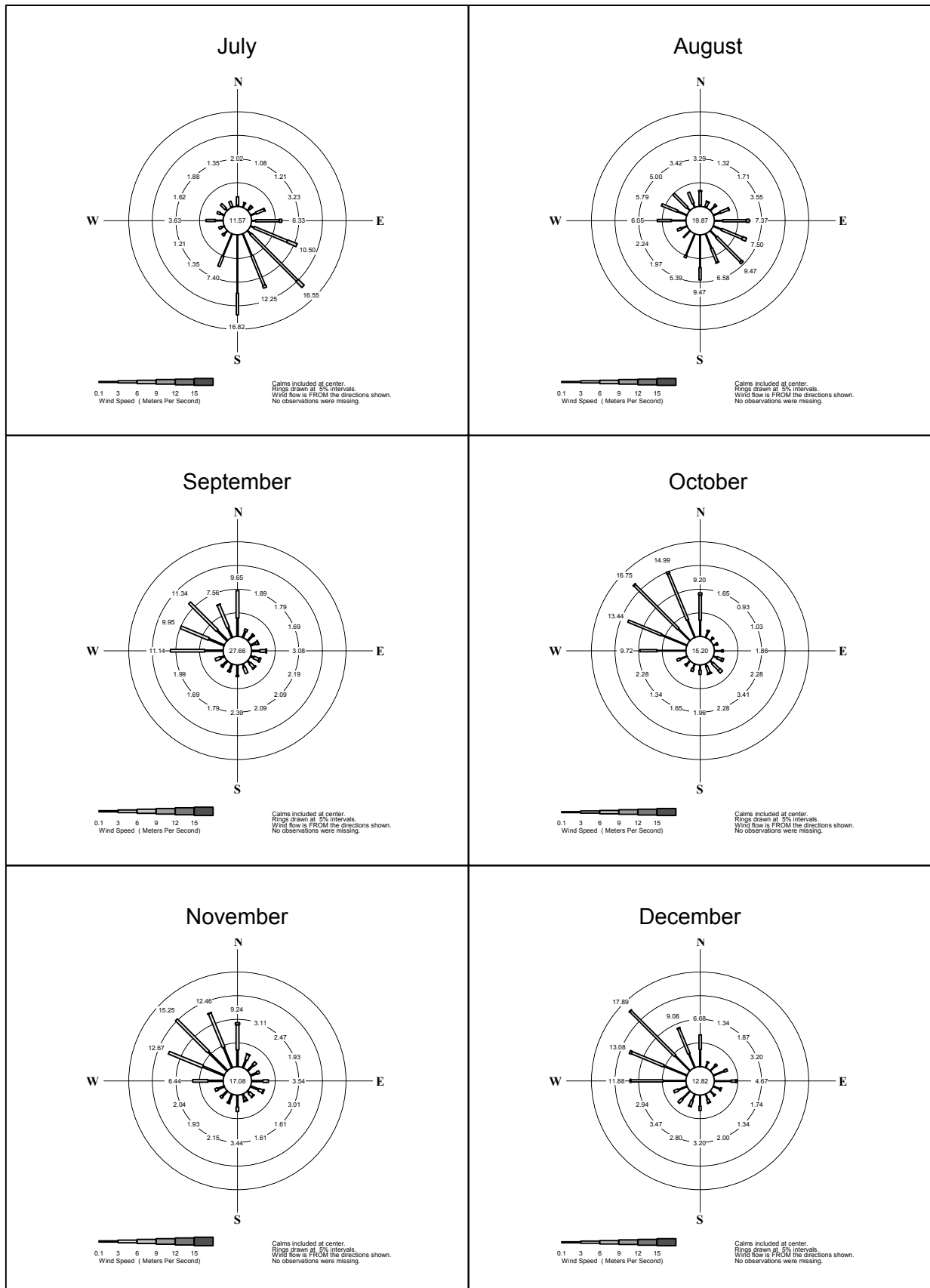
Figure 3.3 Monthly wind roses for Port Keats (2000 -2003)

Figure 4.3 (cont.)



3.5 Oceanography

3.5.1 Water Levels

Astronomical tides

The tides in the Joseph Bonaparte Gulf propagate in from the Timor Sea and circulate around an Amphidromic Point located offshore from Cape Londonderry in the northwest. Tidal ranges increase shorewards with maximum tidal ranges exceeding 8m along the shoreline between Wyndham and Darwin.

The closest tidal station to the Blacktip shore crossing is Port Keats. This is a secondary port located between the two standard ports of Darwin and Cape Domett. Figure 3.4 shows a typical tidal record from Darwin. The tides are semidiurnal (two highs and lows each day) with a slight diurnal inequality (difference in heights between successive highs and low). There is a well defined spring-neap lunar cycle, with spring tides occurring two days after the new and full moon. Table 3.1 provides the standard levels for Port Keats. Highest Astronomical Tide (HAT) exceeds 8m and the mean ranges for spring and neap tides are 5.6m and 1.9m, respectively. Tidal ranges will reduce offshore towards the Blacktip facility.

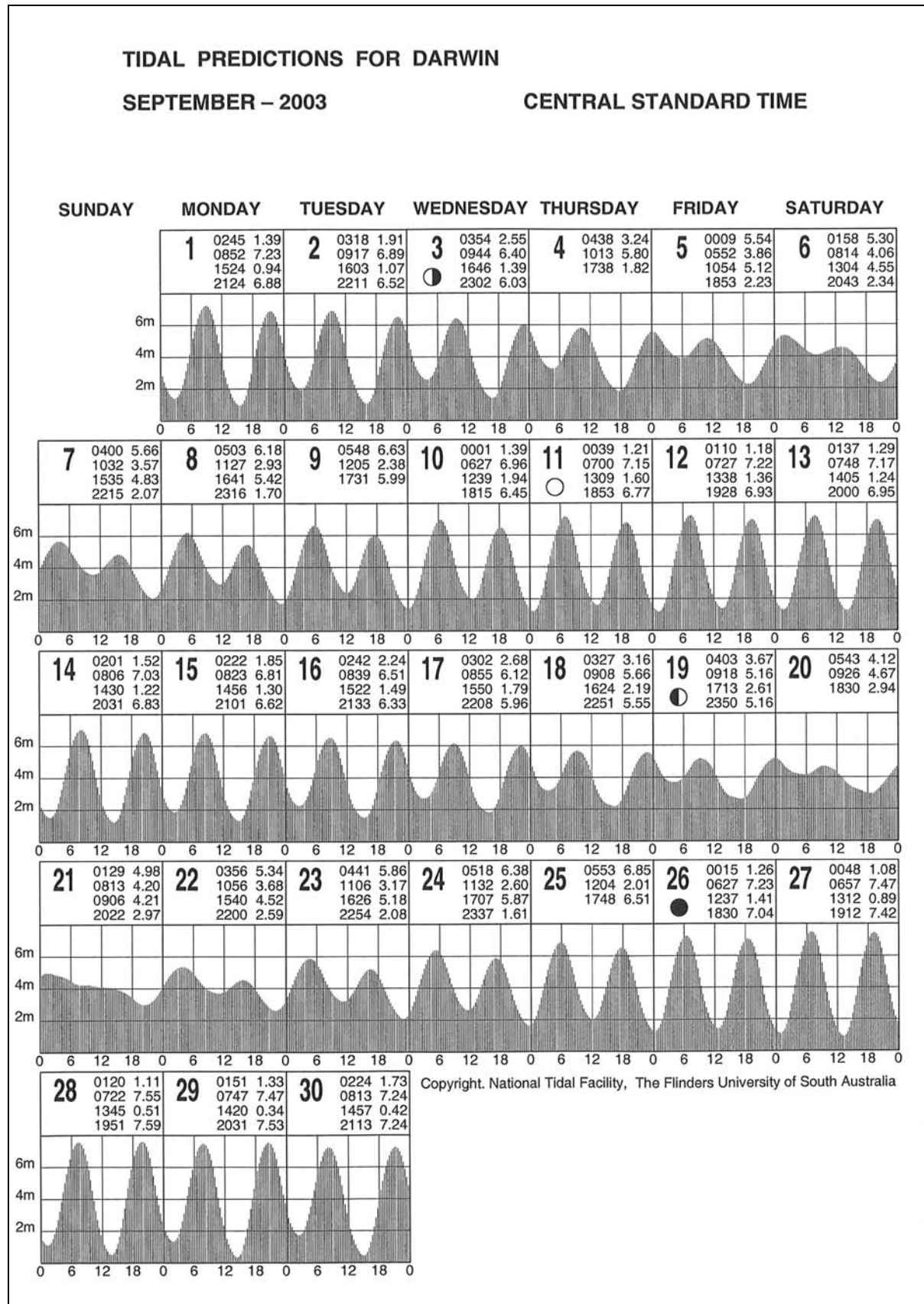
Table 3.1 Standard tide levels for Port Keats (Australian Hydrographic Services, 2003)

Port Keats	Level (m)
Highest Astronomic Tide (HAT)	8.2
Mean High Water Springs (MHWS)	7.2
Mean High Water Neaps (MHWN)	5.3
Mean Sea Level (MSL)	4.4
Mean Low Water Neaps (MLWN)	3.4
Mean Low Water Springs (MLWS)	1.6

Meteorological tides

Superimposed on the astronomical tide are 'meteorological' tides resulting from changes in atmospheric pressure and strong onshore or offshore winds. Storm surges during cyclones, in particular, can appreciably raise sea levels above the predicted astronomical tidal height and inundate low-lying areas.

Figure 3.4 Darwin tide curve for September 2003



3.5.2 Circulation

Tidal currents

Circulation in the Joseph Bonaparte Gulf is dominated by the large tidal currents. There are no site specific current measurements in the region of the Blacktip development, however, the hydrodynamic model developed for this study predicts current speeds at the offshore facility of up to 0.9ms^{-1} on spring tides and up to 0.2ms^{-1} on neaps. The currents rotate in a clockwise direction with the major flood and ebb directions towards the southeast and northwest, respectively. Further towards the shoreline, current speeds increase with tidal range and become directed more longshore. These large currents are responsible for the generation of dune forms on the seabed as noted in Admiralty Charts for the region. Very nearshore currents are influenced by the coastal topography with an anticlockwise gyre forming in the landfall Bay on the flood tide and a clockwise gyre on the ebb (see Figure 4.6).

Non-tidal currents

Non-tidal current drift might be associated with:

- local winds;
- river inflow along the coastal boundary;
- large scale ocean circulation in the Timor Sea;
- continental shelf waves; and
- meteorological effects.

Local Winds

The typical “rule of thumb” for surface current flow is 2% to 4% of the wind speed. Surface currents are expected to reflect seasonal wind regimes with flows towards the southeast during summer and westerly flows during winter. Local wind-driven surface currents may attain maximum speeds of 0.7ms^{-1} during extreme monsoonal or Trade Wind surges. More typically speeds would be in the range of 0.2ms^{-1} to 0.4ms^{-1} .

River inflow

Four major rivers flow into the Joseph Bonaparte Gulf:

- Ord River;
- Victoria River;
- Fitzmaurice River; and
- Daly River.

The influence of these rivers on circulation within the Gulf will be greatest during periods of high flow that may occur during the wet season and minimal during the dry.

Large Scale Ocean Circulation

Large scale ocean circulations are forced by synoptic scale winds. The SE Trade Winds drive a mean westerly of up to 0.2ms^{-1} in the Timor Sea. In the wet season, currents reverse to flow towards the east. The influence of these large scale circulations in the Joseph Bonaparte Gulf is unknown.

3.5.3 Waves

Wave data were derived from a two degree global database constructed from a combination of remotely sensed satellite and modelled data (Young, 1999). The monthly mean significant wave heights (H_s), spectral periods (T_m) and directions for the nearest grid point (approximately 100km to the north northeast) are plotted in Figure 3.5. Note that wave heights are likely to be overestimated as the database location will be more exposed to westerly swell than Blacktip and have greater fetches from the south and southeast.

During the winter season, the ambient wave climate at Blacktip will be composed of waves generated from the prevailing south and southeasterly trade winds. Wave generation will be fetch limited and mean monthly significant wave heights are predicted to be fairly constant, ranging between 0.8m and 1.0m with mean period of between eight and nine seconds. Wave height and period will decrease shoreward along the pipeline route. Longer period swell waves from the Indian Ocean are unlikely to diffract around into the Joseph Bonaparte Gulf.

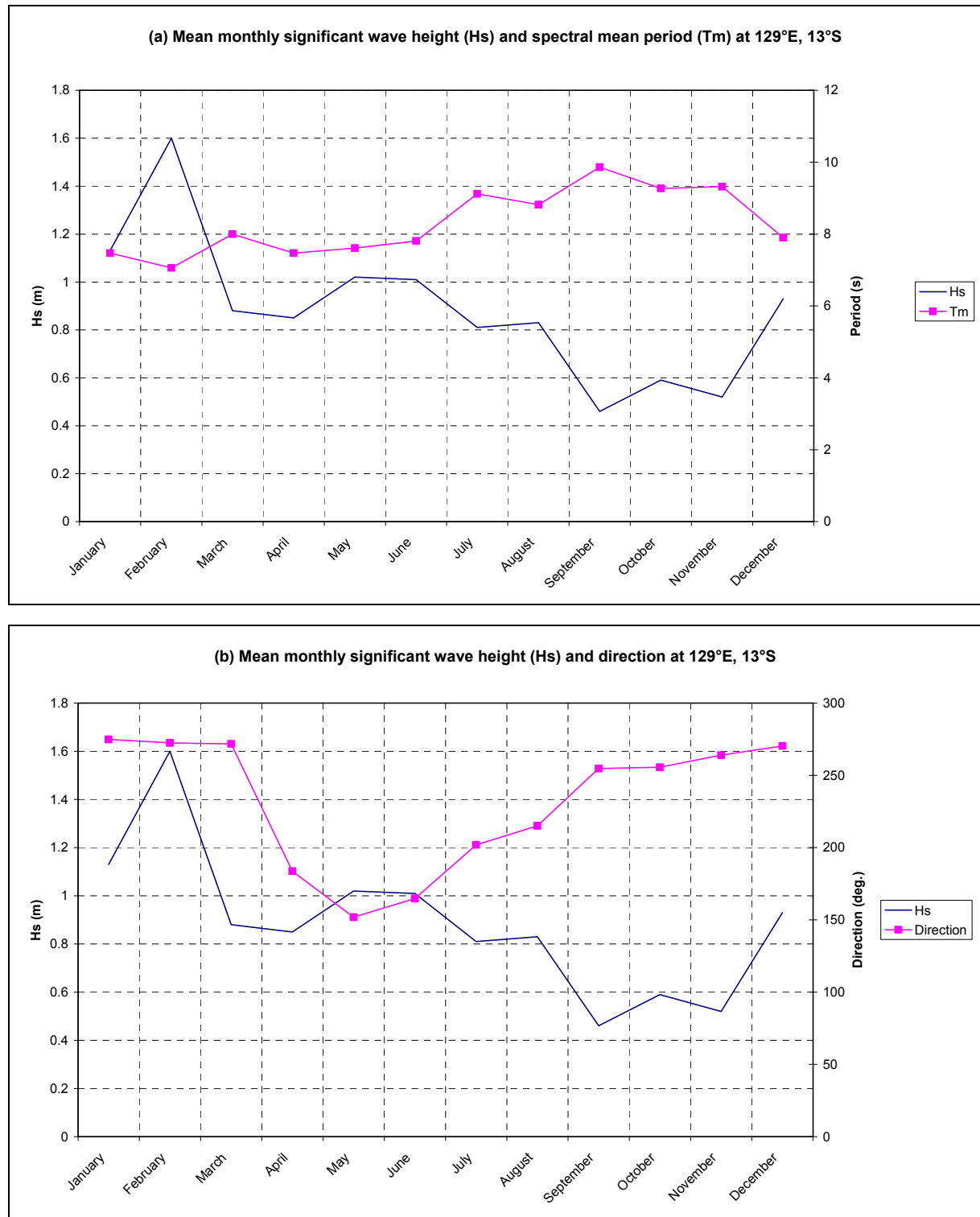
During the summer season, Blacktip is exposed to both sea and swell generated from the prevailing northwesterly monsoon winds blowing across the Timor Sea. As such the predominant swell direction at Blacktip is from the northwest with mean monthly periods of between seven and 10 seconds. Monthly mean significant wave heights range from a minimum of 0.45m in September to a maximum of 1.6m during February. As prevailing winds are onshore, wave heights in the summer will increase shoreward along the pipeline route.

Extreme waves are generated by cyclones during the summer season. The 100 year return period wave will be of the order 5m.

3.5.4 Water temperatures

Mean monthly temperatures in the vicinity of the Blacktip field vary between about 25.8°C in August and 30.5°C in December (AODC, 2004). Due to the large tidal range and high currents, the water column is expected to be well mixed all year around with respect to temperature. During heavy rainfall, there may be some salinity stratification in the south of the Gulf.

Figure 3.5 Monthly mean wave parameters for grid location 129°E, 13°S (approximately 100km NNE of Blacktip)



3.6 Biological Environment

3.6.1 Habitats

Coastal habitats in the Gulf include beaches, rocky coastlines and mangroves. The predominant coastline features in the vicinity of the proposed pipeline shore crossing are sand/mud beaches with occasional rocky headlands, small pockets of mangroves and occasional tidal creeks (Figure 1.2). The coasts to the north and south are predominantly sandy beaches with no mangroves. Approximately five kilometres to the south of the shore crossing lies the entrance to a small tidal creek lined with mangroves. Wadeye, approximately 17km to the north of the shore crossing, is the only large tidal inlet system nearby. The nearest significant mangrove conservation areas lie inside the Cambridge Gulf approximately 100km south-west of the project site. Joseph Bonaparte Gulf is not considered to be a significant mangrove area with only 20 known species and densities that are up to 20 times lower than at Gove or Darwin (LDM, 1994).

3.6.2 Flora and Fauna

General

Large terrigenous inputs and re-suspension by large tides are expected to limit the development of corals, seagrasses and other epibenthic organisms. A survey carried out by the WA Museum did not record any intertidal seagrasses in the Joseph Bonaparte Gulf, and no evidence of drift material was found at any of the sites surveyed (Walker *et al.*, 1996), though LDM (1994) reported that discussions with local Aboriginal people indicated that seagrass and dugongs may occur along the coastline between Cape Hay to the north and Point Pearce to the south. The nearest large reefs or shoals that might support corals, Howland Shoals and the Emu Reefs, are located approximately 20 to 30km north of the proposed landfall.

Mammals

Whales and dugongs are not expected to be common inhabitants of the Joseph Bonaparte Gulf. The dugong (*Dugong dugon*) is a migratory species listed as vulnerable under the International Union for the Conservation of Nature and Natural Resources, Red Data Book of Threatened Species (IUCN). Dugongs are patchily distributed throughout tropical and subtropical waters of the Indian and Pacific Oceans, with major concentrations of dugongs coinciding with sizeable seagrass beds, on which they feed. The lack of seagrass in Joseph Bonaparte Gulf is expected to limit the distribution of dugongs, though anecdotal evidence reported by local Aboriginals suggests that dugongs can occur between Cape Hay and Point Pearce (LDM 1994).

The two whale species recorded in the Northern Territory are unlikely to be found in the shallow waters of the project area as they are usually restricted to deep waters (sperm whale) or are very rare (blue whale). The northern migration of the humpback whale

terminates in Campden Sound over 400km to the west of the proposed Blacktip Development and they are not expected to occur in the Joseph Bonaparte Gulf. A number of dolphins have wide distributions and are expected to occur within the Joseph Bonaparte Gulf including the Irrawaddy dolphin inhabits tropical, the spotted bottlenose dolphin, Risso's dolphin, Indo-Pacific humpback dolphin and pantropical spotted dolphin (Convention of Migratory Species 2004).

Reptiles

Reptiles in the Joseph Bonaparte Gulf include:

- turtles;
- saltwater crocodiles,
- the mangrove snake; and
- the mangrove monitor.

Turtles

Six species of marine turtle known to occur in Northern Australian waters, however data collected on turtle abundance and distribution in the Joseph Bonaparte Gulf is scarce and numbers are unknown. Examination of the turtle habitat database developed and supplied by Ray Chatto of the Parks and Wildlife Commission of the Northern Territory (PWCNT) indicates that suitable coastal saline flats habitat for sea turtles exist in the southeast of the Joseph Bonaparte Gulf at Turtle point at the mouth of the Victoria River and the Whale Flat area near the mouth of the Fitzmaurice River and to the north of the project area around Anson Bay.

Significant Flatback turtle breeding and nesting sites are documented on the north side of Cape Domett in the inner, western Joseph Bonaparte Gulf (Woodside, 2003) and anecdotal evidence suggests that they may historically have nest on sandy beaches to the north of the pipeline landfall. However, discussions with Wadeye Elders indicate that turtles have not nested in any number following a beach recession event about 15 years ago.

Saltwater Crocodiles

The Northern Territory's saltwater crocodile population is the largest in Australia. The species is protected under Section 43 of the Territory Parks and Wildlife Conservation Act 2000, although it is not listed as threatened under the Commonwealth Environment Protection and Biodiversity Conservation (EPBC) 1999 Act. Generally high densities of crocodiles occur in tidal portions of mangrove-lined rivers, particularly those associated with extensive freshwater wetlands or floodplains. However, Studies on crocodile populations in the Victoria and Fitzmaurice Rivers suggest that the project area is not significant for crocodile populations. Nesting sites are limited and recruitment rates are generally low.

Crocodiles are however reported to be in the upper reaches of most rivers and creeks around the Wadeye area. The Ord River system has been gazetted as a nature reserve to protect crocodile breeding habitats in the area (LDM, 1994).

Sea Snakes

Sea snakes are very common in subtropical and tropical Australian waters and occupy a wide range of habitats and water depths, extending offshore from the coast to the reefs and banks of the Sahul Shelf. Although there are no records of their specific occurrence in the Joseph Bonaparte Gulf, sea snakes are expected to be very common, with as many as fifteen species known to occur in the Northern Territory (Storr *et al.*, 1986).

Fish

A number of fisheries can operate within waters of the Joseph Bonaparte Gulf, however, it appears that fishing effort is limited in all fisheries except for the Northern Prawn Fishery. Prawns are commercially caught in areas of the Joseph Bonaparte Gulf, mainly in the west of the gulf and, to the north, in Fog Bay. The juvenile prawns that migrate offshore to the fishery come from mangrove nursery habitats from the Victoria River in the east of the Gulf, to the Ord River and Cambridge Gulf in the west, forming a very extensive migration throughout the lower region of the Joseph Bonaparte Gulf. Although there is no data on the exact timing of the migration, it is likely to be from February to April and October to December (Neil Loneragan, Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Marine Research, pers. comm., February 2004).

4 DISPERSION MODELLING

4.1 General

Modelling of effluent dispersion from a pipeline is generally divided into two distinct zones:

- near field; and
- far field.

In the near field, transport is governed by the momentum of the discharge and the buoyancy resulting from the density difference between the effluent and the receiving waters. The dilution achieved as the wastewater rises to the surface is known as the initial dilution. Thereafter the plume is transported passively by advection and diffusion in the far field. The following sections describe the modelling work undertaken to simulate dispersion in these two zones for the Blacktip discharge.

4.2 Near field Dispersion

4.2.1 Objective

The objectives of the near field modelling are:

- to compute the initial dilution and to demonstrate the effectiveness of the diffuser design; and
- to provide near field dimensions for input to the far field model.

4.2.2 Model Overview

Initial dilution was simulated using Cornell Buoyant Jet Integral Model (CORJET). This model is part of the Cornell Mixing Zone Expert System (CORMIX), a USEPA recommended analysis tool for industrial, municipal, thermal, and other point source discharges to receiving waters. The three-dimensional hydrodynamic equations governing the conservation of mass and momentum along the curved trajectory of a buoyant jet are solved yielding:

- the trajectory position; and
- centreline concentrations of pollutant mass, density deficit, temperature and salinity.

The computation ceases when the plume impinges on a boundary, after which time the physics change and the results are transferred to the far field model. Cross-sectional values are fixed as a Gaussian distribution. Theoretical details and the validation of CORJET are presented in Jirka *et al.* (1996).

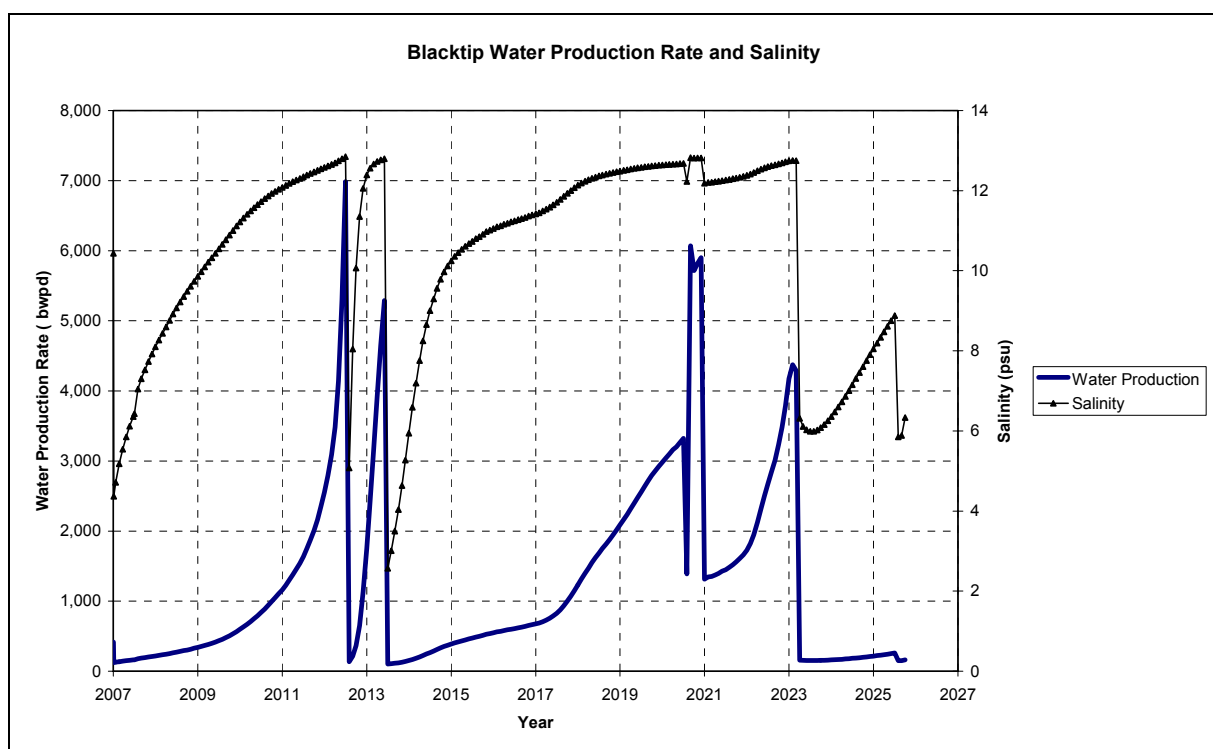
4.2.3 Model Setup

Discharge Flows

Figure 4.1 shows the projected PFW discharge rates over the life of the field. Flows increase from a minimum of 200bbl per day to a maximum of 7,000bbl per day. For the modelling three design flows were used:

- minimum – 200bbl per day;
- base – 2,000bbl per day; and
- maximum future – 7,000bbl per day.

Figure 4.1 Projected PFW flow rate and salinity for the life of the field (from WEL)



Preliminary Diffuser Design

Submarine outfalls consist of the pipe carrying the effluent to the discharge area and the end section or diffuser. For the Blacktip outfall, a six inch pipe has been proposed, however, the design of the diffuser is still yet to be decided. Best practice for diffuser design dictates that:

- the total cross sectional area of the ports must not exceed 65% of cross-sectional area of the pipe, to ensure that flow is distributed evenly through all the ports;
- port diameters should be between 20mm to 150mm to prevent blockage;
- discharge velocities range from 3ms^{-1} to 8ms^{-1} (higher velocities may require excessive pumping costs);
- the densimetric Froude number should exceed one to prevent saltwater intrusion; and

- port spacing should be in the range one-third to one-sixth of the water depth, so that the plumes from the individual ports just merge on reaching the surface.

Table 4.1 presents a preliminary diffuser configuration that complies with these design criteria

Table 4.1 Preliminary diffuser configuration

Parameter	Value
Diffuser diameter	60mm
No of diffusers	4
Length of diffuser	15m

The parameters used to set-up the model runs are summarised in Table 4.2. Diffuser alignment was set perpendicular to the ambient current direction. Ports were:

- single and unidirectional;
- discharge horizontally and point downstream (ie, co-flowing); and
- located 1m above the seabed.

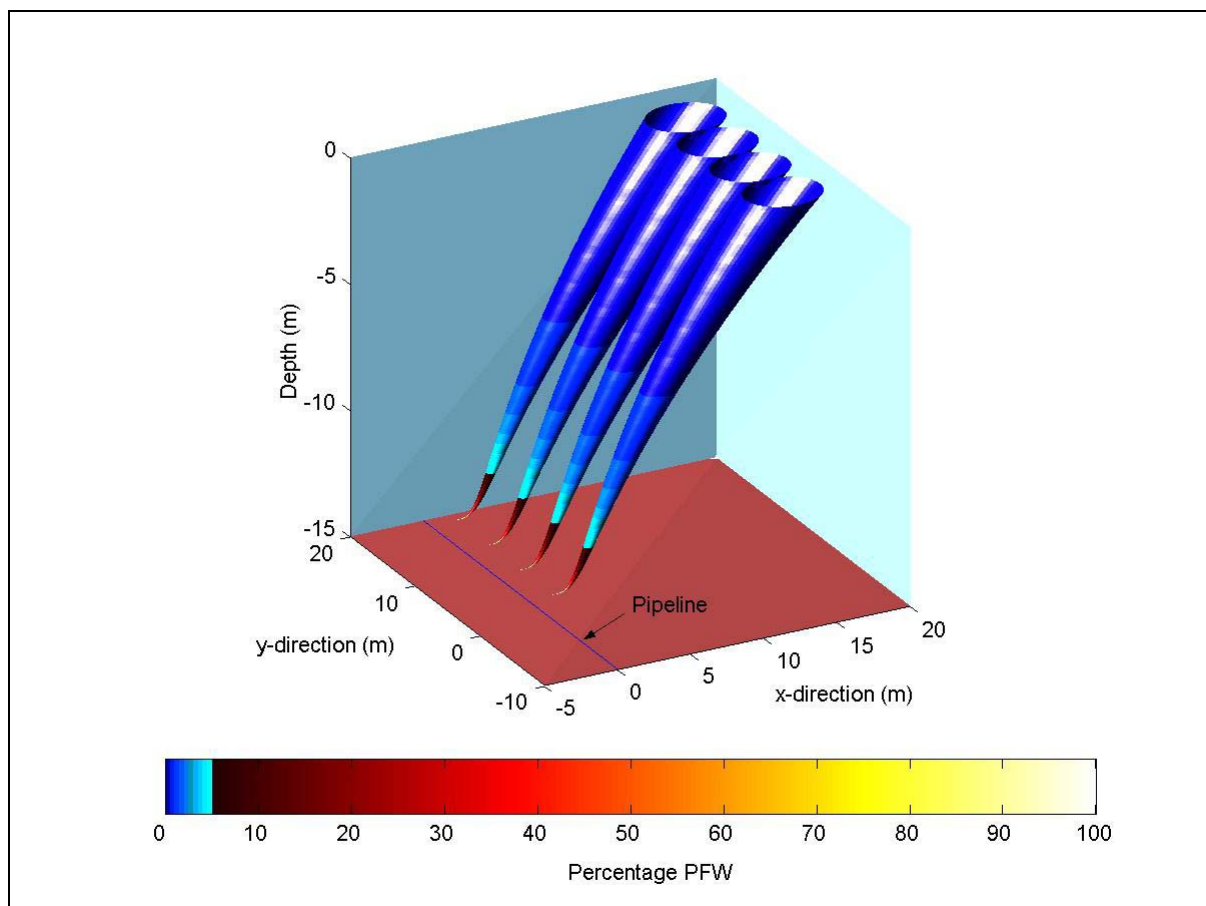
Table 4.2 Model set-up for initial dilution CORJET modelling

Parameter	Value
Ambient conditions	
Average depth	15m
Depth at discharge	15m below LAT
Ambient velocity (CORJET)	0.05ms ⁻¹
Stratified condition	Unstratified
Ambient temperature	28°C
Ambient salinity	34psu
Discharge parameters	
Discharge orientation	Horizontal (co-flowing)
Port diameter	60mm
Discharge flowrate	7000bbl per day
Temperature	28°C
Salinity	10psu
Concentration	100%
Coefficient of decay	0s ⁻¹

4.2.4 Model Results

Figure 4.2 shows the predicted horizontal and vertical trajectories of the jet plume in the near field region. The PFW emits from the discharge pipe 14m below the sea surface and rises under the influence of its own buoyancy towards the surface. Due to the relatively low flows, initial dilution is high. Within the first 5m, 100 dilutions are achieved and by the time the plume hits the surface, it has received 700 dilutions. On reaching the surface it spreads horizontally whilst mixing vertically downwards. At this point, dispersion becomes controlled by far field processes (ambient current and passive diffusion).

Figure 4.2 Initial dilution for preliminary diffuser design (worst-case future discharge rate)



4.3 Far Field Dispersion Modelling

4.3.1 Objective

The objectives of the far field modelling were:

- to derive an effective disposal strategy by predicting the fate of PFW discharged from different locations; and
- to predict the environmental risk associated with the discharge.

The far field model is made up of two modules:

- a hydrodynamic module that provides the necessary velocity fields to advect the PFW; and
- a dispersion model that simulates the fate and behaviour of the PFW.

These modules are described in more detail in the following subsections.

4.3.2 Hydrodynamic Model

Overview

The hydrodynamics applied in the present study were computed using the ADvanced CIRCulation model (ADCIRC). This model is a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions (Westerink *et al.*, 1994). The algorithms that comprise ADCIRC utilise the finite element (FE) method in space and the model can be applied to computational domains encompassing the Deep Ocean, continental shelves, coastal seas and small scale estuarine systems.

Model Details

Figure 4.3 shows the grid for the Joseph Bonaparte Gulf. Elevations and currents were computed at 11,621 points (nodes) in the model domain. Using the significant flexibility provided by the FE method, grid resolution was increased considerably towards the coast and in particular towards the landfall for the Blacktip pipeline (Figure 4.4). The fine nearshore grid spacing was necessary to resolve the complex coastline geometry whilst coarse offshore resolution aids in computational efficiency.

Node resolution varies from approximately 50km offshore to 50m inshore. Model bathymetry is shown in Figure 4.5. This was interpolated from the Australian Geological Survey Office (AGSO) database. The model was forced from the open boundary by tidal elevations calculated from the M2, S2, N2, O1 and K1 tidal constituents. The amplitudes and phases for these were taken from the FES-95.2 global ocean model (Le Provost *et al.*, 1998).

The model was validated against tidal stations around the coastline. Examples of vector fields for a spring tide at mid ebb and flood are shown in Figure 4.6 (a) and (b), respectively.

4.3.3 PFW Dispersion Module

Model Overview

The PFW dispersion module is based on the classic random walk particle tracking method (Sherwin, 1992) and assumes that the mass of the discharge can be idealised as a large number of particles that move independently under the action of tide and wind. The particle tracking is integrally linked with the FE model and uses a highly accurate fourth order Runge-Kutta method to interpolate velocities between nodes (Blanton, 1995).

The motion of the particles is the sum of two effects:

- advection by the tidal currents, and
- dispersion due to turbulence and current shear effects.

Advection is calculated by stepping through the variations in the current field in time and space. Dispersion is included by subjecting each particle to a random displacement at each time step. The dispersive displacement (random step) of each particle at each time step (dt) is scaled by the square root of the increment in the variance of the effluent plume which is given by the product:

$$(\text{increment in variance}) = 2Kdt$$

where K is the horizontal (K_{xy}) or vertical (K_z) diffusion coefficient. The actual step length taken by each particle is also determined by a random number selected from a normal distribution with zero mean and unit variance which is scaled by the product ($2Kdt$). Steps in the x , y and z co-ordinate directions are made independently. Steps in the vertical plane allow for reflection of the particle from the seabed and surface. The current velocity applied to each particle is corrected according to its level in the water column using a Van Veen profile.

Model grid

The model was set up over a 16km x 16km rectilinear grid, with a resolution of 100m. The time step for particle tracking was set at 180 seconds.

Figure 4.3 Hydrodynamic model grid

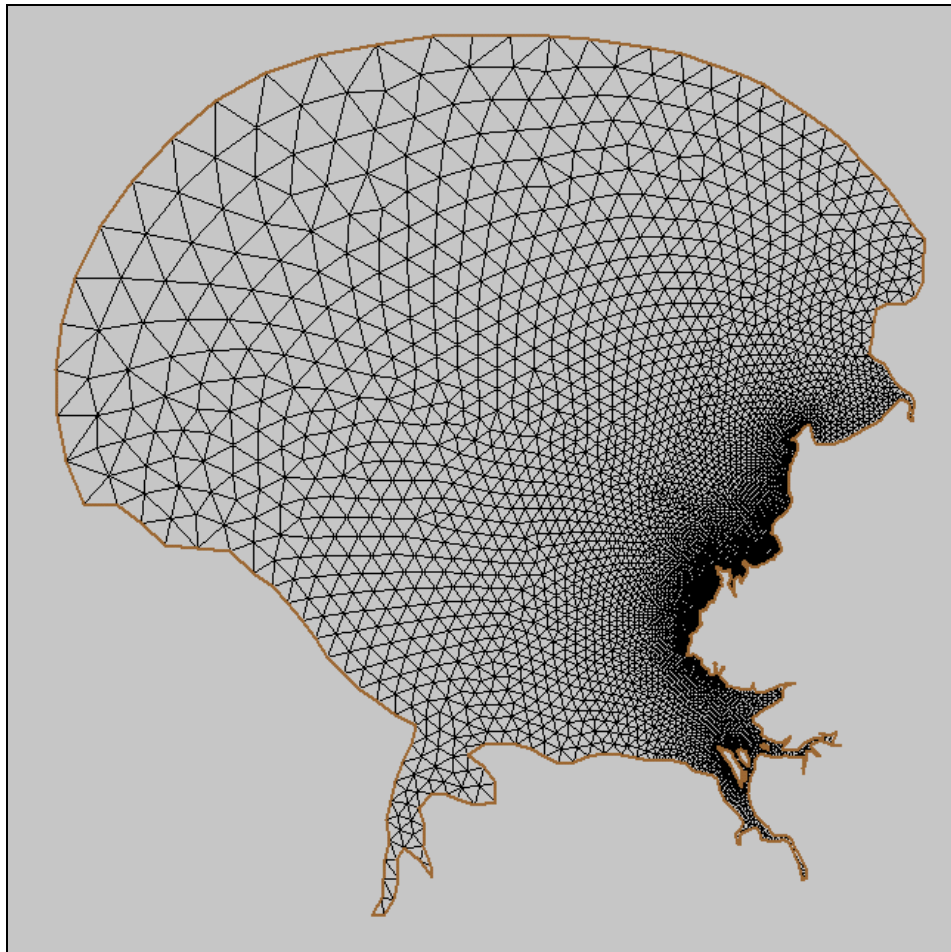


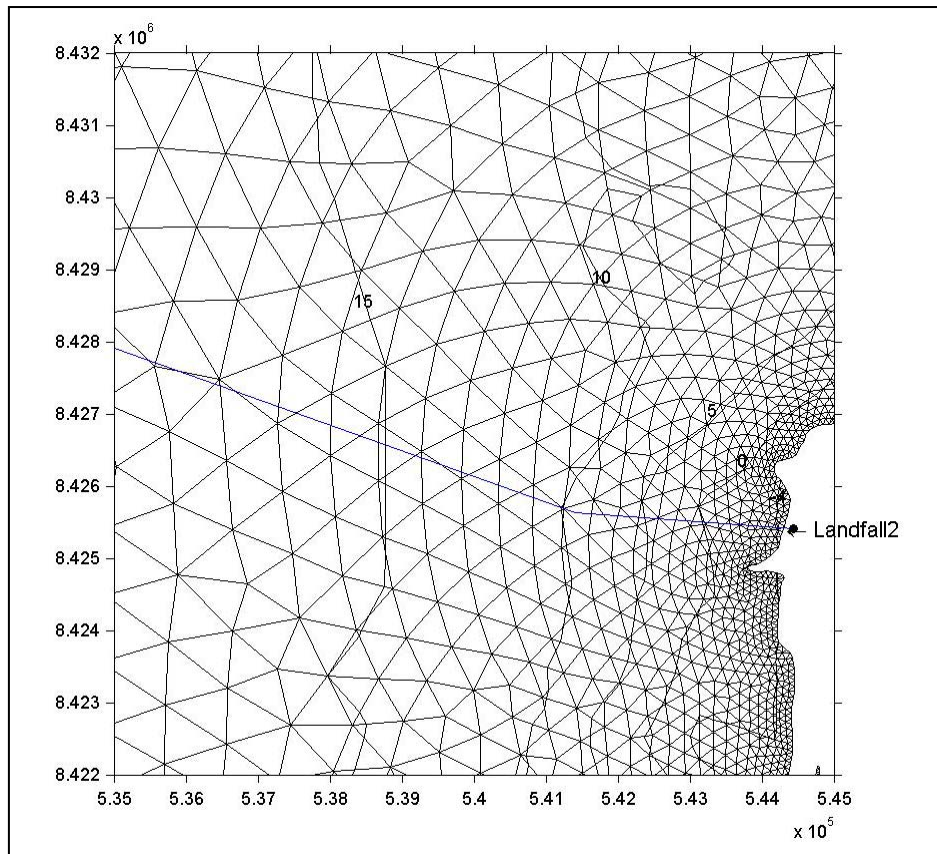
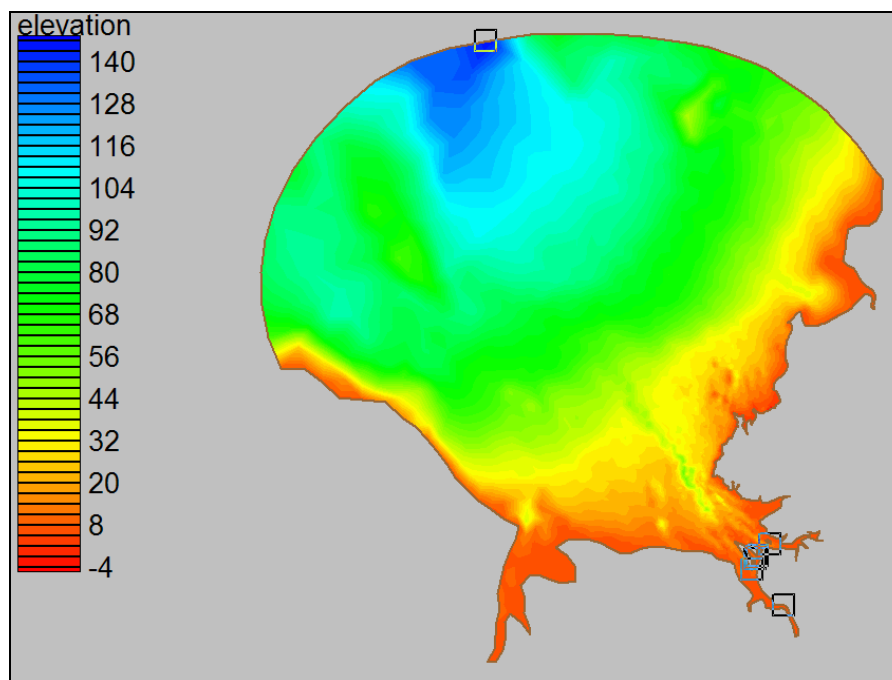
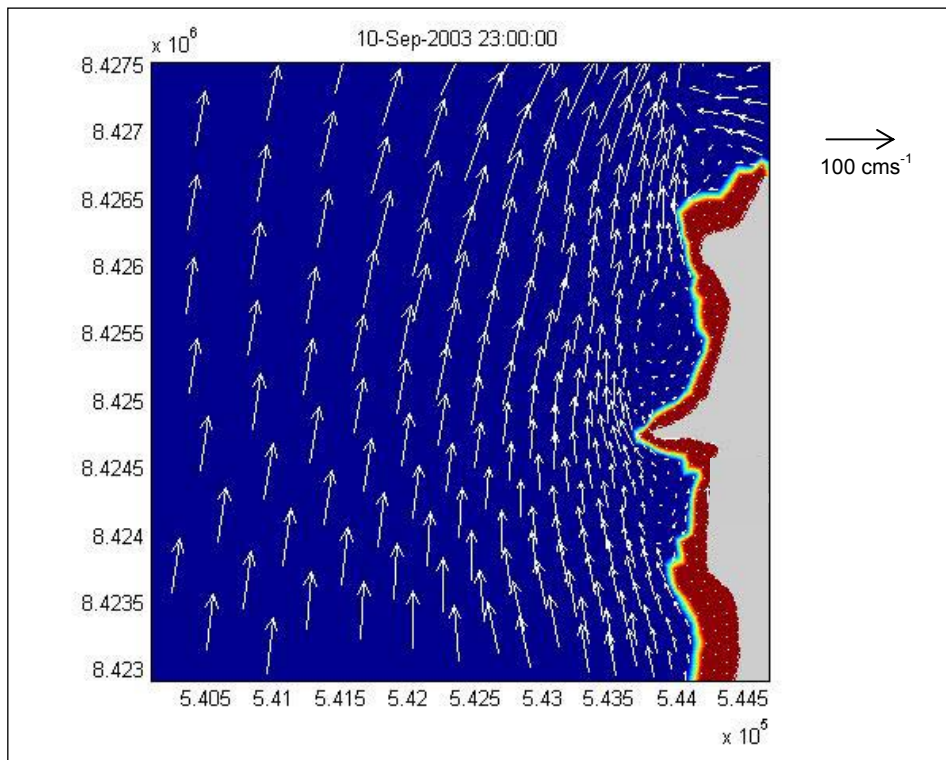
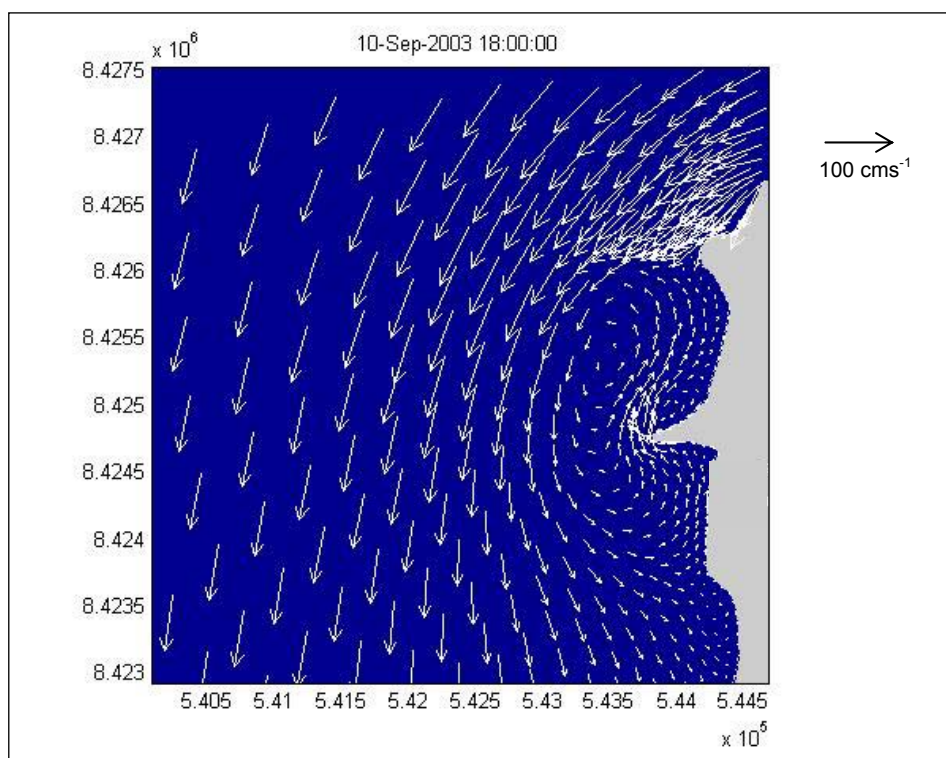
Figure 4.4 Details of model grid in the vicinity of the outfall**Figure 4.5 Model bathymetry in metres**

Figure 4.6 Predicted spring tide vector fields in the vicinity of the landfall for the Blacktip pipeline

(a) Ebb Tide



(b) Flood Tide



4.3.4 Model scenarios

Table 4.3 summarises the model scenarios undertaken. These used seven different discharge locations, (Figure 4.7), three discharge flows, spring and neap tides and onshore “worst-case” wet season wind conditions.

Worst-case periods were targeted as it is reasonable to assume that if the risk is acceptable under such conditions then it will be acceptable for all other times when conditions are more favourable for dilution and mixing. These simulations do not take into consideration biodegradation as this is unknown for the whole PFW.

Figure 4.7 Positions of discharge locations tested

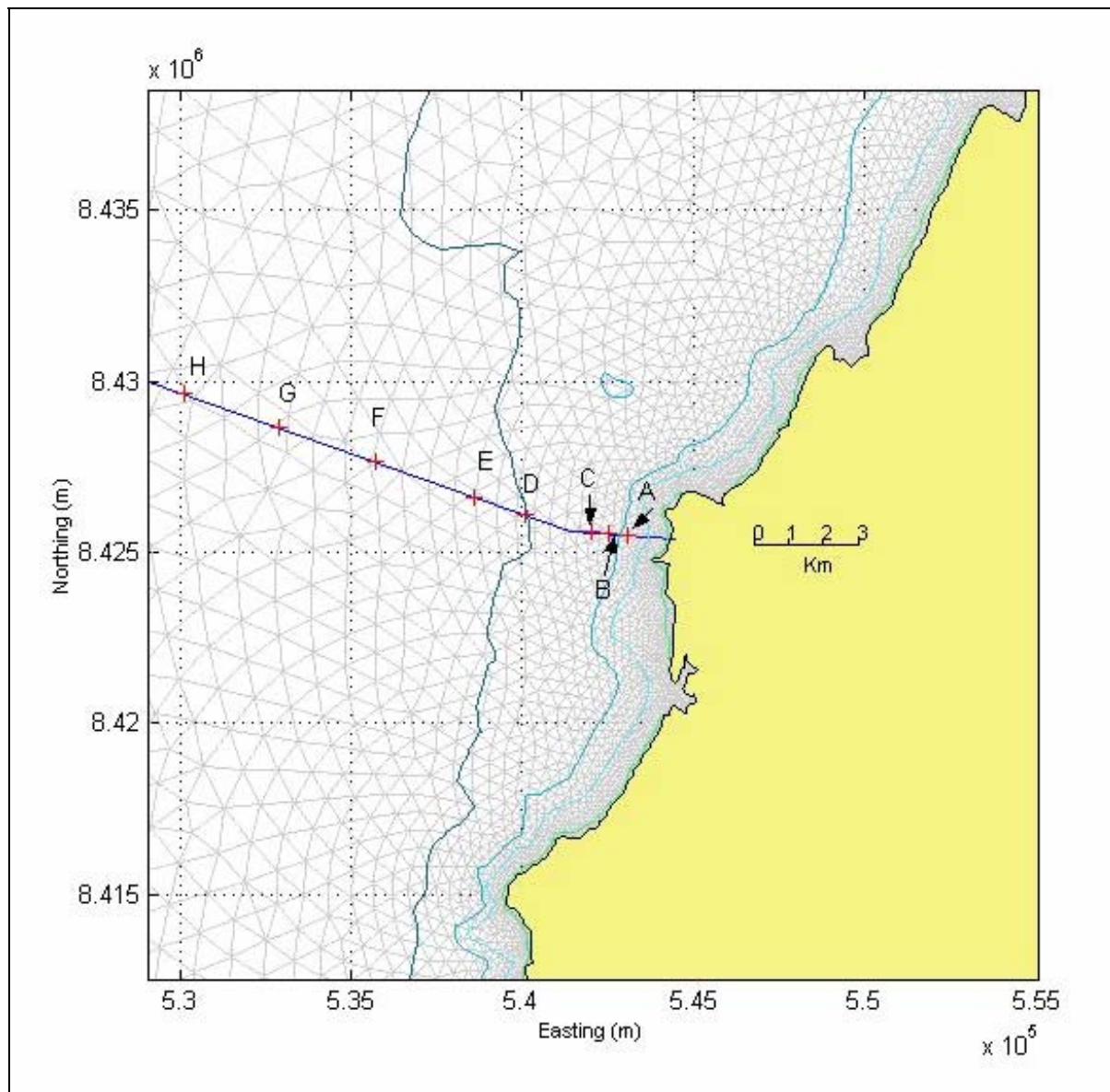


Table 4.3 Summary of model runs

Scenario No.	Discharge Location	Discharge flow (bbl/day) ¹	Tide	Wind
1	A	6,000	Neap	2ms ⁻¹ NW
2			Spring	
3	B		Neap	
4			Spring	
5	C		Neap	
6			Spring	
7		200	Neap	
8			Spring	
9		15,000	Neap	
10			Spring	
11	6,000	Neap	Typical wind profile for wet season	
12		Spring		
13	C	6,000bbl/hr		Neap
14	D	6,000		
15	E (6km)			
16	F (9km)			
17	G (12km)			
18	H (15km)			

¹ unless otherwise specified

4.3.5 Brief Description of Results

The following presents a brief description of the outcomes from the simulation. This is followed by a more in-depth discussion of the results from the preferred discharge location. Animations and plots for all simulations are presented digitally on CD.

Continuous discharge from locations A to C

Scenarios 1 to 12 examined the impact for continuous discharges from locations A to C (Figure 4.7). These were undertaken for the three design flow rates on spring and neap tides and under typical wind conditions for the “wet season”.

For location A, the plume was entrained into the nearshore gyre and coastline impact occurred during the first tidal cycle (Figure 4.8). Due to the high dilution and large tidal currents, levels and duration of impact were low with predicted nearshore peak concentrations of 0.01% PFW (10,000 dilutions) occurring for just one to two hours at any single location per tidal cycle.

Locations B and C were outside the influence of the nearshore gyre and the plume generally remained further offshore. The wind gradually forced the plume shoreward and after about two tidal cycles there was a low concentration coastline impact at about 0.005% PFW (Figure 4.9). Again due to strong tidal currents, this impact was very sporadic with concentration peaks occurring for about one hour per tidal cycle.

Batch discharge

Simulation 13 was undertaken to assess the impact of a batch discharge from Location C. For this 7000 bbls of PFW were released over one hour on the ebb tide (Figure 4.10). As the discharge rate had increased, plume concentrations were higher than the continuous discharge (typically 0.15% PFW (600 dilutions) at 100m from the discharge location). Coastline impact occurred after four tidal cycles at 0.02% PFW (5000 dilutions).

Locations D to H

Simulations 14 to 18 examined the effect of moving the discharge progressively offshore, from 4km (Location D) to 15km (Location H). These were undertaken for maximum future discharge flows, neap tides and typical winds for the “wet season”. All locations demonstrated high rates of dilution and minimal coastline impact.

There are a number of logistical advantages with discharging from the Swamp Mooring and this location is the preferred option at the present time. A full set of results and impact assessment are presented in the following section.

Figure 4.8 Predicted PFW concentration from discharge Location A

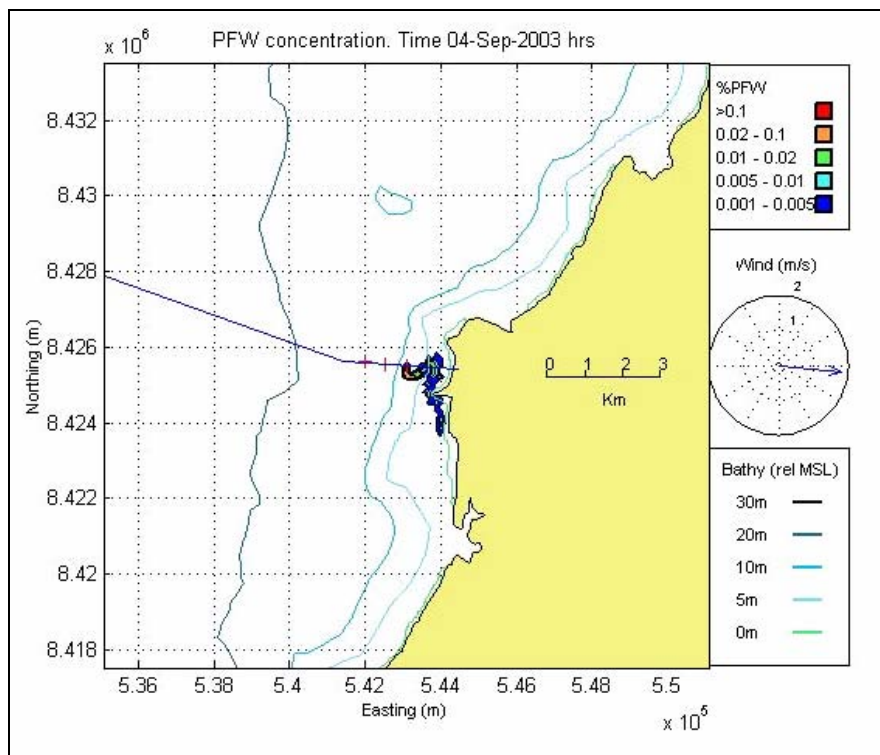
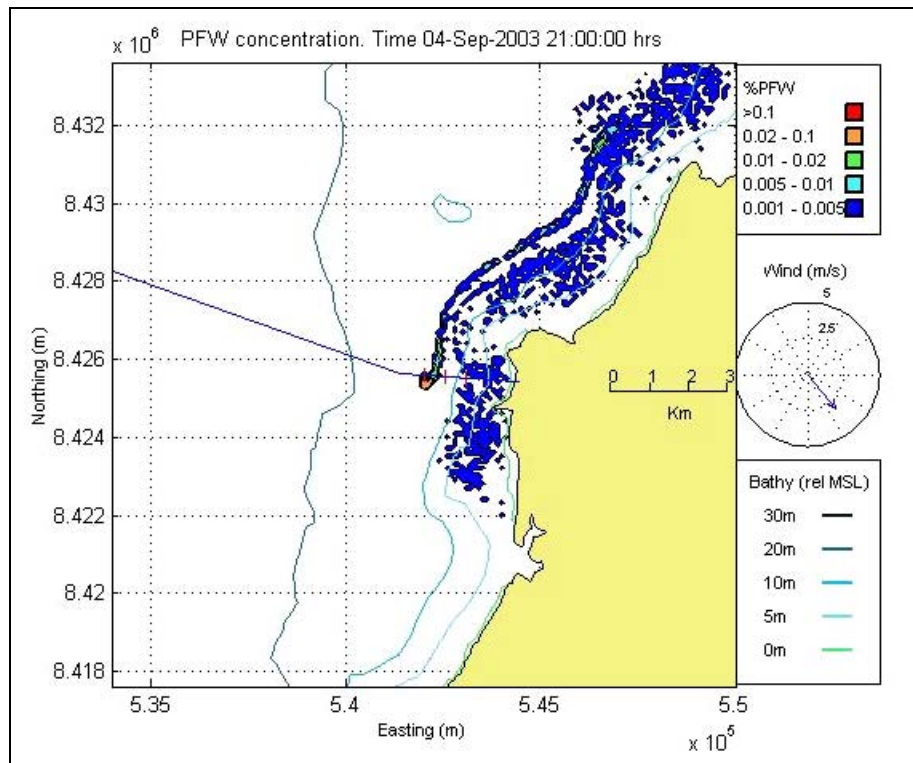
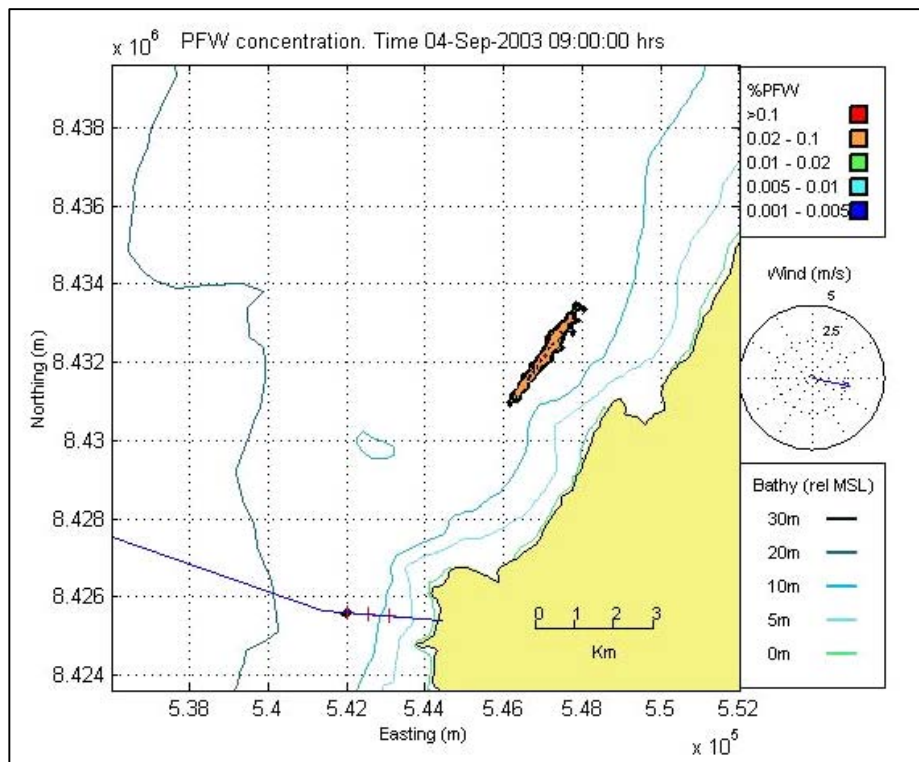


Figure 4.9 Predicted PFW concentration from discharge Location C**Figure 4.10 Predicted PFW concentration for batch discharge from discharge Location C**

4.3.6 Preferred Discharge Location

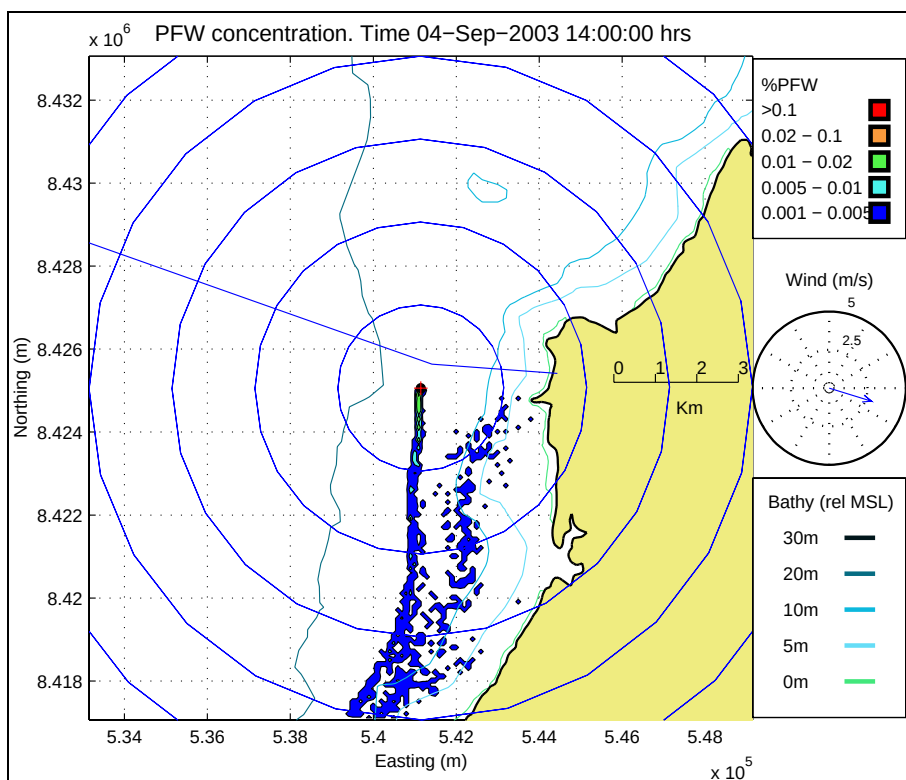
The optimal balance in terms of minimal environmental impact and acceptable cost to the project is to position the discharge in the vicinity of the Swamp Mooring. Figure 4.11 (a) – (i) present a series of plots showing the predicted concentration of PFW at three hour intervals for maximum future flows under “worst-case” ambient conditions (neap tide and typical “wet season” winds).

At high water (Figure 4.11(a)), PFW pools at slack water and concentrations increase to a maximum of 0.05% PFW. On the ebb tide, the plume is advected parallel to the bathymetry for a distance of approximately seven kilometres towards the north. With the increasing ambient flow, there is additional dilution and concentrations reduce to 0.01% PFW. At low water the discharge pools and once again concentrations build up to a maximum of 0.05%. The flood tide advects the plume about six kilometres towards the south.

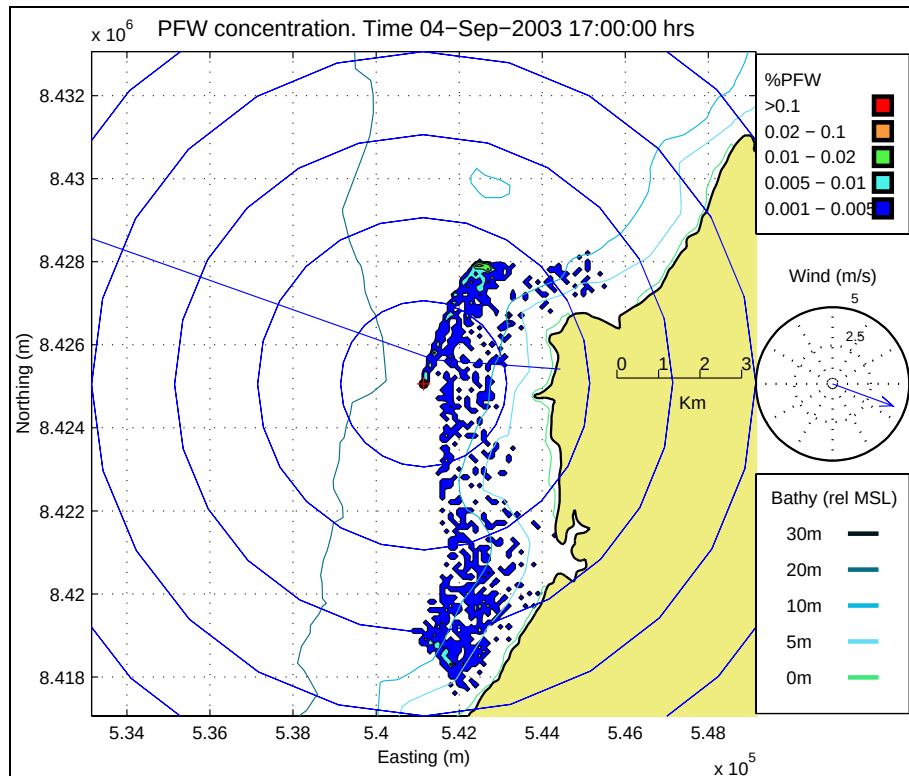
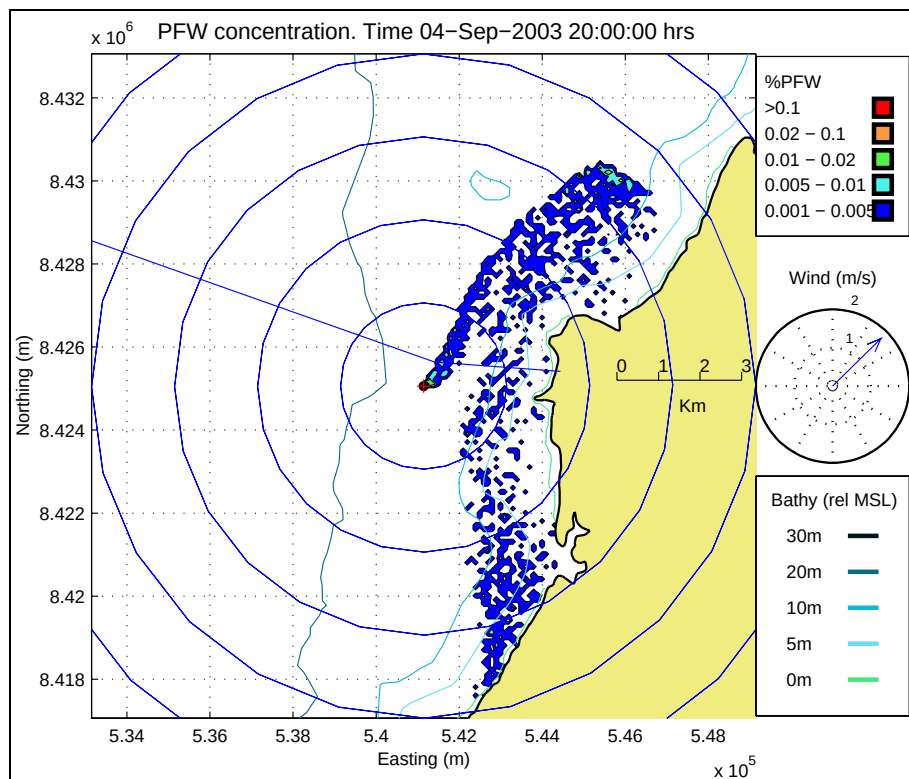
Approximately six hours after discharge, the plume starts to break up and fragment. This fragmented plume continues to move up and down the coastline with the tide. Superimposed on the ebb and flood of the tide is a persistent onshore surface drift driven by wind and waves. After three tidal cycles the plume impacts the coastline with a very low concentration of between 0.001% and 0.005% PFW (100,000 to 20,000 dilutions).

Figure 4.11. Predicted PFW concentration on a neap tide

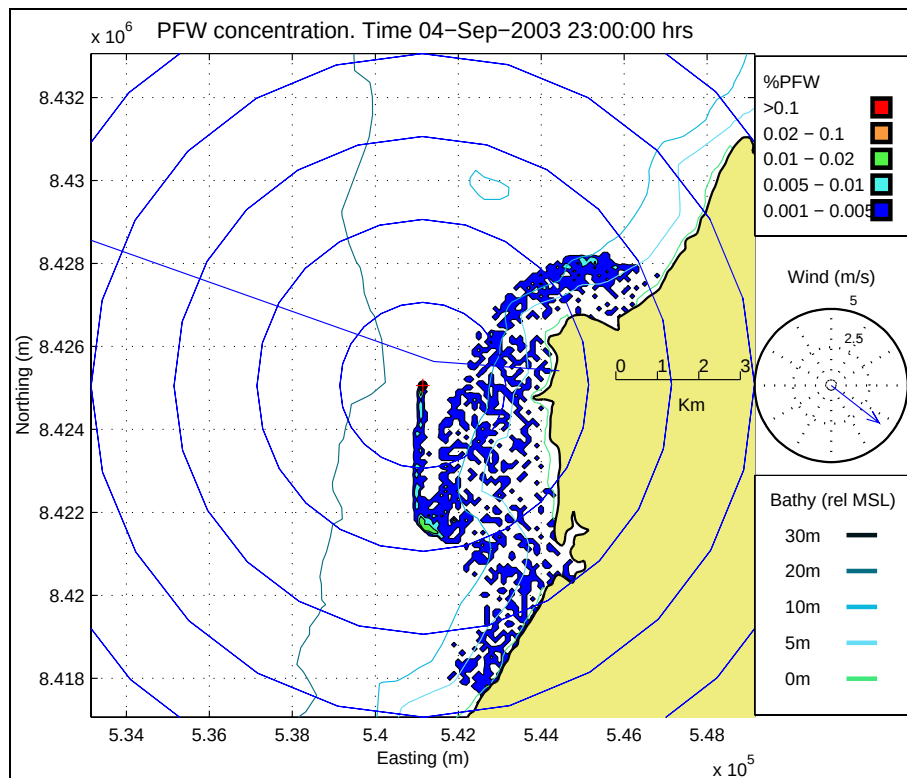
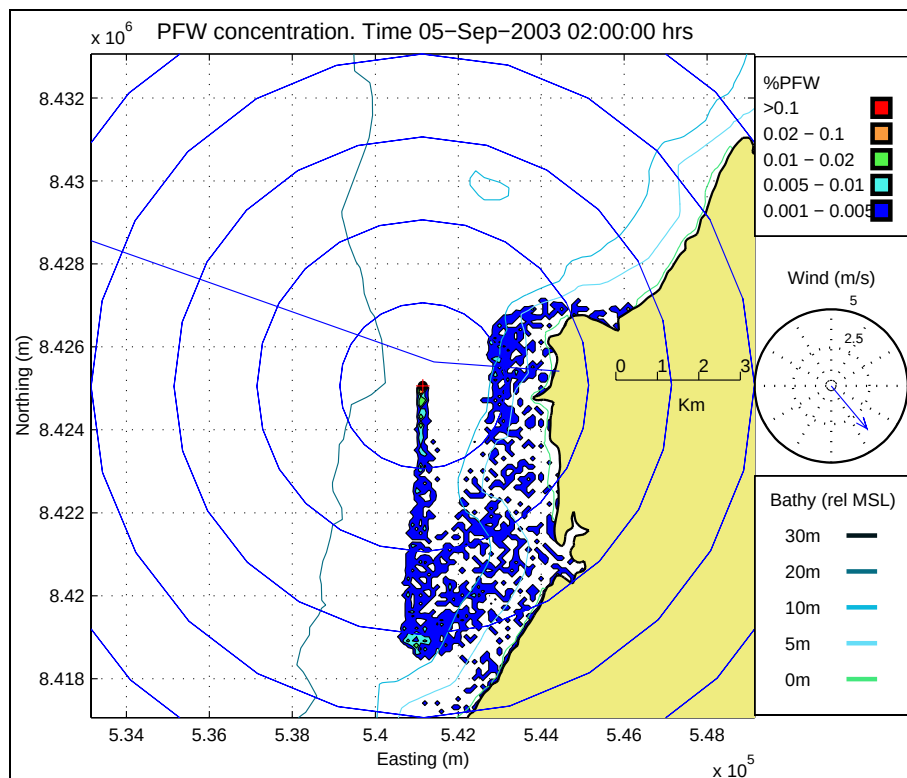
(a) High Water



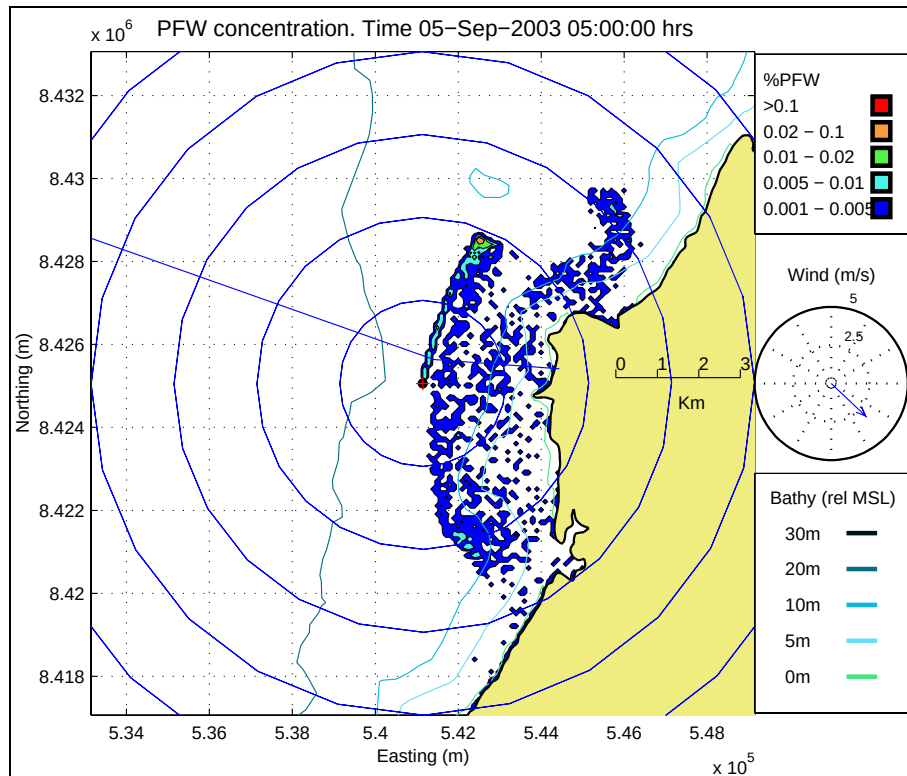
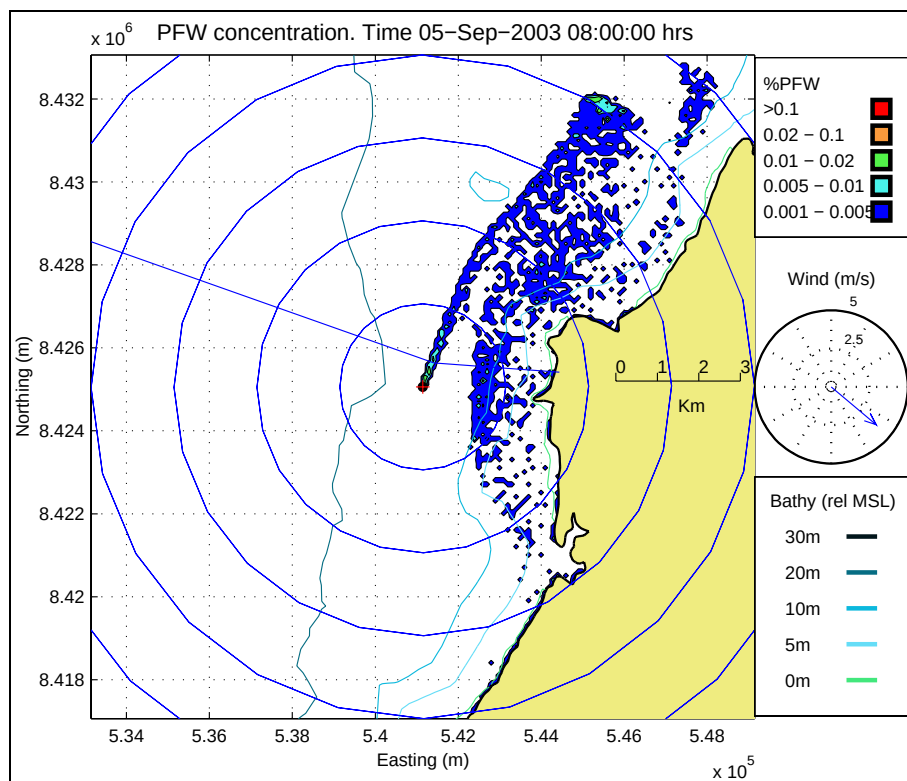
Note: Range rings are drawn at 2km intervals centred on the discharge point

(b) Mid ebb**(c) Low water**

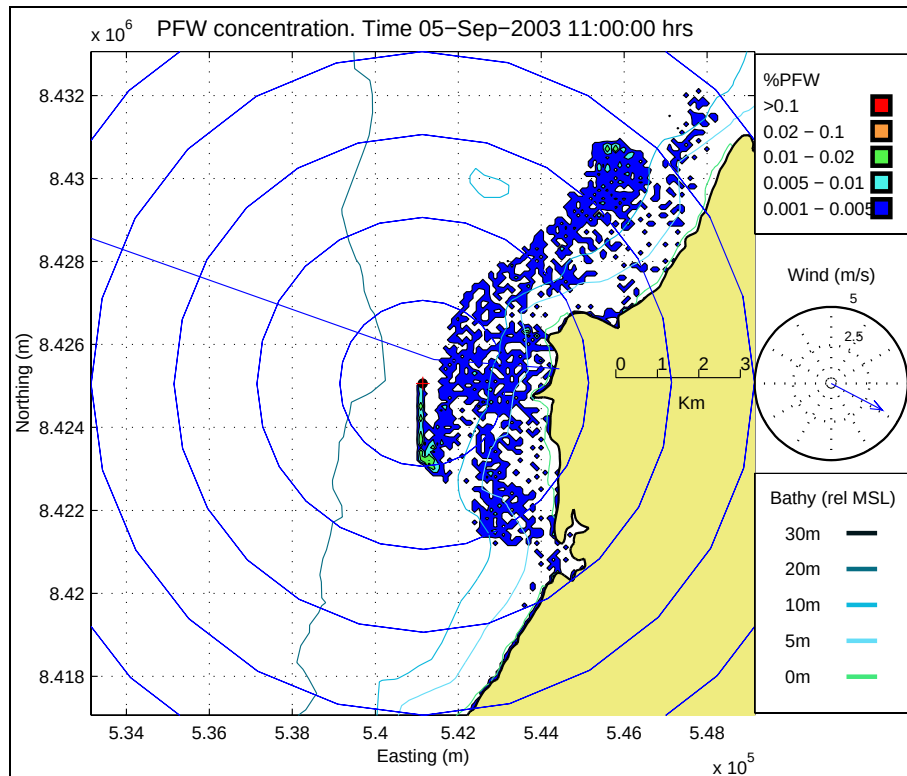
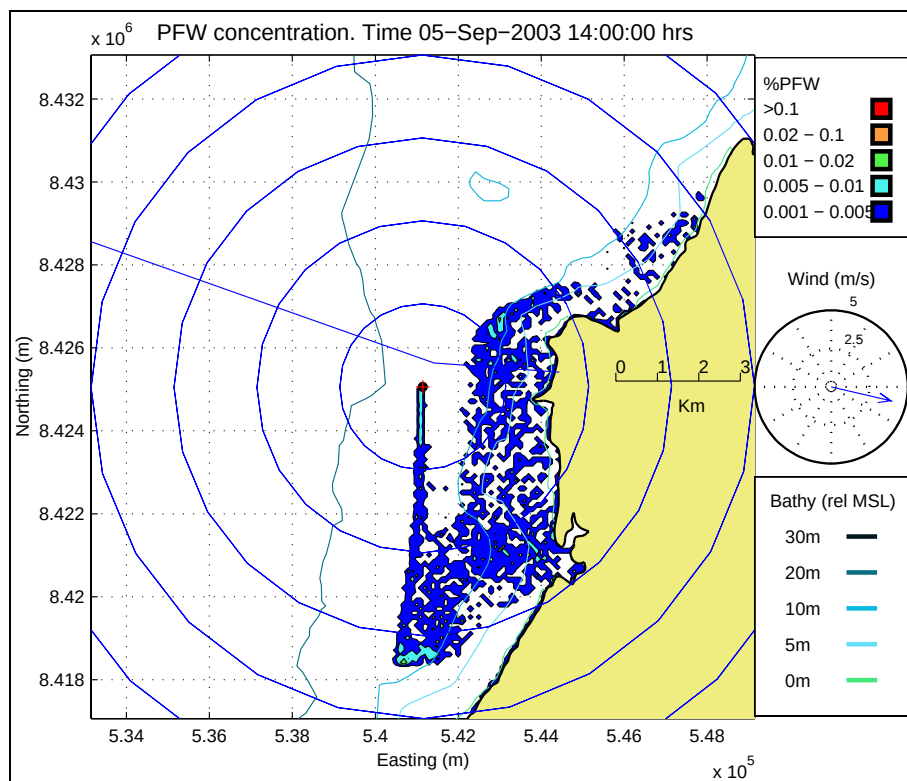
Note: Range rings are drawn at 2km intervals centred on the discharge point

(d) Mid flood**(e) High water**

Note: Range rings are drawn at 2km intervals centred on the discharge point

(f) Mid ebb**(g) Low water**

Note: Range rings are drawn at 2km intervals centred on the discharge point

(h) Mid flood.**(i) High water.**

Note: Range rings are drawn at 2km intervals centred on the discharge point

4.3.7 Risk Assessment

The traditional PEC/PNEC approach was used to assess the risk. As described in Section 2.5.3, this approach demonstrates the zone of potential affect by calculating and presenting contours of the PEC/PNEC ratio. Any value over one then indicates a potential zone of impact. In the absence of any ecotoxicology data for the PFW, the PNEC was set at 0.1% PFW, the lowest no observed effect concentration (NOEC) measured from all WEL's assets on the North West Shelf (IRCE, 2003a).

Figure 4.12 – Figure 4.15 show (a) the maximum predicted PFW concentration that occurred over the three tidal cycle simulation and (b) the corresponding PEC/PNEC ratio contours, for model layers one to 4, respectively. Highest concentrations occur in the surface waters around the discharge location. These peak at just over 0.1% PFW within the surface waters, up to 400m from the discharge point. The highest concentrations would occur for short periods of time as the tides turn at slack waters. PEC/PNEC ratios therefore exceed one for only a short duration.

4.3.8 Evaluation of Environmental Effects

General

The PEC/PNEC approach is highly conservative as it assumes an ecological response immediately on contact with PFW exceeding the PNEC. In contrast, the PNECs are derived from ecotoxicology studies in which organisms are exposed to the PFW for durations that are unlikely to be experienced in the field. The objective of this section is to present a more intuitive assessment of the risk posed to biological communities from the PFW being discharged from the Blacktip outfall. These communities include:

- benthos;
- plankton;
- sessile Invertebrates (communities attached to the platform);
- fish;
- marine mammals; and
- sea birds.

Benthos

Benthos communities are found in or around the seabed. They are unlikely to be affected because the plume disperses rapidly in the water column and does not impact directly on the seabed. Furthermore adsorption onto suspended sediment particles will be low, limiting the extent of sedimentation to the seabed.

Plankton

Planktonic organisms live freely in the water column and drift with the water currents. Plankton may also include the early stages (eg. egg, larva and spores) of non-planktonic

species (fish, benthic invertebrates and algae). Figure 4.16 illustrates the typical exposure period for passive floating organisms. Once discharged to the receiving environment, dilution reduces the concentration of toxic chemicals in the PFW. Under the present discharge rate and configuration, initial dilutions are high. For a worst-case scenario, a freely floating organism passing directly over the discharge pipe may be exposed to PFW concentrations above the PNEC value in the mixing zone for a short duration. There is therefore the potential for impact, however, the exposure concentration will be continually diluting and only organisms residing directly in the plume would be impacted, which constitutes a small proportion of the community.

Sessile marine invertebrates

Sessile marine invertebrates are those that are attached to the substrata and infrastructure surrounding the discharge. These do not have the opportunity to move to avoid toxic affects and potentially are the most exposed communities to the plume. Even though these organisms cannot move, the plume would be continually moving around them depending on the direction and speed of ambient currents. Sessile invertebrates may therefore be impacted sporadically by high concentrations of PFW, however, when they encounter clean seawater, they would have the opportunity to release accumulated hydrocarbons.

Fish

Figure 4.16 shows the typical exposure periods for motile organisms such as fish. These have the ability to swim and might move in and out of the plume. Exposure periods are therefore sporadic and unlikely to be at levels which would harm the organism. Moreover, the volume of water exposed to concentrations above PNEC values is relatively small both under present and projected discharge rates.

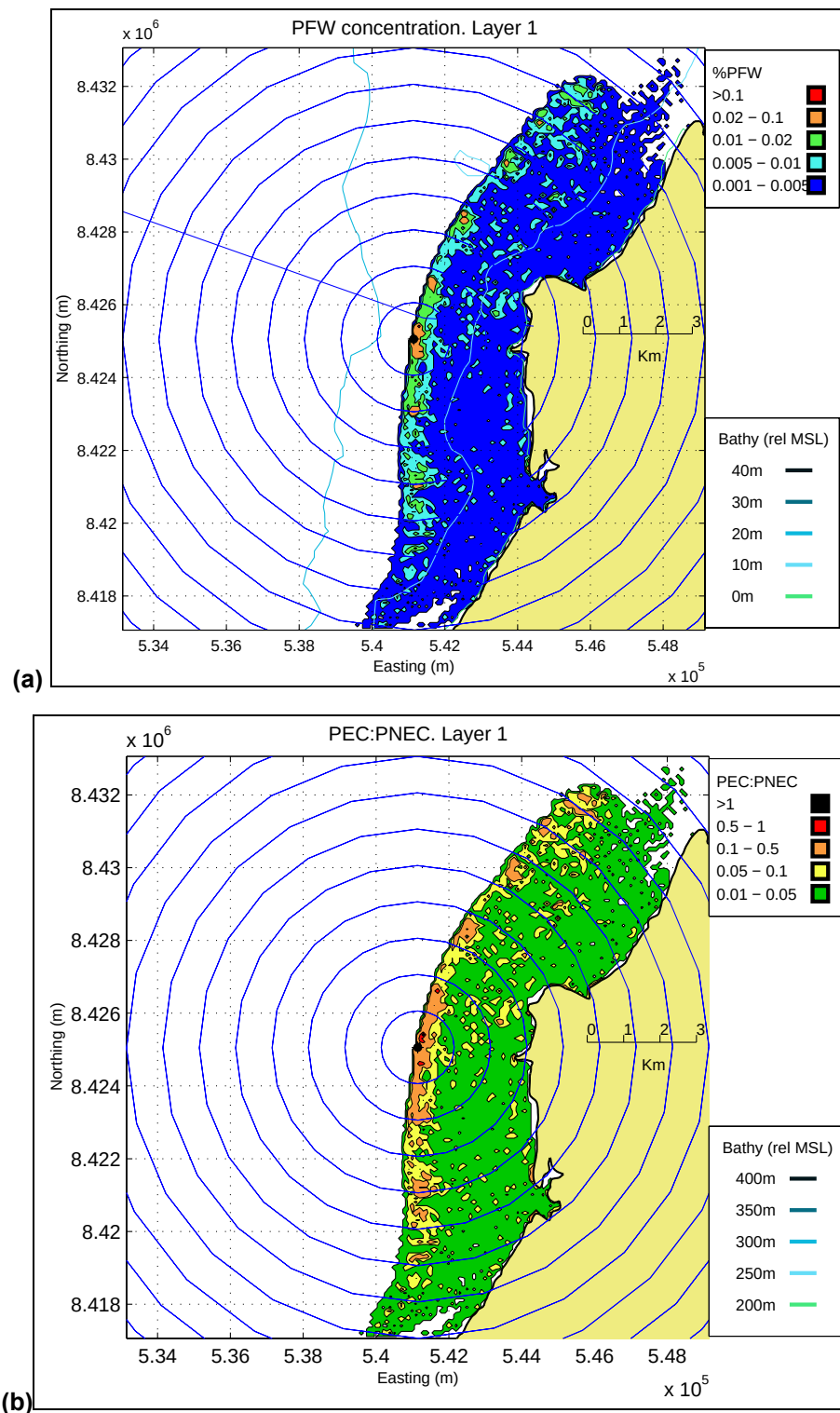
Marine mammals

As marine mammals feed on fish and/or plankton, they are most likely to be affected by trophic transfer (ie, bioaccumulation of chemicals from food) and potential biomagnification. However, vertebrates are able to metabolise and excrete the type of chemicals that contribute most to the risk. They are also generally migratory so individuals are not likely to be affected by any localised contamination that may occur.

Seabirds

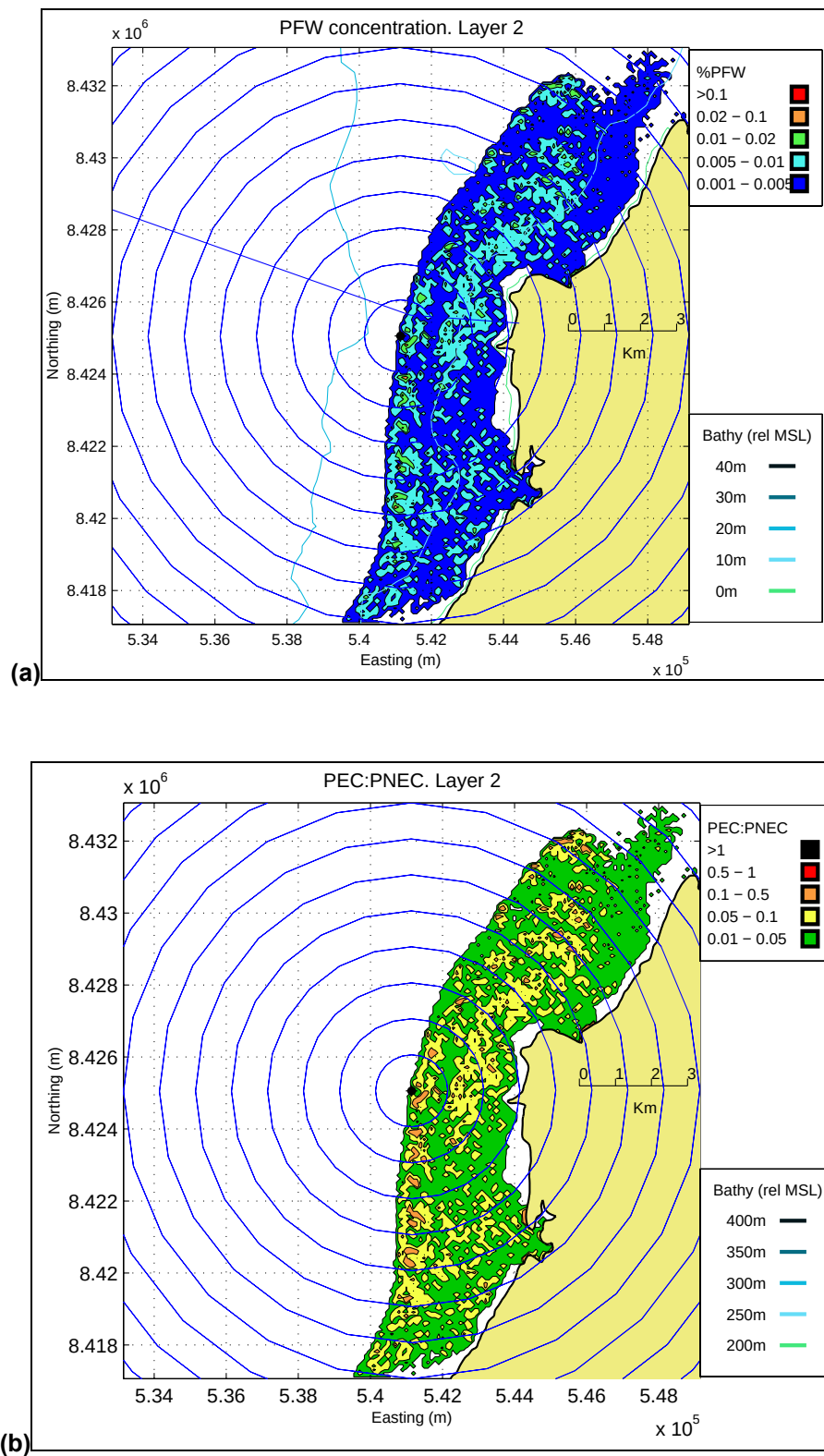
Seabirds are harmed mainly by the physical properties of floating oil and not the toxicity. (Furness and Camphuysen, 1997). As with the marine mammals, there is the potential for trophic transfer and indirect effects such as changes in the availability of food sources. As the food source is not likely to be impacted, the risk to sea birds is low.

Figure 4.12. Scenario 14: (a) maximum PFW concentrations and (b) PEC/PNEC ratios over three tidal cycles for layer one (0-2 m) on a neap tide



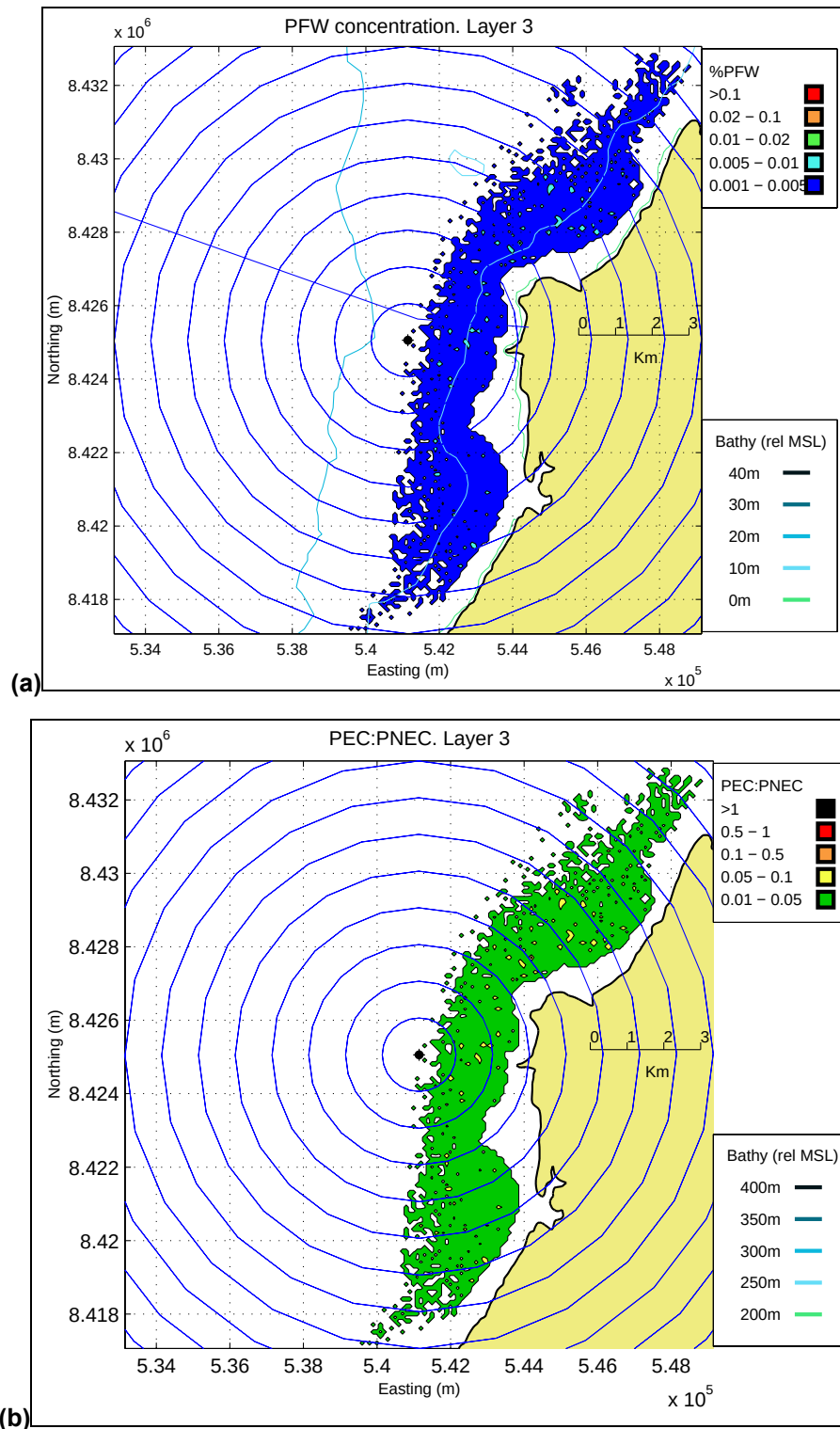
Note: Range rings are drawn at 1km intervals centred on the discharge point

Figure 4.13. Scenario 14: (a) maximum PFW concentrations and (b) PEC/PNEC ratios over three tidal cycles for layer two (2-4 m) on a neap tide



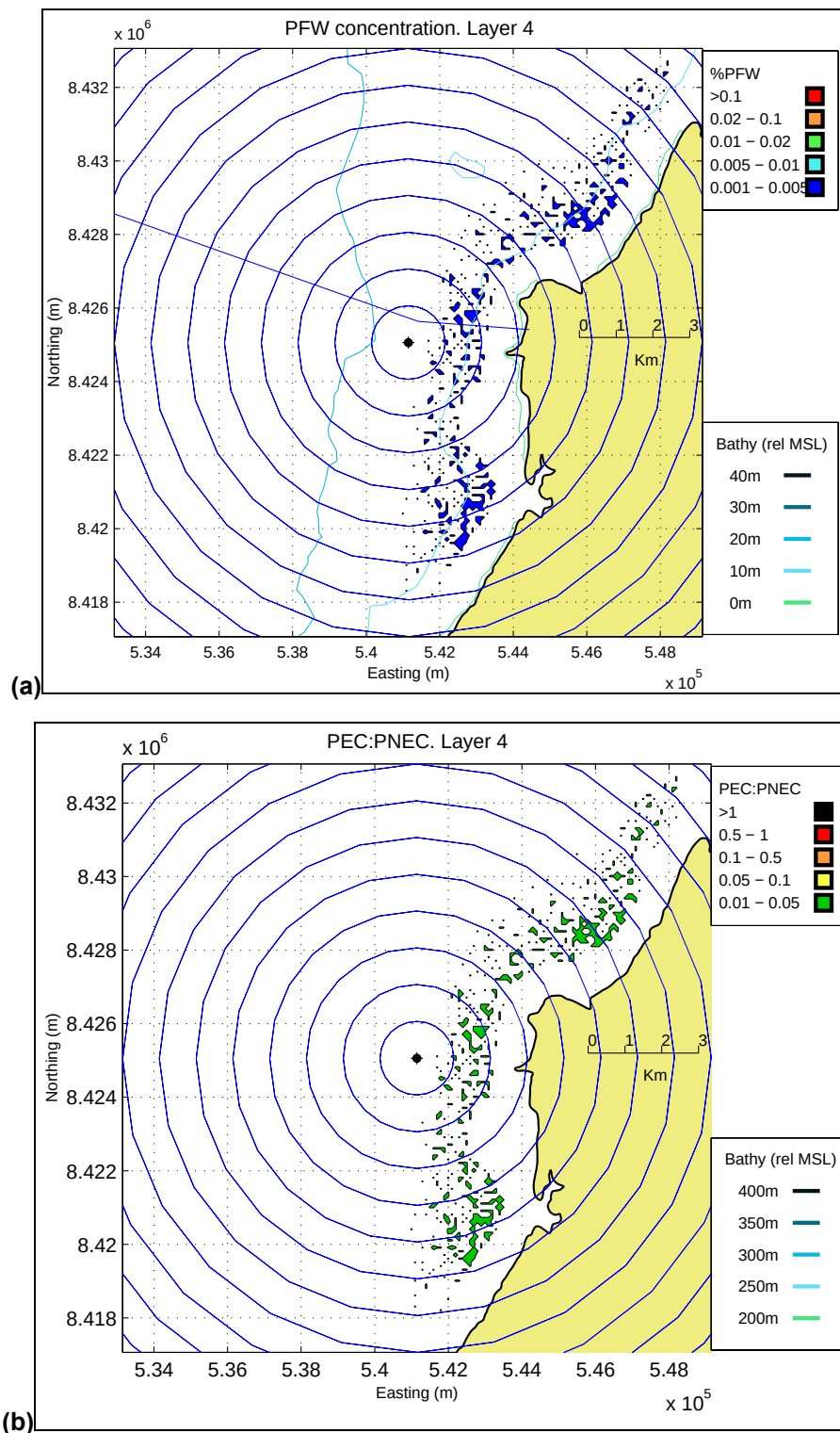
Note: Range rings are drawn at 2km intervals centred on the discharge point

Figure 4.14. Scenario 14: (a) maximum PFW concentrations and (b) PEC/PNEC ratios over three tidal cycles for layer three (4-6 m) on a neap tide

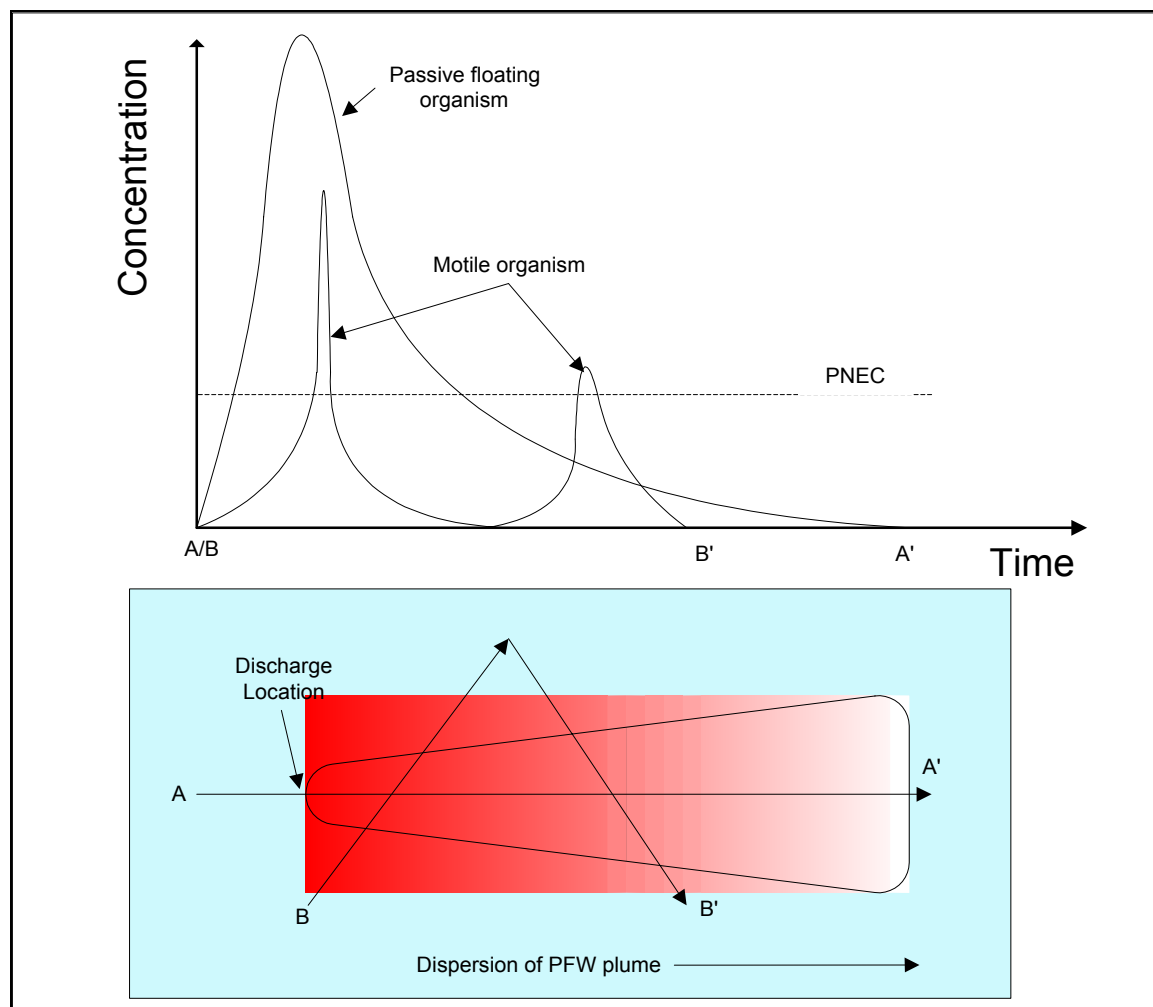


Note: Range rings are drawn at 2km intervals centred on the discharge point

Figure 4.15. Scenario 14: (a) maximum PFW concentrations and (b) PEC/PNEC ratios over three tidal cycles for layer four (6 - 10 m) on a neap tide



Note: Range rings are drawn at 2km intervals centred on the discharge point

Figure 4.16 Conceptual model for PFW exposure times for passive and motile organisms

4.4 Dissolved Oxygen

4.4.1 General

Prior to discharge PFW is likely to have little or no DO. This should not be a problem as even under worst-case conditions the discharged plume should receive 700 initial dilutions (see Section 2.3.5), which mean that by the time the plume reaches the sea surface DO concentrations should be virtually back to ambient levels. However, the PFW discharge will contain a range of organic compounds and chemicals that will start to decompose and utilise oxygen immediately on discharge. The rate at which oxygen is utilised is measured by the Biochemical Oxygen Demand (BOD) of the effluent.

This section presents an assessment on the likely impact of this oxygen utilisation on DO levels in the receiving waters. From this analysis, maximum BOD concentrations are given that will most likely maintain oxygen levels above 90% saturation limits as required by the ANZECC guidelines.

4.4.2 Receiving Waters

The concentration of DO is highly dependent on temperature, salinity, biological activity (microbial primary production) and rate of transfer from the atmosphere. Based on water temperatures (26 to 30°C) and salinity (34psu) of the receiving waters in the vicinity of the Blacktip PFW discharge, DO saturation levels will vary from 6.22mgL⁻¹ to 6.64mgL⁻¹. The 2000 ANZECC guidelines for fresh and marine water quality recommend that DO in tropical Australia should not normally permitted to fall below 90% saturation, determined over at least one tidal cycle. For Blacktip, this equates to 5.6mgL⁻¹.

4.4.3 Biochemical Oxygen Demand

The BOD provides a measure of the rate at which oxygen is consumed by bacterial activity and is thus an indirect measure of the organic content of wastewater. Experiments have shown that BOD decays exponentially with time, *t*, according to the equation:

$$BOD_c = BOD_0 e^{-K_{BOD}t}$$

where:

BOD_c is the concentration at time *t*;

BOD₀ is the original concentration; and

K_{BOD} is the BOD decay rate.

K_{BOD} is temperature dependant and can be calculated from:

$$K_{BOD}^{T_1} = K_{BOD}^{T_2} \theta^{(T_1 - T_2)}$$

where:

$K_{BOD}^{T_1}$ is the decay coefficient at temperature T_1 ;

$K_{BOD}^{T_2}$ is the decay coefficient at 20°C (typically between 0.2 and 0.3); and

θ is the temperature coefficient for reaction rates (typically 1.056 for $T > 20^\circ\text{C}$).

For temperatures of 28°C and $K_{BOD}^{T_2}$ of 0.26 this yields a value of 0.4 day⁻¹.

4.4.4 Oxygen Utilisation

Oxygen utilisation (D_{O_2}) in a bounded stream can be predicted using a modified version of the classic Streeter-Phelps oxygen sag equation (Metcalf and Eddy, 1991), given by:

$$D_{O_2} = \frac{K_{BOD} BOD_0}{K_{O_2} - K_{BOD}} (e^{-K_{BOD}t} - e^{-K_{O_2}t})$$

where:

K_{O_2} is the reaeration coefficient.

The graphical representation of the Streeter-Phelps oxygen sag equation is given in Figure 4.17, using the values specified in Table 4.4. For illustration purposes, the initial BOD concentration was set at 5000mgL⁻¹. After 700 initial dilutions this decreases to 7.14mgL⁻¹. As can be seen from the DO curve, oxygen utilisation commences immediately after discharge. It will continue to fall until a critical point is reached when the rate of oxygen utilised by waste decomposition equals the rate of atmospheric reaeration. Thereafter DO concentrations increase as the rate of reaeration exceeds the rate of utilisation.

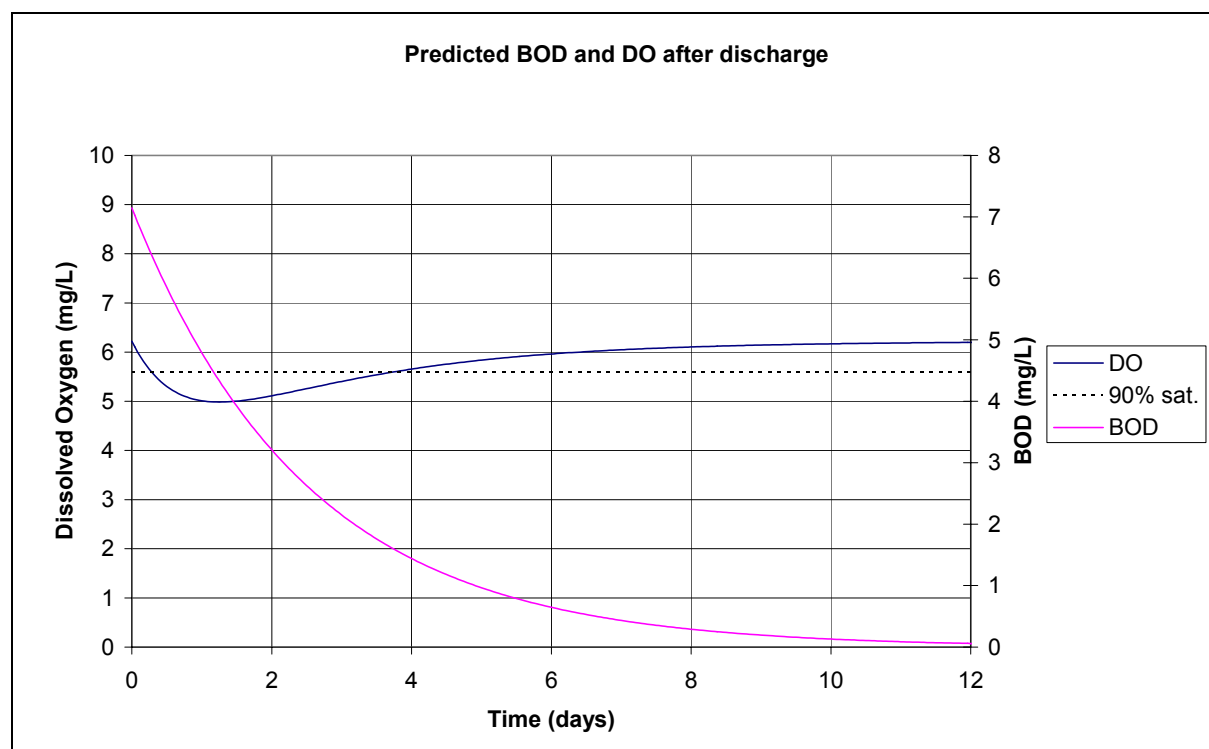
Table 4.4 Summary of values used in Streeter Phelps equation

Parameter	Value
O ₂ sat.	6.22 mgL ⁻¹
BOD ₀	7.14 mgL ⁻¹ (5,000 mgL ⁻¹ prior to initial dilution of 700)
K _{BOD}	0.4 day ⁻¹
K _{O₂}	1.4 day ⁻¹

The principle is the same for the open ocean, however, in addition to the decay process, BOD concentrations reduce through dispersion of the plume in the receiving waters. This may be countered in regions of slow moving currents by build up due to poor flushing and recirculation of the plume over itself.

In studies undertaken for the European Urban Wastewater Treatment Directive it was estimated that where BOD levels deviate by less than 1.5mgL^{-1} from background levels, the resulting impact on DO will be less than 0.5 mg/l . (CSTT; 1993). This can also be seen from the oxygen sag and BOD concentration curve in Figure 4.17. In the dispersion modelling presented next, 1.5mgL^{-1} was used as the threshold value below which there should be no adverse effect in the environment from reduced oxygen levels.

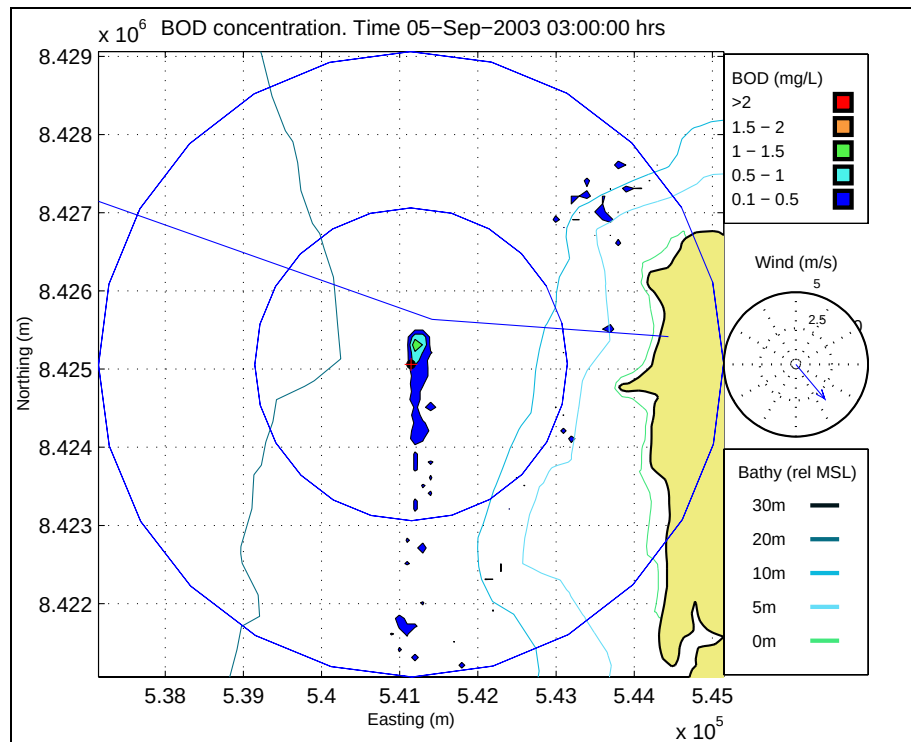
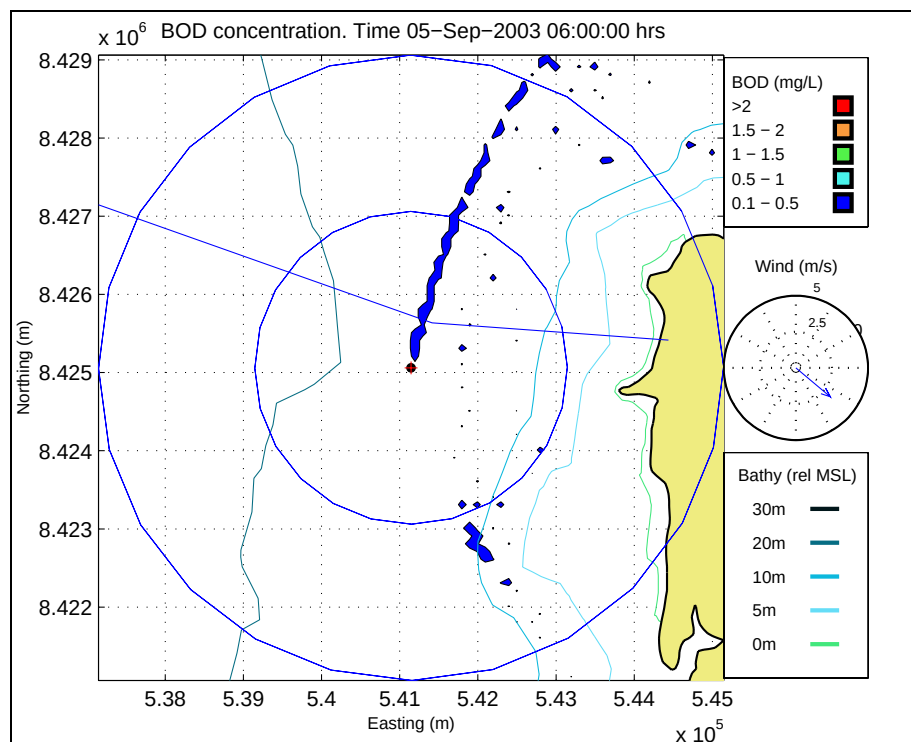
Figure 4.17 Concentrations of BOD and DO predicted by the Streeter-Phelps equation.



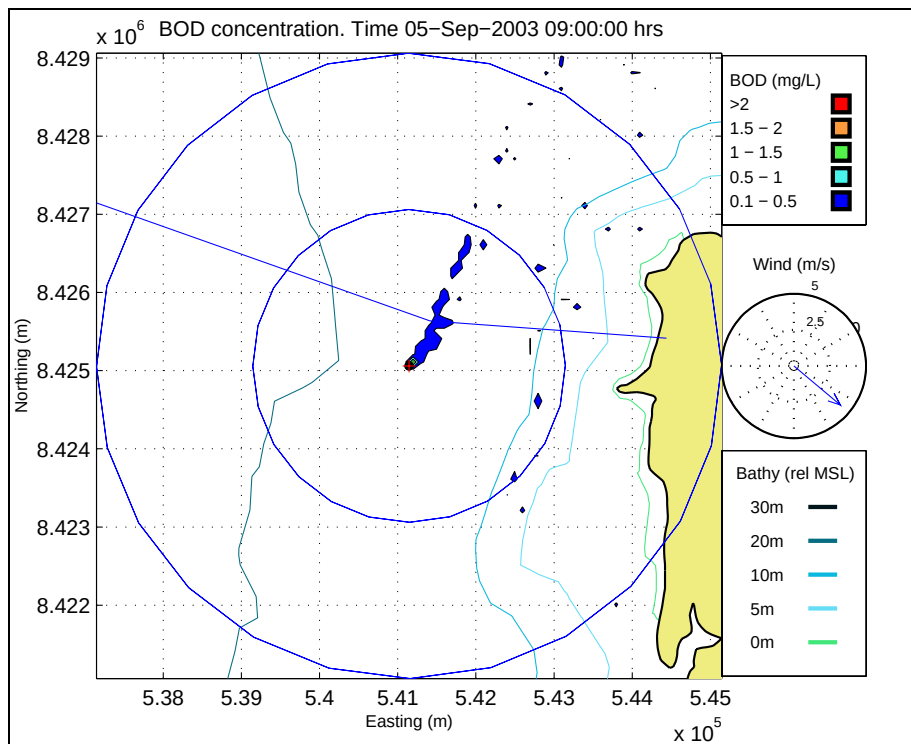
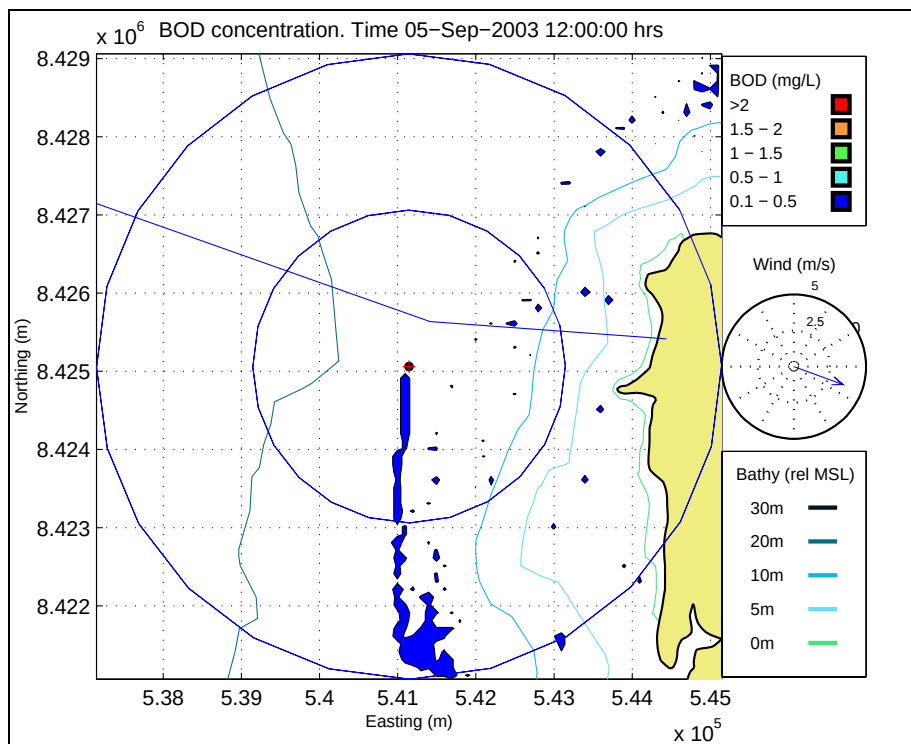
4.4.5 Dispersion Modelling

BOD was simulated using the PFW dispersion model with the objective of deriving a maximum value for the effluent discharge. The scenario undertaken was identical to that described in Section 4.3.6, with the exception that BOD was modelled instead of a conservative tracer. The initial BOD concentration was set at $1,200\text{mgL}^{-1}$ and the decay coefficient at 0.4 day^{-1} .

Figure 4.18 (a) – (d) present a series of plots showing the predicted concentration of BOD at three hourly intervals for maximum future flows under “worst-case” ambient conditions (neap tide and typical “wet season” winds). At high water (Figure 4.11(a)), the plume pools at slack water and BOD concentrations increase to a maximum of 1.5mgL^{-1} . On the ebb tide, the plume is advected parallel to the bathymetry contours for a distance of approximately 12km towards the north. With the increasing ambient flow, there is additional dilution and concentrations reduce to less than 0.5mgL^{-1} . At low water the discharge pools and once again concentrations peak at 1.5mgL^{-1} . The flood tide advects the plume about 10km towards the south.

Figure 4.18. Predicted BOD concentration on a neap tide**(a) High Water****(b) Mid ebb**

Note: Range rings are drawn at 1km intervals centred on the discharge point

(c) Low water**(d) Mid flood**

Note: Range rings are drawn at 1km intervals centred on the discharge point

4.4.6 Risk Assessment

The traditional PEC/PNEC approach was used to assess the risk. As described in Section 2.5.3, this approach demonstrates the zone of potential affect by calculating and presenting contours of the PEC/PNEC ratio. Any value over one then indicates a potential zone of impact. The PNEC was set at 1.5 mg/L BOD. As stated above, this is the concentration at which the change in DO levels will be less than 0.5mgL⁻¹.

Figure 4.19 and Figure 4.20 show (a) the maximum predicted BOD concentration that occurred over the three tidal cycle simulation and (b) the corresponding PEC/PNEC ratio contours, for the top two layers in the model, respectively. Highest concentrations occur in the surface waters around the discharge location. These peak at about 1.5mgL⁻¹ BOD within 100m from the discharge point. The PEC/PNEC ratios peak at about one suggesting that the change in DO levels will be less that 0.5mgL⁻¹ at all times.

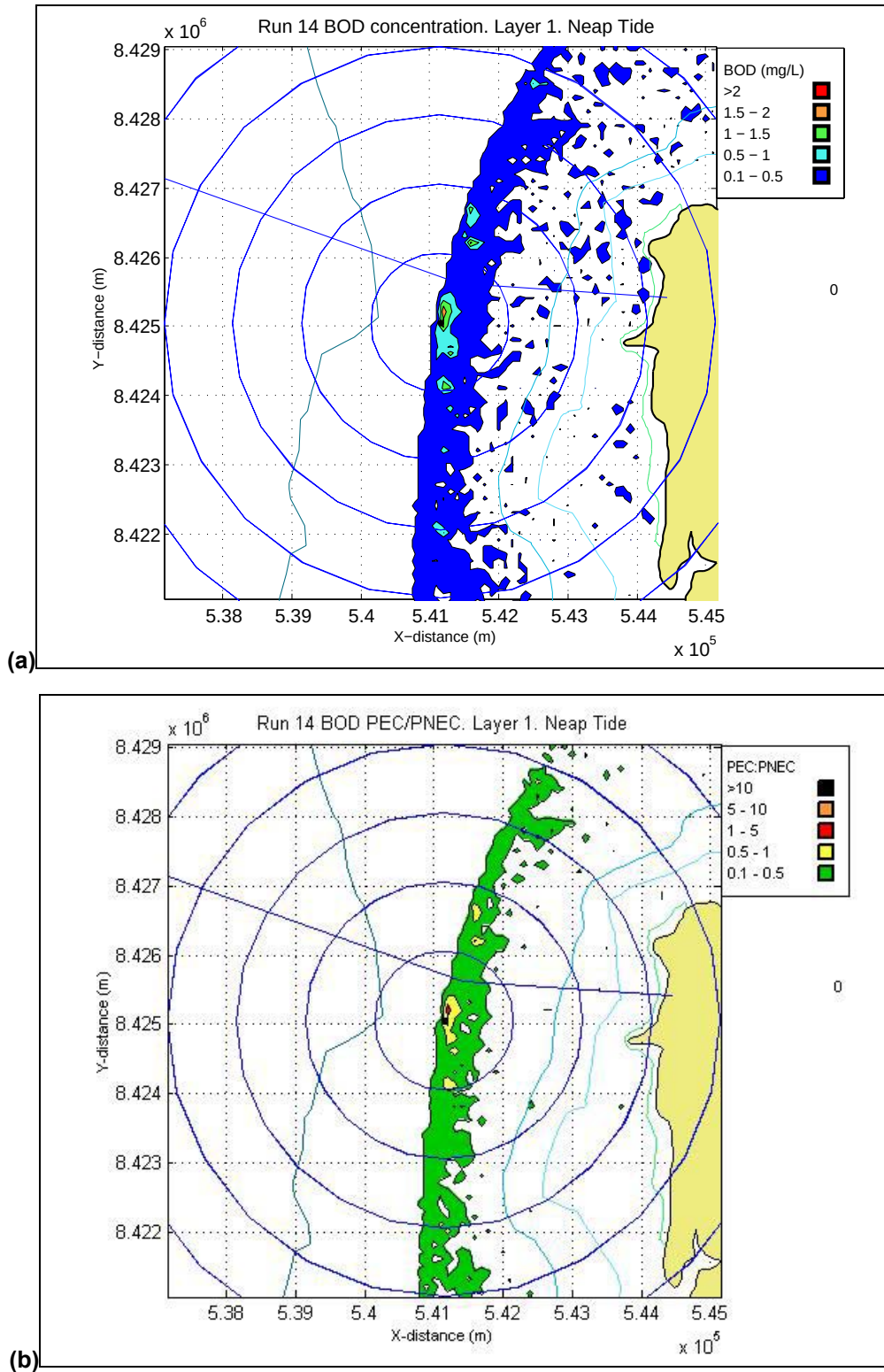
4.4.7 Recommended maximum BOD Concentrations

A BOD concentration of 1,200mgL⁻¹ was found to be the limit for the design rate of 6000 bbl day⁻¹ to maintain BOD levels in the receiving environment below the critical value of 1.5mgL⁻¹. This value was used to scale BOD concentrations for the other design flow rates. Results are presented in Table 4.5.

Table 4.5 Recommended maximum BOD concentrations for each design flow rate.

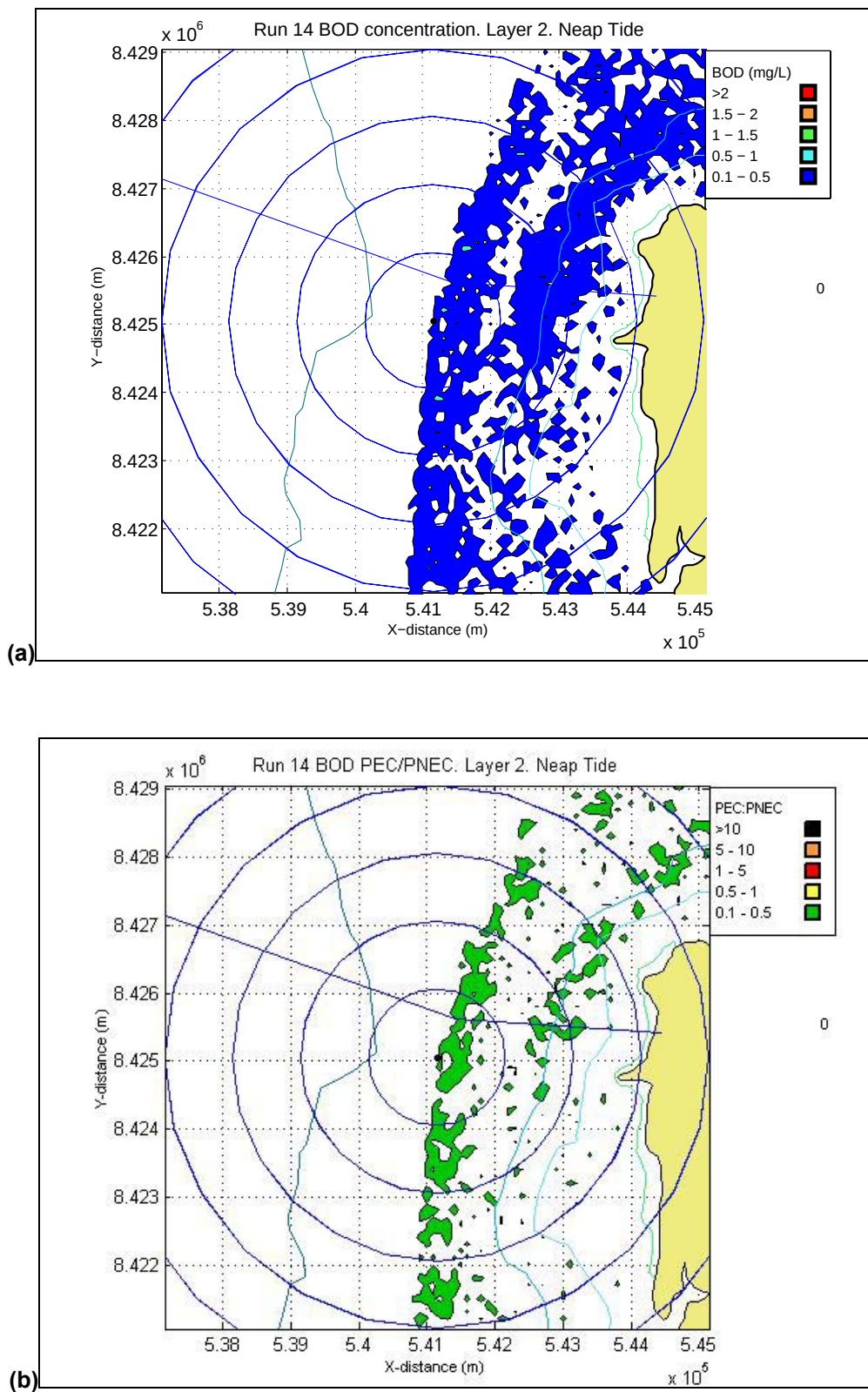
Design flow rate (bbl day ⁻¹)	Maximum BOD conc. (mgL ⁻¹)
6000	2,500
2000	7,500
200	75,000

Figure 4.19. Scenario 14: (a) maximum BOD concentrations and (b) PEC/PNEC ratios over three tidal cycles for layer one (0-2 m) on a neap tide



Notes:

Figure 4.20. Scenario 14: (a) maximum BOD concentrations and (b) PEC/PNEC ratios over three tidal cycles for layer two (2-4 m) on a neap tide



5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It is common practice in the petroleum industry to remove as many hydrocarbons as possible from PFW by physical or enhanced separation techniques and then discharging directly to the ocean. It is recognised that the separation process is not 100% effective and trace concentrations of chemical contaminants can remain in the discharge. Hydrocarbons and process chemicals are the contaminants of most concern in PFW.

Ecotoxicology experiments under laboratory conditions have demonstrated that undiluted PFW can be toxic to marine organisms. In contrast, detecting a measurable impact on marine ecosystems in the vicinity of PFW discharges has proved difficult. The reason for this is that dilution and biodegradation in the receiving environment reduces contaminant concentrations to levels below which they can have an impact on marine organisms. Where concentrations do exceed thresholds, exposure times for free-moving organisms are generally short.

The preferred disposal option for Blacktip PFW is onshore treatment followed by discharge through a long sea outfall. The discharge location will be near the Swamp Mooring, which lies in 15m of water. Corrosion inhibitors, hydrate inhibitor and demulsifiers will be added to the process stream. These will be selected based on their low toxicity and enhanced environmental performance. Onshore treatment allows more scope for treatment as there is not the space restriction of offshore facilities and contaminant concentration will be reduced to as low as practicable prior to discharge.

Numerical modelling has been undertaken to assess the environmental impact and to derive an effective discharge strategy for the Blacktip PFW. The assimilative capacity of the receiving water is high with strong tidal currents of up to 0.9ms^{-1} on a spring tides and 0.2ms^{-1} on neaps. Tides are semidiurnal and currents slacken four times a day.

Using a four port diffuser configuration, near field dispersion modelling showed that at least 700 initial dilutions would be achieved for the maximum future discharge rate. This would reduce PFW concentrations to 0.14%.

Far field modelling predicted that during slack waters PFW would build up and concentrations would reduce to a maximum of 0.1%PFW within 400m from the discharge. Based on ecotoxicology work previously undertaken by WEL on offshore facilities, this is below the predicted concentration at which there could be harm to marine organisms.

These exotoxicity values are believed to be conservative as the tests included sublethal endpoints and were undertaken on organisms in their most sensitive stages of life (eg larval development or fertilisation). Moreover, exposure times were greater than those likely to be experienced in the natural environment. Assuming that the treated Blacktip PFW is no more

toxic than PFW from other Woodside Assets, there should be minimal environmental impact from discharging it to the 15 m depth contour in the Joseph Bonaparte Gulf.

5.2 Recommendations

Once PFW becomes available, ecotoxicology tests should be undertaken and the toxicity of process chemicals should be reviewed. Ecotoxicity should include tests on juvenile prawns as this species constitutes an important fishery in the Joseph Bonaparte Gulf.

As well as reducing the concentration of dispersed oil, treatment should focus on removing PAHs and reducing the toxicity of process chemicals, the compounds of most concern in PFW. Model results should take into consideration any further benefits provided by the proposed treatment.

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