# NWS Project Extension

Woodside Energy Ltd.

## Air Quality Impact Assessment

Final Report | Revision 4

25 October 2019

# NWS Project Extension

Project No: IW212400
Document Title: Air Quality Impact Assessment
Revision: Revision 4
Date: 25 October 2019
Client Name: Woodside Energy Ltd.
Project Manager: Sarah Blackford & Jon Davies
Author: Barbara Brown & Matthew Pickett
File Name: Woodside_NWS Air Quality Assessment_Rev 4_Final

Jacobs Group (Australia) Pty Limited
ABN 37 001 024 095
Level 6, 30 Flinders Street
Adelaide SA 5000 Australia
T +61 8 8113 5400
F +61 8 8113 5440
www.jacobs.com



## Document history and status

| Revision | Date | Description | By | Review | Approved |
|---|---|---|---|---|---|
| 0 | 3 Jul 2019 | For Client | B Brown & A Boyd | M Pickett & S Blackford | M Goodwin |
| 1 | 17 Jul 2019 | For Client | B Brown & A Boyd | M Pickett & S Blackford | M Goodwin |
| 2 | 31 Jul 2019 | For Client | B Brown & A Boyd | M Pickett & S Blackford | M Goodwin |
| 3 | 16 Aug 2019 | For Client | B Brown, A Boyd & M Murphy | M Pickett & S Lakmaker | M Goodwin |
| 3 | 20 Aug 2019 | For Client | B Brown, A Boyd & M Murphy | M Pickett & S Lakmaker | M Goodwin |
| 3 | 23 Aug 2019 | For Client | B Brown, A Boyd & M Murphy | M Pickett & S Lakmaker | M Goodwin |
| 3 | 9 Sep 2019 | For Client | B Brown, A Boyd & M Murphy | M Pickett & S Lakmaker | M Goodwin |
| 4 | 10 Oct 2019 | For Client | B Brown, A Boyd & M Murphy | M Pickett | M Goodwin |
| 4 | 18 Oct 2019 | For Client (minor additions) | B Brown, A Boyd & M Murphy | M Pickett | M Goodwin |
| 4 | 25 Oct 2019 | For Client (minor additions) | B Brown, A Boyd & M Murphy | M Pickett | M Goodwin |

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# Executive Summary

This report details the results of air quality modelling conducted to support the environmental approvals for the North West Shelf (NWS) Project Extension Proposal (the Proposal). As a part of this assessment, the existing air emissions scenario, and potential future air emissions scenarios, were developed for the Burrup Peninsula. Air dispersion modelling was undertaken to determine how emissions from all identified sources may impact on sensitive receptors on the Burrup Peninsula. The model predictions were assessed against air quality assessment standards, to gauge potential future (cumulative) air quality impacts on human health and vegetation.

The CSIRO meteorological, air dispersion and photochemical model, 'TAPM-GRS' (The Air Pollution Model – Generic Reaction Set) was selected for modelling for reasons of reliability, efficiency and the ability to simulate the effects of long-term variations in meteorological conditions. Model input emissions inventories were developed in consultation with Woodside, based on reasonable and conservative emissions estimates, considering available datasets, design data, monitoring data and for proposed developments, preliminary design data based on early 'front end engineering design' concepts. Third party emissions were represented based on consideration of publicly available literature and input following consultation with some parties. To confirm that TAPM-GRS performance was fit for purpose, modelled results were compared to measured results from Woodside ambient air monitoring programs. When compared to ambient air monitoring results for Nitrogen Dioxide ($NO_2$) and Ozone ($O_3$) from 2014, when the North West Shelf (NWS) Project: Karratha Gas Plant (KGP) and Pluto Liquified Natural Gas Development began operating together at or near capacity, model results were found to support actual results and the TAPM-GRS model was therefore deemed suitable and with an accuracy appropriate for the assessment of the Proposal.

The scope of this air quality impact assessment included modelling $NO_2$, $O_3$ and Sulfur Dioxide ($SO_2$) for assessment against National Environmental Protection (Ambient Air Quality) Measure (NEPM [Ambient Air Quality]). Results for annual average (airborne) $NO_x$ and $SO_2$ were obtained for comparison against the European Union (2008) air quality standards for the protection of vegetation. Results for $NO_2$ and $SO_2$ deposition modelling were provided to support any future assessment of potential impacts to landforms, including the rock art of the Burrup Peninsula.

Monitoring of hydrocarbons undertaken during 2009-2015 showed that emissions of Benzene, Toluene and Xylenes (BTX), as indicators of all Volatile Organic Compounds (VOCs), had insignificant air quality effects at the monitoring locations of Dampier, Karratha, and Burrup Road. For most of the time, monitored BTX concentrations were nil at those locations. From a risk assessment it was concluded that formaldehyde would have low concentrations similar to those of benzene. As such individual VOCs such as benzene and formaldehyde were excluded from the assessment. However, estimates for emissions of VOCs were included in the modelling as part of photochemical model input requirements to obtain results for $NO_2$ and $O_3$.

Airborne particulate matter (PM) as $PM_{10}$ and $PM_{2.5}$ from the Proposal was not modelled. Although exceedances of ambient air quality standards for these air quality pollutants occur on the Burrup Peninsula, they are primarily due to, smoke from bushfires and controlled burns, raised dust, and other industrial sources. Emissions of particulate matter from the Proposal are negligible in relation to these sources.

Key results for the Proposal's air quality impact assessment were that:

- There were no predicted exceedances of NEPM (Ambient Air Quality) standards for $NO_2$, $O_3$, and $SO_2$ for any of the emission scenarios that were investigated as part of this assessment. All results for these pollutants were well below NEPM (Ambient Air Quality) standards.
- There were no predicted exceedances of European Union (2008) air quality standards for oxides of nitrogen ($NO_x$) and $SO_2$ for the protection of vegetation, for any of the emission scenarios.

In conclusion, there is a low risk of air quality impact on human health and vegetation from the Proposal, where "low risk" has been defined from predicted concentrations well below relevant air quality standards.

## Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to provide air quality assessment services for the North West Shelf Project Extension Proposal in accordance with the scope of services set out in the contract between Jacobs and the Client, Woodside Energy Ltd.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

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# Abbreviations and Definitions

| Abbreviation | Expansion / Definition |
|---|---|
| ABS | Australian Bureau of Statistics |
| BAAMP | Burrup Ambient Air Monitoring Program |
| BoM | Bureau of Meteorology |
| CBM | Current Baseline |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DANHP | Dampier Archipelago National Heritage Place |
| EPA | Environmental Protection Authority (Government of Western Australia) |
| FBSIA E&A | Future Burrup Strategic Industrial Area State – existing and approved development, representing Current Baseline and the NWS Extension Project with implementation of improvement opportunities |
| FBSIA-KIO | Future Burrup Strategic Industrial Area (State) with KGP Improvement Opportunities |
| FEED | Front-End Engineering and Design |
| GLC | Ground Level Concentration; an output from an air dispersion model commonly used for assessment |
| GRS | Generic Reaction Set – a photochemical modelling scheme in-built to TAPM; e.g., see Hurley (2008a). |
| Jacobs | Jacobs Group (Australia) Pty. Limited |
| KGP | Karratha Gas Plant |
| KIO | CBM with KGP Improvement Opportunities |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| meq/m$^2$/year | Milliequivalents per square metre per year – deposition flux units; a milliequivalent is one thousandth of a chemical equivalent. An equivalent of an ion is the mass in grams of the ion divided by its molecular weight and multiplied by the charge on the ion; e.g., Gillett (2014) |
| Mtpa | Mega (million) tonne per annum |
| NEPM | National Environment Protection Measure |
| $NH_3$ | Molecular formula for ammonia |
| NO | Molecular formula for nitric oxide |
| $NO_2$ | Molecular formula for nitrogen dioxide |
| $NO_x$ | Molecular formula for oxides of nitrogen, the sum of NO and $NO_2$ |
| NPI | National Pollutant Inventory |
| $O_3$ | Molecular formula for ozone |
| NWS Project | The existing NWS Project including the existing Karratha Gas Plant |
| PAQS | Pilbara Air Quality Study |
| PLP | Pluto on-shore LNG Plant |
| $PM_{2.5}$ | Particulate Matter 2.5 – mass concentration of particles with aerodynamic diameters less than 2.5 microns. |
| $PM_{10}$ | Particulate Matter 10 – mass concentration of particles with aerodynamic diameters less than 10 microns. |
| The Proposal | The North West Shelf Project Extension Proposal |
| SIA | (Burrup) Strategic Industrial Area |
| SKM | Sinclair Knight Merz |

| Abbreviation | Expansion / Definition |
|---|---|
| $SO_2$ | Molecular formula for sulfur dioxide |
| TAN | Technical Ammonium Nitrate (Yara Pilbara Nitrates) |
| TAPM | The Air Pollution Model – a meteorological and air dispersion model developed by CSIRO (Hurley, 2008). |
| Tpd | tonne per day |
| WEL | Woodside Energy Limited |
| FBSIA E&A | Woodside Future SIA State – NWS Extension Project including KGP Improvement Opportunities |

# 1. Introduction

## 1.1 Overview

Woodside Energy Ltd (Woodside), as operator for and on behalf of the North West Shelf Joint Venture (NWSJV), is proposing to continue and extend the operating life of the North West Shelf (NWS) Project through the long-term processing of third-party gas and fluids and the long-term processing of existing and future NWSJV field resources. This proposal is referred to as the NWS Project Extension Proposal (the Proposal).

This air quality impact assessment, based on air pollutant dispersion modelling, was prepared to support applications for environmental approvals and to inform Woodside of the potential impacts to air quality from the long-term processing of third-party gas and fluids, and the long-term processing of existing and future NWSJV field resources.

## 1.2 Project Background

The NWS Project is one of the world's largest liquefied natural gas (LNG) producers, supplying oil and gas to Australian and international markets from offshore gas, oil, and condensate fields in the Carnarvon Basin off the north-west coast of Australia. For more than 30 years, it has been Western Australia's largest producer of domestic gas. The associated gas processing plant is located on the Burrup Peninsula, Western Australia (WA), approximately 6 km from Dampier.

## 1.3 Scope

This report provides an air quality impact assessment of the Proposal. The following items are within the scope of this report:

- Modelling of air emissions associated with the proposed future operations of the Proposal.
- Demonstration of cumulative air quality impacts associated with the best case, realistic worst case and most likely future emission scenarios for Burrup Peninsula.

## 1.4 Geographical Summary

The Proposal is located on the central Burrup Peninsula on a lease area of approximately 200 ha. The Burrup Peninsula forms part of the Dampier Archipelago on the Pilbara coast and is a low-lying, rocky peninsula approximately 40 km in length, including Dolphin Island. The highest terrain elevations are between approximately 100–120 m above sea level.

The towns of Dampier and Karratha are located approximately 15 km and 30 km, respectively, from the Proposal.

The Burrup Peninsula has significant cultural heritage value to Aboriginal people, particularly due to the large collection of rock art in the form of petroglyphs, standing stones, and other cultural sites such as foraging areas, ceremonial sites and hunting areas. The area is traditionally referred to as Murujuga and includes areas with protection as a National Heritage Place and National Park.

Vegetation with heritage value is also found on the Burrup Peninsula. Ethnographic studies have identified two bush-medicine plants growing at Withnell Bay—one is used as a healing balm for physical injuries and colds, and is also a spiritual protection for people visiting country; the other is used to settle the stomach which is also a source of food (Integrated Heritage Services, 2018). The Murujuga Cultural Management Plan (MAC, 2016) also places emphasis on the heritage value of vegetation on the Burrup Peninsula. Some trees provide medicine for colds and flus, shade for shelter and ceremonial tools. *Jami* bush is used to treat aches, pains and cuts. Mangroves are used for fishing and spinifex seeds are used to make damper.

The location of the Proposal in relation to the towns of Dampier and Karratha is shown in Figure 1-1.


Figure 1-1 NWS Project Extension Location

# 2. Air Quality Assessment Criteria

## 2.1 Overview

This section sets out legislation, policy and guidelines applicable to air assessments in WA, and which are relevant to the Proposal.

## 2.2 Ambient Air Quality Standards – Criteria Pollutants

The WA Environmental Protection Authority (EPA) provides guidance for assessing the potential impacts of a proposal on air quality in the Environmental Factor Guideline: Air Quality, published in 2016 (EPA, 2016), whilst this does not specify air quality standards for assessment it does provide the following considerations:

- Whether numerical modelling and other analyses to predict potential impacts have been undertaken using recognised standards with accepted inputs and assumptions.
- Whether existing background air quality, including natural variations, have been established through monitoring and accepted proxy data.
- Whether analysis of potential health and amenity impacts have been undertaken using recognised criteria and standards, where relevant, informed by Australian and international standards.

In the absence of specific air quality standards from the EPA, it is common practice for the NEPM (Ambient Air Quality) to be adopted for air quality impact assessments in WA. Therefore, to assess potential ground level concentrations (GLC) for the Proposal, modelled predictions were assessed against the relevant NEPM (Ambient Air Quality) standards shown in Table 2-1.

Table 2-1: NEPM (Ambient Air Quality) Standards relevant to the NWS Project Extension[1]

| Air pollutant | Averaging period | Maximum concentration standard | Maximum allowable exceedances |
|---|---|---|---|
| Nitrogen dioxide ($NO_2$) | 1 hour<br>1 year | 120 ppb<br>30 ppb | 1 day a year<br>None |
| Ozone ($O_3$) | 1 hour<br>4 hours | 100 ppb<br>80 ppb | 1 day a year<br>1 day a year |
| Sulfur dioxide ($SO_2$) | 1 hour<br>1 day<br>1 year | 200 ppb<br>80 ppb<br>20 ppb | 1 day a year<br>1 day a year<br>None |

1. It is noted that the Commonwealth of Australia has published a Notice of Intention to vary the NEPM (Ambient Air Quality). However, as that amendment has not been formalised this air assessment has only considered the 2015 standards, which were in force at the time of writing this air quality impact assessment.

## 2.3 Investigation Levels for Hydrocarbons

When assessing BTX as an indicator of VOCs, the National Environment Protection (Air Toxics) Measure 2011 and the NSW EPA assessment criteria (NSW EPA, 2016) are two relevant frameworks.

The NEPM (Air Toxics) contains Monitoring Investigation Levels (MILs) that are used in the assessment of ambient hydrocarbon concentrations. The MILs that are relevant to the Proposal are shown in Table 2-2. The NEPM (Air Toxics) sets out standards for long term (annual) averages because these are more readily related to human health effects than shorter term averages.

The New South Wales (NSW) Environment Protection Authority assessment criteria (NSW EPA, 2016) are relevant as they set out hourly average concentration assessment criteria and were used to assist with interpretation of measured hourly average concentrations. (Information is lost if only assessing longer term averages). The NSW EPA (2016) assessment criteria relevant to the Proposal are also shown in Table 2-2.

Table 2-2: Air Toxics NEPM Monitoring Investigation Levels and NSW EPA Assessment Criteria

| Pollutant | NEPM MIL, averaging period | NSW EPA (2016) assessment criterion, averaging period |
|---|---|---|
| Benzene | 3 ppb, annual | 9 ppb, 1 hour |
| Toluene | 1000 ppb, 24 hours | 90 ppb, 1 hour |
| | 100 ppb, annual | |
| Xylenes | 250 ppb, 24 hours | 40 ppb, 1 hour |
| | 200 ppb, annual | |

## 2.4 Vegetation Protection Standards

Air quality standards for the protection of vegetation have been set out by the World Health Organization (WHO, 2000), and the European Union (EU, 2008). While these standards were developed for the protection of a variety of vegetation in the European region, they have had wider application and have been used for the assessment of proposals in WA previously. SKM (2006) used the WHO (2000) standards. This air quality impact assessment has adopted the EU (2008) standards given they are the most recent; the relevant standards are listed in Table 2-3. To enable comparison with the results from the $NO_x$ and $SO_2$ dispersion modelling, the units of the EU (2008) standards were converted to ppb. A temperature of 30°C was used for this conversion, which is a typical ambient temperature relevant to the Proposal. Note that SKM (2006) used zero degrees Celsius for the conversion calculations (that is, at standard temperature and pressure).

Table 2-3: EU (2008) Air Quality Standards for the Protection of Vegetation

| Air Pollutant | EU (2008) Air Quality Standard | Standard Adopted for Assessment; Annual Average |
|---|---|---|
| $SO_2$ | 20 µg/m$^3$, annual | 7.8 ppb at 30 °C |
| $NO_x$ | 30 µg/m$^3$, annual | 16.2 ppb at 30 °C |

Air dispersion models calculate surface deposition for airborne substances using an airborne concentration near ground-level, a deposition velocity for the substance of interest, and other parameters (Seinfeld and Pandis, 2016). These parameters are difficult to accurately quantify, and therefore the standards for deposition have greater uncertainties than the standards based on airborne concentrations only.

## 2.5 Land Surface Protection Standards

Aside from particulate matter, there are no accepted or commonly applied standards for assessing deposition of air pollutants on land surfaces, such as Burrup Peninsula Aboriginal rock art. The Government of WA Murujuga Rock Art Strategy (2019) indicates further research is needed in this area.

While this assessment report provides results for $NO_2$ and $SO_2$ deposition, no assessment, or commentary is provided about the potential impacts on rock art. In this case, model results for deposition were provided primarily for comparisons with other results obtained from measurements.

# 3. Existing Air Quality

## 3.1 Overview

The purpose of this section is to describe existing air quality in the Burrup Peninsula region, primarily by a review of Woodside ambient air quality monitoring data. Local meteorology is important for developing an understanding of air quality on the Burrup Peninsula and the surrounding region; a review is provided in Appendix B. Local Meteorology.

Woodside established the Burrup Ambient Air Monitoring Program (BAAMP) in 2008, which continued to 2011. As part of the Pluto project, Woodside continued the monitoring program to the end of 2015 (Jacobs, 2016). Prior to these more recent monitoring programs, the Pilbara Air Quality Study (PAQS) was undertaken by the Government of Western Australia (GWA) in the early 2000s (GWA, 2004), which included investigations of monitoring data. CSIRO (2006) reported on monitoring undertaken specifically to assess the potential for air pollutant impacts on petroglyphs, including measurements of gaseous and particulate pollutants, deposited dust, meteorological parameters, rainwater composition, and the deposition of nitrogen and sulfur.

The PAQS established a baseline for future assessments such as the Burrup Peninsula air pollution study by CSIRO Marine and Atmospheric Research (CSIRO, 2008), and air dispersion modelling studies to investigate the potential for air quality impacts; e.g., SKM (2009), and Air Assessments (2010b). Other similar air quality studies, and their supporting studies and reports, were completed around the same time.

The purpose of this section is to set out existing air quality for the Burrup Peninsula, with a focus on results from more recent monitoring programs that are most closely associated with current air pollution sources. More information about sources of air pollution on the Burrup Peninsula ('air emissions inventory'), and the outcomes of a risk assessment of those emissions, is provided in Section 4.2. A review of the modelling methods used to assess the emissions is provided in Section 5.2.

In summary, the review of the more recent (Woodside) air quality monitoring data for the Burrup Peninsula study area showed that $NO_2$, $O_3$, $PM_{10}$ and $PM_{2.5}$ are the highest risk air quality indicators. While $NO_2$, $O_3$ and $SO_2$ concentrations have not exceeded NEPM (Ambient Air) standards, $PM_{10}$ and $PM_{2.5}$ concentrations have exceeded the NEPM (Ambient Air) standards on several occasions each year, primarily due to dust storms or bushfires.

## 3.2 Air Quality Effects from Fires

There are a number of air quality reports that suggest bush fires noticeably influence the air quality in the Pilbara region. Air pollutant levels typically affected by bush fires are reported to be $O_3$, $PM_{10}$, carbon monoxide (CO), $NO_x$ and $NO_2$. Golder (2014) suggested that the highest $O_3$ levels detected at Karratha in 2012 may have been caused by fires rather than industrial sources (see next section).

## 3.3 Nitrogen Dioxide and Ozone

$NO_x$ and $O_3$ are key pollutants associated with the Proposal. Whilst $NO_x$ is emitted from the Proposal, $O_3$ is a more complex process. In general, $O_3$ is not emitted directly from combustion and can be generated from $NO_x$ and other pollutants such as VOCs and CO through a photochemical reaction that occurs in the presence of ultraviolet light (Seinfeld and Pandis, 2016). More information about $O_3$ is provided in the last paragraph of this section.

The entire BAAMP dataset of hourly average $NO_x$ and $O_3$ acquired from 2008 to 2015 was re-analysed for this project. $NO_x$ is an expression of the total amount of both nitric oxide (NO) and $NO_2$ in a gas, with the mass of $NO_x$ calculated by assuming that all of the NO has been oxidised to $NO_2$. Data capture for each pollutant, for each location, was an important consideration in the review. The results confirmed what was found in the previous reviews by Golder (2014b); i.e. that $NO_2$ is typically observed well below the relevant NEPM (Ambient Air Quality) standard of 120 ppb for $NO_2$. (There is no ambient air quality standard for NO.) The monitoring results showed that $O_3$ is a higher risk air pollutant for the Burrup Peninsula based on relative comparisons with the corresponding NEPM (Ambient Air Quality) standard of 100 ppb.

The monitoring results showed higher $O_3$ concentrations in Dampier and Karratha in comparison with $NO_2$. The opposite was the case for the Burrup Road ('Burrup') station, located closer to the sources. An interpretation is $NO_x$, assumed to be emitted primarily by Woodside sources, was dispersed to lower concentrations by the time it reached the townships of Dampier and Karratha. Therefore, there was less $NO_x$ in the townships to destroy the $O_3$ that built up to higher concentrations there. A review of ambient monitoring data between 2010-2013 by Golder (Golder, 2014) identified four small exceedances only of the NEPM (Ambient Air Quality) standard for maximum 4-hourly average $O_3$ concentration (80 ppb), which all occurred on 24 and 26 October 2012. A detailed analysis by Golder (2014) could not determine the source of this anomaly.

BAAMP data capture for $NO_2$ and $O_3$ for the three monitoring stations is set out in the tables overleaf for 2009-2015. In the tables, data capture less than 80% is indicated in red. Years for which no measurements occurred are indicated by 'ND' (No Data). Annual and campaign data capture results are provided for $O_3$.

Table 3-1: Karratha Air Quality Monitoring – Data Capture $NO_2$ and $O_3$

| Substance | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|
| $NO_2$ | 91.8% | 93.1% | 92.4% | 94.8% | 94.4% | 91.5% | 94.6% |
| $O_3$ | 70.8% (year)<br>94% (1 April to 31 Dec) | 94.3% | 90.6% | 90.1% | 91.3% | 89.0% | 91.2% |

Table 3-2: Dampier Air Quality Monitoring Results – Data Capture $NO_2$ and $O_3$

| Substance | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|
| $NO_2$ | 89.2% | 86.9% | 86.9% | 87.4% | 92.2% | 89.6% | 92.4% |
| $O_3$ | 3% (year)<br>51% (10 Dec to 31 Dec) | 90.9% | 95.4% | 94.5% | 95.3% | 92.5% | 95.9% |

Table 3-3: Burrup Road Air Quality Monitoring Results – Data Capture $NO_2$ and $O_3$

| Substance | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|
| $NO_2$ | 82.7% | 91.5% | 84.0% | 88.4% | 94.7% | 92.6% | 91.3% |
| $O_3$ | 8.8% (year)<br>94.3% (24 Oct to 27 Nov.) | ND | ND | ND | ND | ND | ND |

Statistical summaries of the BAAMP results determined from hourly average $NO_2$ concentrations for the three monitoring locations are illustrated in Figure 3-1 (Karratha), Figure 3-2 (Dampier), and Figure 3-3 (Burrup). The statistics determined from the hourly averages are: maximum, 99.9$^{th}$ percentile, etc., down to the median and annual averages.

The NEPM (Ambient Air Quality) maximum hourly average $NO_2$ standard is 120 ppb, and the annual average standard is 30 ppb. Inspection of the maximum hourly average and annual average $NO_2$ concentrations (ppb) for the years shown in Figure 3-1 (Karratha), Figure 3-2 (Dampier), and Figure 3-3 (Burrup), demonstrate clearly that there have been no exceedances of any $NO_2$ standards over the monitoring period of several years. This includes 2014 when the Pluto LNG Development Plant (PLP) had ramped up to full production, and the

Karratha Gas Plant (KGP) at the NWS Project was operating to capacity. Statistical summaries of results for hourly average $O_3$ concentrations are shown for the two monitoring locations where data capture was adequate: Karratha (Figure 3-4) and Dampier (Figure 3-5). The corresponding NEPM (Ambient Air Quality) standard (maximum hourly average, 100 ppb) was not exceeded in any hour measured over 2009-2015.

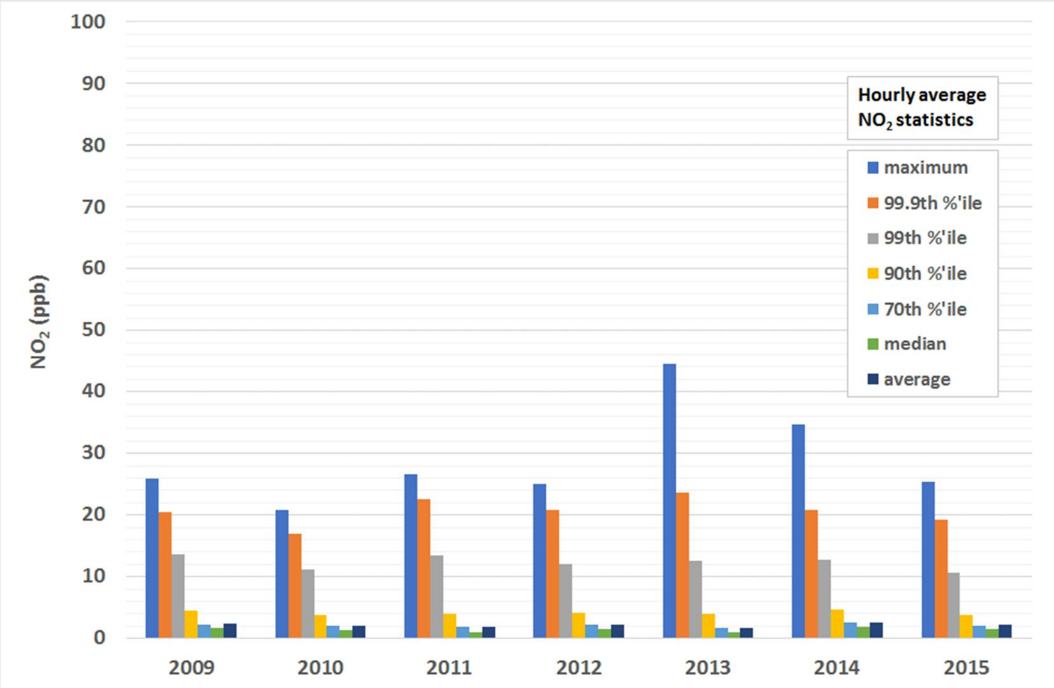



Figure 3-1: Woodside Air Quality Monitoring Results 2009-2015: Karratha $NO_2$

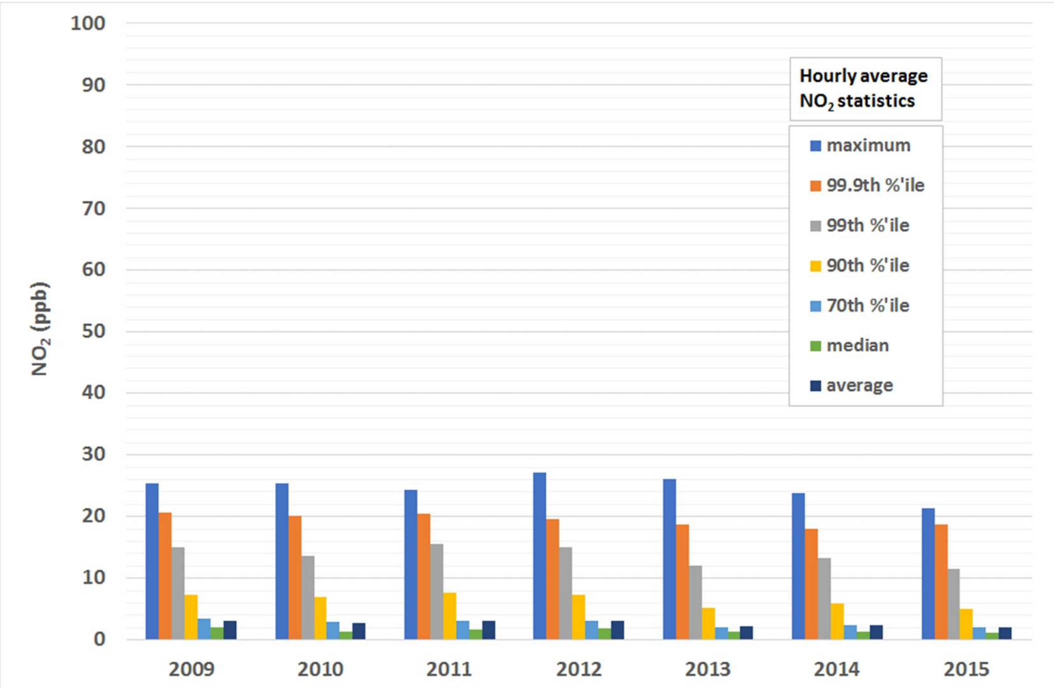



Figure 3-2: Woodside Air Quality Monitoring Results 2009-2015: Dampier $NO_2$

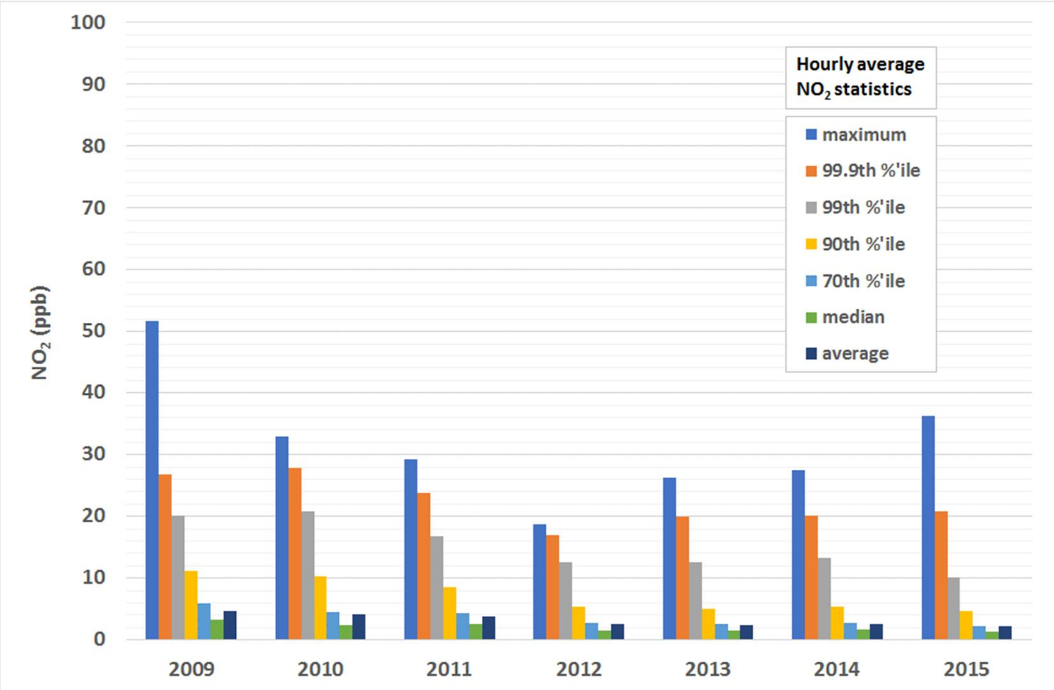



Figure 3-3: Woodside Air Quality Monitoring Results 2009-2015: Burrup $NO_2$

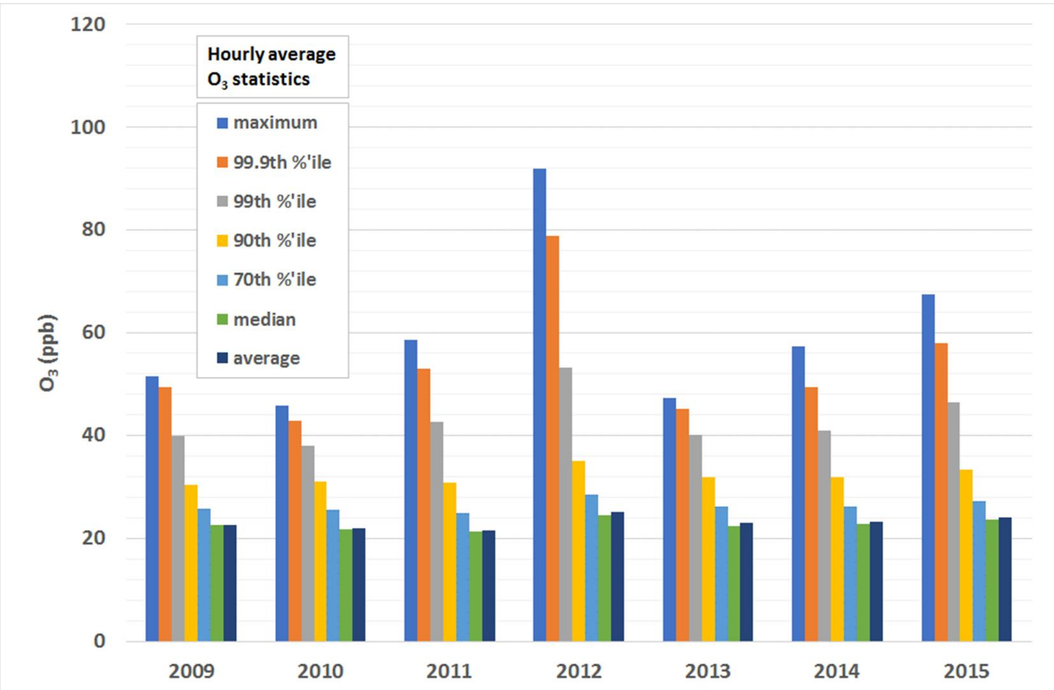



Figure 3-4: Woodside Air Quality Monitoring Results 2009-2015: Karratha $O_3$

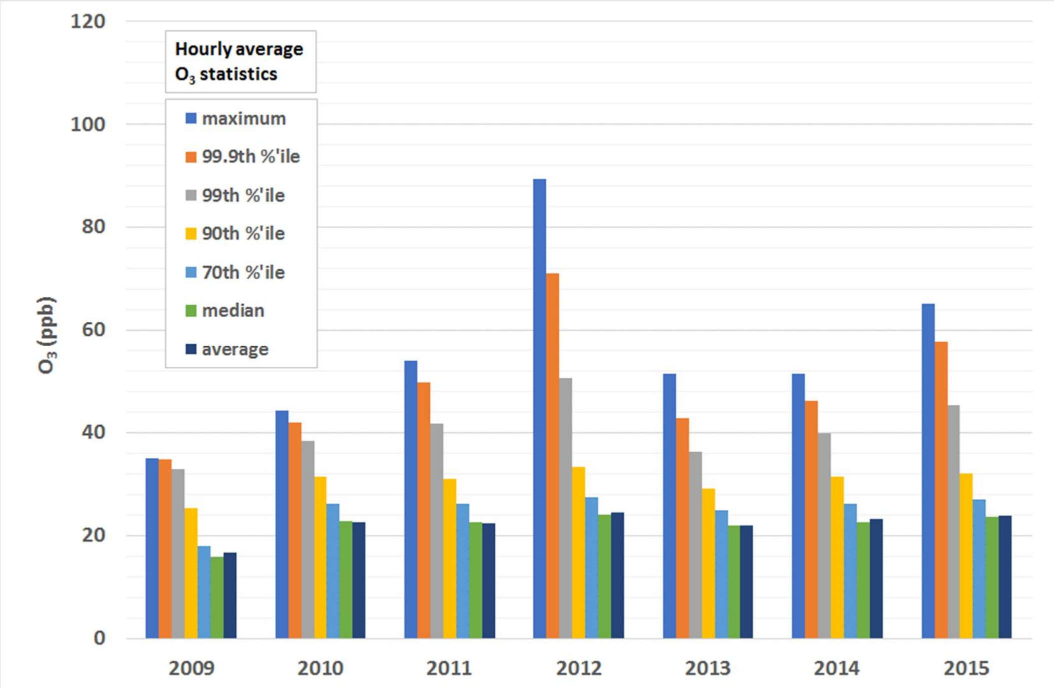



Figure 3-5: Woodside Air Quality Monitoring Results 2009-2015: Dampier $O_3$

Some additional commentary is provided about the $O_3$ observations. In the Burrup region, which is exposed to prevailing westerly winds from over the Indian Ocean, large fractions of the measured $O_3$ would be of marine (oceanic) origin, with some of this $O_3$ brought down to sea level due to mixing of air from the free troposphere into the marine boundary layer; e.g., see Ayers et al. (1992). For example, at Cape Grim in north-west Tasmania, during marine baseline conditions when the air is almost purely of Southern Ocean origin, the $O_3$ concentrations range from approximately 15-20 ppb in summer to 30-35 ppb in winter (Galbally et al., 1986; Oltmans et al., 2006). Emissions of $NO_x$ over land has the effect of destroying $O_3$ near the $NO_x$ sources, lowering its concentrations there; e.g., Galbally et al. (1986). From a review of the literature, Pilbara air at sea level should contain baseline (oceanic) $O_3$ ranging from approximately 15 ppb to 30 ppb, depending on the season. This means that approximately 25%-50% of the higher $O_3$ concentrations observed on the peninsula would have been due to natural, background levels. Isolated, elevated levels of short-term average $O_3$ concentrations would be due to contributions from a combination of $NO_x$, hydrocarbon and other emissions from bushfires and controlled burns, and industrial sources, with emissions from shipping and road vehicles contributing also.

## 3.4 Hydrocarbons – Benzene, Toluene, and Xylenes

A statistical analysis was undertaken for the whole benzene, toluene and xylene (BTX) ambient air monitoring dataset (hourly averages), which were measured at Burrup ambient air monitoring stations between 2008-2015, and Dampier and Karratha ambient air monitoring stations over 2008-2010. A summary of the key findings is provided in the following paragraphs.

**Benzene.** Maximum hourly average concentrations measured at Dampier and Karratha over 2008-2010 (approximately 11,000-12,000 hourly averages) never exceeded 3 ppb. For comparison, the corresponding NSW EPA (2016) assessment criterion is 9 ppb (NSW DEC, 2016); see Section 2.2 for more detail on relevant assessment criteria. The measured 90$^{th}$ percentile hourly average benzene concentrations at both locations was 0.1 ppb. There were some exceedances of the NSW EPA (2016) assessment criterion for benzene (9 ppb) at the two Burrup monitoring stations: 14 hours at ‘Burrup 1’ (0.03% of total hours), and 12 hours at ‘Burrup 2’ (0.04% of total hours). When assessing these exceedances it is relevant to consider that there were very few instances and they are unlikely to impact on sensitive receptors. The NEPM (Air Toxics) MIL for benzene is 3 ppb as an annual average and from the ambient monitoring results the annual average benzene is typically less than 0.1 ppb.

**Toluene and Xylenes.** From a review of all ambient air quality monitoring results over 2008-2015 for all monitoring locations, toluene and xylenes were found to be lower levels than benzene. This is based on analysis of the concentrations and comparisons with relevant air quality standards. Therefore, benzene could be assigned as a 'trigger pollutant' for the BTX group; i.e. if benzene does not cause air quality impacts then it is unlikely that any other of the BTX components will cause air quality impacts.

The BAAMP results for data capture for BTX are listed in the tables below for: Karratha (Table 3-4), Burrup (Table 3-5), and Dampier (Table 3-6). Years for which no measurements occurred are indicated by 'ND' (i.e. no data).

Table 3-4: Karratha Air Quality Monitoring – Data Capture for BTX

| Substance | 2009 | 2010 | 2011 |
|---|---|---|---|
| **Benzene** | 91% | 32% | ND |
| **Toluene** | 91% | 32% | ND |
| **Xylene** | 91% | 32% | ND |

Table 3-5: Burrup Air Quality Monitoring – Data Capture for BTX

| Substance | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|
| **Benzene** | 90% | 89% | 72% | 75% | 75% | 77% | 73% |
| **Toluene** | 90% | 89% | 72% | 75% | 75% | 77% | 70% |
| **Xylene** | 88% | 84% | 70% | 63% | 75% | 74% | 62% |
| **Benzene 2*** | ND | 57% | 81% | 76% | 76% | 73% | 78% |
| **Toluene 2*** | ND | 57% | 81% | 76% | 76% | 73% | 78% |
| **Xylene 2*** | ND | 57% | 81% | 76% | 76% | 73% | 78% |

*Duplicate BTX samples undertaken at Burrup Road monitoring station from 2010 onwards; therefore the true data capture is higher than indicated here.

Table 3-6: Dampier Air Quality Monitoring – Data Capture for BTX

| Substance | 2009 | 2010 | 2011 |
|---|---|---|---|
| **Benzene** | 91% | 35% | ND |
| **Toluene** | 91% | 35% | ND |
| **Xylene** | 91% | 35% | ND |

A statistical summary of the hourly average BTX monitoring results for 2009, the only year where data capture was greater than 75% for each station, is provided in Table 3-7. The statistics listed are maxima, 99.9 percentile hourly average, etc. The results show the BTX concentrations were very low for the great majority of time (99.9% of hours). The summaries are based on data from 2009 until April 2015 (at the time of writing this air quality impact assessment, the data post-April 2015 were unavailable for analysis). In 2015, BTX was measured at Burrup only, with data available for analysis to April 2015.

Table 3-7: Air Quality Monitoring 2009 – BTX Statistics at Karratha, Burrup and Dampier

| Hydrocarbon | Benzene (ppb) | | | Toluene (ppb) | | | Xylenes (ppb) | | |
|---|---|---|---|---|---|---|---|---|---|
| **Station** | Karratha | Burrup | Dampier | Karratha | Burrup | Dampier | Karratha | Burrup | Dampier |
| **Data Capture** | 91% | 90% | 91% | 91% | 90% | 91% | 91% | 88% | 91% |
| **Max.** | 3.45 | 12.29 | 0.91 | 37.44 | 65.80 | 0.95 | 0.93 | 6.83 | 0.58 |
| **NSW Assessment Criterion** | 9 | | | 90 | | | 40 | | |
| **99.9th percentile 1h avg.** | 0.37 | 8.77 | 0.29 | 3.88 | 13.78 | 0.34 | 0.51 | 3.92 | 0.27 |
| **99th percentile 1h avg.** | 0.19 | 0.99 | 0.12 | 0.75 | 2.36 | 0.14 | 0.21 | 0.55 | 0.07 |
| **90th percentile 1h avg.** | 0.07 | 0.31 | 0.06 | 0.13 | 0.17 | 0.05 | 0.07 | 0.18 | 0.03 |
| **70th percentile 1h avg.** | 0.04 | 0.08 | 0.03 | 0.05 | 0.03 | 0.02 | 0.05 | 0.03 | 0.02 |

## 3.5 Airborne Particulate Matter as $PM_{10}$ and $PM_{2.5}$

Although PM is not a high emission from LNG facilities, relative to other emissions, the existing environment is characterised by high levels of PM, relative to air quality standards, which is relevant to providing context of the existing air quality.

Rio Tinto conducts PM monitoring at Dampier, Karratha, King Bay, Wickham, Point Samson and Roebourne (Rio Tinto, 2015). Monitoring reports were not available for review at the time of writing, however, recent data are published online and can be used for assessment (Pilbara Iron, 2019). On the 9th May 2019, very high $PM_{10}$ (particulate matter less than 10 µm in diameter) concentrations were observed at Dampier, Karratha, Wickham, Point Samson, and Roebourne. The strong correlation between these measurements, taken by several monitors on this day, suggests a dust storm was the probable cause. A review of 30 days of $PM_{10}$ data for Karratha (10 April to 10 May 2019) indicates the 'clean air background' $PM_{10}$ levels are approximately 10 µg/m$^3$, with a median or average closer to approximately 20 µg/m$^3$. These values are typical of $PM_{10}$ concentrations measured in other parts of Australia.

SKM (2005) provided a useful time series plot of daily $PM_{10}$ measured at Dampier by Hamersley Iron over 2001-2004. Some broad conclusions about the variations in $PM_{10}$ on the Burrup Peninsula can be drawn by inspection of this relatively long-term record. The record provides information about the clean-air background and air quality impacts, with the latter likely due to local particulate emissions from bushfires, dust storms, and some industry. The $PM_{10}$ concentrations peaked during higher wind speeds in January, with typical daily concentrations ranging between 30-40 µg/m$^3$. Exceedances of the NEPM (Ambient Air Quality) standard of 50 µg/m$^3$ ranged from approximately 5-10 exceedances per year. Mid-year, during the dry season with corresponding lower wind speeds, typical daily concentrations varied between 10-20 µg/m$^3$.

The Pluto LNG Development Cumulative Air Quality Study (SKM, 2006) reviewed monitoring results for particulate matter as $PM_{10}$. The study found that existing industrial activity in the Pilbara air shed mainly contributed to emissions of $PM_{2.5}$ and $PM_{10}$, with PM exceeding NEPM (Ambient Air Quality) standards. SKM (2006) stated that higher $PM_{10}$ concentrations were observed on days of high wind speeds. On these days the $PM_{2.5}$/$PM_{10}$ fraction was reduced from approximately 50% to approximately 20%, indicating wind-blown dust caused the high $PM_{10}$ concentrations, as the small particle fraction is higher in smoke emissions.

The review by Air Assessments (2010a) indicated that measurements of $PM_{10}$ at Dampier tend to be high, and "exceed the NEPM (Ambient Air Quality) standard". Air Assessments (2010a) indicated the major sources of particulate matter in the Burrup region are: smoke from fires, dust from wind storms and iron ore stockpiling, and ship-loading operations at the ports of Dampier and Cape Lambert. Emissions of particulate matter from the on-shore gas plants were recognised as small and of little relevance in comparison with these other sources.

Golder (2014) reviewed $PM_{2.5}$ monitoring results acquired at Karratha, Dampier and Burrup monitoring stations from December 2011 to December 2012. Although a number of exceedances of NEPM standards for $PM_{2.5}$ were recorded at the three locations, based on back-trajectory analysis, flare rate, black smoke and $PM_{2.5}$ concentrations, Golder (2014) concluded there was sufficient evidence to suggest that air emissions from the Pluto LNG Project were not associated with the exceedances. Also, iron ore handling was stated as a probable cause of exceedences of $PM_{2.5}$ standards detected at Dampier monitoring station.

## 3.6 Sulfur Dioxide

A review of $SO_2$ monitoring results on Burrup Peninsula was undertaken by Air Assessments (2010b). Conservative assumptions were applied to several fixed industrial emissions sources, noting very low sulfur in fuel concentrations. For this reason, estimates for exhaust $SO_2$ for most sources are at or near the limit of detection, thus a reasonable estimate for an annual average would be 0.1 ppb (the NEPM (Ambient Air Quality) standard for annual $SO_2$ is 20 ppb). Maximum hourly average concentrations would not be expected to exceed 10 ppb for most locations away from engine exhausts on ships, the most significant source in the region. The comparable maximum hourly average NEPM (Ambient Air Quality) standard is 200 ppb.

## 3.7 Deposition Fluxes of Nitrogen and Sulfur

On the Burrup Peninsula, Gillett (2008) determined total deposition flux of nitrogen and sulfur at a number of measurement sites in 2004/2005 and 2007/2008 by calculating the wet and dry deposition of all nitrogen and sulfur species in the gas and aqueous (rainwater) phases. This included $NO_2$, $SO_2$, nitric acid and ammonia gases, and some other species in rainwater. The study showed that the total wet and dry deposition flux of nitrogen and sulfur ranged from 19.8-31.6 milliequivalents per square metre per year ($meq/m^{-2}/yr^{-1}$) over the two monitoring periods from 2004 to 2008. Units of '$meq/m^2/year$' were used to enable comparisons with previous monitoring results.

Dry deposition of $NO_2$ was estimated to contribute to between 16% and 36% of total deposition flux in the region (Gillett, 2008), and $SO_2$ 6% to 8% based on 2004/2005 data. The 2007/2008 data ranged from 12% to 20% $NO_2$ contribution to total deposition flux, and from 4% to 7% for $SO_2$ (Gillett, 2008).

Woodside engaged CSIRO carried out a study to determine the nitrogen deposition flux (between February 2012 and June 2014) on and around the Burrup Peninsula before and after the commissioning of the Pluto LNG Plant (Gillett, 2014).

A summary of results for the ranges of total measured nitrogen (N) and sulfur (S) fluxes is provided in Table 3-8. Inspection of these results shows they have been reasonably consistent over a long period of sampling.

Table 3-8: Summary of Results for Burrup N and S Deposition Monitoring Programs

| Monitoring Program | Analyte | Range of Deposition Excl. Background Sites | Dry Deposition $NO_2$ Fraction |
|---|---|---|---|
| 2004–2005 and 2007–2008 | Total nitrogen and sulfur | 19.8 – 31.6 $meq/m^2/year$ | 16%-36% of total N & S |
| 2008–2009 | Total nitrogen | 18.4 – 32.9 $meq/m^2/year$ | 19%-29% of total N only |
| 2012–2014 | Total nitrogen | 17.1 – 28.8 $meq/m^2/year$ | 17%-34% of total N only |

# 4. Emissions Sources and Estimates

## 4.1 Overview

The principal emissions from the LNG process arise from combustion of natural gas. The most significant products of gas combustion include: carbon dioxide ($CO_2$), $NO_x$, carbon monoxide (CO) and unburnt hydrocarbons (VOCs). There may also be traces of particulate and $SO_2$ but such emissions are generally considered negligible due to the firing of very low sulfur content natural gas in a controlled environment. $NO_x$ will be the predominant pollutant of interest.

To determine what the key air pollutants and sources are for the Proposal, in terms of potential impacts, a broad-level risk assessment was conducted. The purpose of the assessment was to determine the relative risk of air pollutants and emission sources in proximity to the Proposal, with a focus on the Burrup Strategic Industrial Area and the surrounding region. This assessment reviewed previous air assessments and other relevant publicly available information, as a part of validation of the existing air quality environment and model inputs. The outcomes of this risk assessment identified what facilities should be included in the modelling and what substances should be modelled.

Emission inventories were developed in consultation with Woodside, based on reasonable and conservative emission estimates, consideration of available datasets, design data, and monitoring data for the Proposal. Representative third-party emissions were based on consideration of publicly available literature and input following consultation with some external parties.

## 4.2 Outcomes of Risk Assessment

A risk assessment based on a broad survey of Burrup Peninsula air quality studies, emission inventories and other information, was conducted to determine key air pollutants and their sources. The assessment determined that the key substance for assessment was $NO_x$, with the highest $NO_2$ and $O_3$ concentrations to be determined using photochemical modelling.

An early aggregated air emissions inventory for the Pilbara region was developed by SKM (2003) for the WA Department of Environmental Protection. The inventory included emissions from facilities with stacks not reportable to the National Pollutant Inventory (NPI), biogenic emissions of $NO_x$ from soils, hydrocarbons from vegetation, and $PM_{10}$ from a variety of natural sources. As mentioned in Section 3.1, the GWA (2004) PAQS objectives included developing understanding of air quality in the Karratha-Dampier coastal areas and the meteorology affecting air quality. These earlier air quality surveys were the foundation for many modelling studies; e.g., SKM (2009), with the elaborate review and modelling by Air Assessments (2010b) capping this first assessment phase for Burrup Peninsula. Further details about a string of previous modelling studies used as the basis for this project are provided in the review of modelling (Section 5.2).The major sources of airborne particulate matter in the region are smoke from bushfires and dust raised during high winds. Particulate emissions from the Proposal are negligible and unlikely to cause measurable air quality effects. As such, the particulate assessment parameters $PM_{10}$ and $PM_{2.5}$ were excluded from the modelling study.

Based on the risk assessment, VOCs were excluded from the assessment for the Proposal. Monitoring undertaken during 2009-2015 showed that emissions of BTX, as an indicator of VOCs, had insignificant air quality effects at the sensitive receptor locations of Dampier and Karratha. For most of the time, BTX concentrations were nil at those locations. It was concluded that formaldehyde would have low concentrations that were approximately the same as benzene. However, estimates for total VOC emissions were included in the modelling as a part of the input for the photochemical modelling.

None of the previous air quality studies had identified $H_2S$ as an elevated-risk pollutant, therefore it was eliminated as a substance of interest from this assessment.

Regional (beyond the Burrup Peninsula) emission sources were excluded from the air quality assessment because previous modelling studies demonstrated that while there may be some transfer of air pollutants, these would be minimal, given the distance. The Air Assessments (2012) results clearly show that air quality effects on the Burrup Peninsula are primarily due to sources on the Burrup Peninsula. In any case, the air quality effects from smaller or lower risk sources were accounted for to some extent by the inclusion of background air pollutant concentrations in the modelling. The lower risk sources fell into these classes:

- Too small as emitters by mass.
- Too distant for the dispersed pollutants to make a significant contribution to ambient levels around the Burrup Peninsula; e.g. beyond approximately 50 km from Dampier and Karratha.
- Substances emitted not associated with air quality effects caused by emissions from the Proposals processing facilities; e.g. $NH_3$ and particulate matter from ship-loading.

The risk assessment also demonstrated that emissions from regional shipping have the potential to make a significant contribution to ambient $NO_x$ levels and need to be considered in the modelling.

Based on the findings of the risk assessment, 94 existing air pollutant “point” sources (stack) on the Burrup Peninsula were identified to be included in the modelling. A summary of these point sources, with total $NO_x$ emissions (g/s), is presented in Table 4-1. Emission source locations are shown in Figure 4-1.

Table 4-1: Summary of Current Air Emissions Sources Considered in the Modelling Assessment

| Industrial Facility | Number of Emission Sources | Total $NO_x$ Emission Rate (g/s) |
|---|---|---|
| Karratha Gas Plant | 44 | 281 |
| Pluto LNG Plant | 11 | 34.1 |
| Yara Technical Ammonium Nitrate and Liquid Ammonium Plant | 4 | 30.3 |
| Pilbara Iron Yurralyi Maya Power Station | 5 | 28.2 |
| Santos Devil Creek Power Station | 7 | 4.5 |
| ATCO Karratha Power Station | 2 | 12.0 |
| EDL West Kimberley Power Plant | 3 | 1.2 |
| All shipping berths on the Burrup Peninsula | 13 | 26.0 |
| All shipping berths at Cape Lambert | 5 | 10.0 |

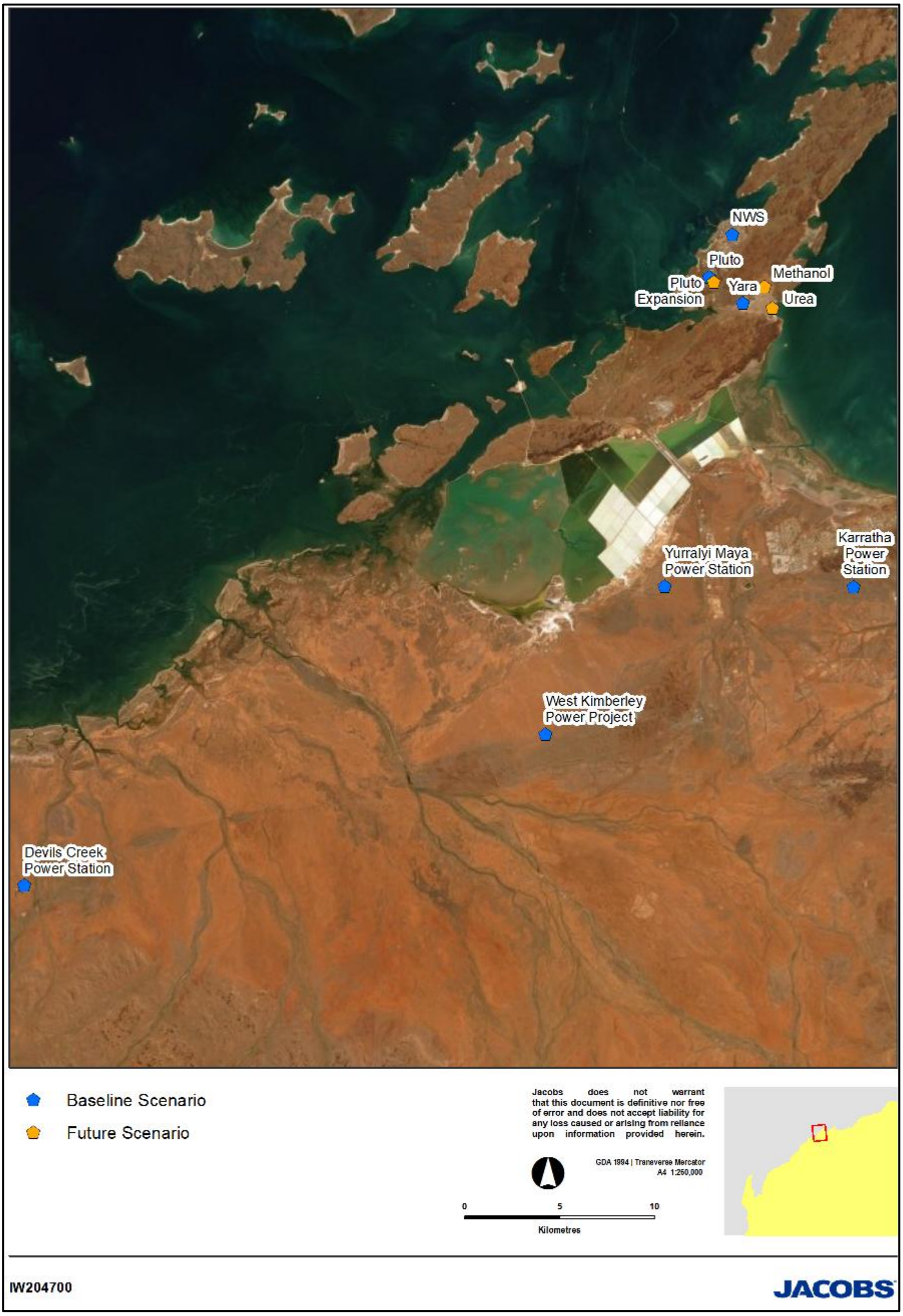



Figure 4-1 Locations of Modelled Emissions sources

## 4.3 Model Scenarios

The Proposal does not include the material additional or additive processing or power generation equipment with respect to emissions rates. Therefore, emissions are expected to be similar to or less than that from the Existing NWS Project. However, as the Proposal is implemented Woodside has proposed emission reduction opportunities to reduce NOx emissions from the Proposal. Therefore, modelled scenarios are based on cumulative impacts and emissions reduction scenarios.

Five air emissions scenarios were tested by modelling to support the Proposal. These scenarios are detailed in Table 4-2; further details about specific sources for modelling are set out in the following sub-sections.

Table 4-2: NWS Extension Air Emissions Scenarios for Assessment

| Scenario | Description and Emission Sources |
|---|---|
| (1) Current Baseline (CBM)<br><br>Near-term, most likely | The CBM scenario represents all current air pollutant sources,. There are existing air quality effects that are demonstrated by the current phase.<br>CBM represents the existing air emissions scenario mostly applicable to the BSIA and the region to use as a baseline for assessment, including air emissions estimates for these facilities currently operating:<br>· KGP<br>· PLP<br>· Yara Technical Ammonium Nitrate and Liquid Ammonium Plant<br>· Pilbara Iron Yurralyi Maya Power Station<br>· Santos Devil Creek Power Station<br>· ATCO Karratha Power Station<br>· EDL West Kimberley Power Plant<br>· All shipping berths on the Burrup Peninsula<br>· All shipping berths at Cape Lambert<br>CB represents a current and near-term operating scenario and could be described as the near term 'most likely' case (EPA, 2019). |
| (2) CBM with KGP Improvement Opportunities (KIO)<br><br>Best-case | The purpose of the KIO scenario was to illustrate the potential future effects of the Proposal in the frame of current emissions in the region, with no other expansion of industry on Burrup Peninsula.<br>The KGP data for modelling were modified to reflect likely improvement opportunities representing feasible and significant $NO_x$ reduction options.<br>The KIO scenario could be described as a 'best case' considering emissions reduction opportunities, and there is no cumulative effects from proposed future developments. |
| (3) Future SIA State – Existing and Approved (FBSIA E&A)<br><br>Long-term, most likely | The purpose of FBSIA- E&A is to illustrate the potential future effects of the existing and approved sources, in the frame of current emissions in the region.<br>FBSIA E&A represents Current Baseline, NWS Extension Project with implementation of improvement opportunities, expansion of Pluto (Train 2), however excludes recently referred Urea and Methanol proposals (which are currently proposed but not referred)<br>The FBSIA E&A is the most likely long term. |
| (4) Future Burrup Strategic Industrial Area State (FBSIA)<br><br>Worst-case | FBSIA represents the future state aligned with current operations, but with the proposed Burrup SIA future Pluto Expansion, and indicative representation of Urea and Methanol proposals. The FBSIA scenario represents best estimates of potential future worst-case air quality on Burrup Peninsula. |

| Scenario | Description and Emission Sources |
|---|---|
| | Assumes all future developments approved and NWS operating at current levels.. The FBSIA scenario could be described as a 'worst case' (EPA, 2019). |
| (5) Future Burrup Strategic Industrial Area (State) with KGP Improvement Opportunities ('FBSIA-KIO')<br><br>Long-term, possible | The FBSIA-KIO scenario represents KGP Improvement Opportunities, inclusive of indicative expansion on the Burrup Peninsula.<br>FBSIA-KIO represents a realistic, cumulative scenario of the Proposal including implementation of KGP improvement opportunities, future developments represented by the Pluto expansion initial design, and indicative representation of Urea and Methanol proposals, and continuing operation of other current facilities.<br>The FBSIA-KIO scenario could be described as a 'most likely' (EPA, 2019) air emissions scenario for the longer term. |

## 4.4 Existing Emission Sources

### 4.4.1 Karratha Gas Plant

The existing key KGP air emission sources comprise:

- Four domestic gas (Domgas) GTCs.
- Trains 1, 2 and 3 - each consisting of five GTCs, with one GTC exhaust per train with integrated Acid Gas Removal Unit (AGRU) $CO_2$ vent stack system.
- Trains 4 and 5 – each consisting of two GTCs, with one machine each including two WHRU exhaust stacks.
- 10 power generation gas turbines, with two providing integrated AGRU $CO_2$ vent stack systems for LNG Trains 4 and 5.

Air emission parameters for the KGP sources are listed in Table 4-3. The existing KGP emissions data are relevant for the scenarios CBM and FBSIA.

Table 4-3: NWS Karratha Gas Plant Air Emissions Parameters

| Emissions Source | Stack Height (m) | Stack Radius (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| Domgas GTC 1 | 24.0 | 0.98 | 42.3 | 815 | 0.01 | 3.81 | 0.12 | 0.01 |
| Domgas GTC 2 | 24.0 | 1.40 | 43.4 | 764 | 0.01 | 12.02 | 0.25 | 0.01 |
| Domgas GTC 3 | 24.0 | 0.98 | 42.3 | 815 | 0.01 | 3.81 | 0.12 | 0.01 |
| Domgas GTC 4 | 24.0 | 1.40 | 43.4 | 764 | 0.01 | 12.02 | 0.25 | 0.01 |
| TRAIN 1 – GTC 1 | 40.0 | 1.94 | 19.5 | 777 | 0.01 | 10.15 | 0.27 | 0.01 |
| TRAIN 1 – GTC 2 | 40.0 | 1.94 | 19.5 | 782 | 0.01 | 9.68 | 0.27 | 0.01 |
| TRAIN 1 – GTC 3 | 40.0 | 1.80 | 22.7 | 767 | 0.01 | 9.81 | 0.27 | 0.01 |
| TRAIN 1 – GTC 4 | 40.0 | 1.80 | 21.7 | 771 | 0.01 | 9.19 | 0.27 | 13.5 |
| TRAIN 1 – GTC 5 | 40.0 | 1.36 | 18.9 | 795 | 0.01 | 3.55 | 0.12 | 0.01 |
| TRAIN 2 – GTC 1 | 40.0 | 1.94 | 19.5 | 777 | 0.01 | 10.15 | 0.27 | 0.01 |
| TRAIN 2 – GTC 2 | 40.0 | 1.94 | 19.5 | 782 | 0.01 | 9.68 | 0.27 | 0.01 |

| Emissions Source | Stack Height (m) | Stack Radius (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| TRAIN 2 – GTC 3 | 40.0 | 1.80 | 22.7 | 767 | 0.01 | 9.81 | 0.27 | 0.01 |
| TRAIN 2 – GTC 4 | 40.0 | 1.80 | 21.7 | 771 | 0.01 | 9.19 | 0.27 | 13.5 |
| TRAIN 2 – GTC 5 | 40.0 | 1.36 | 18.9 | 795 | 0.01 | 3.55 | 0.12 | 0.01 |
| TRAIN 3 – GTC 1 | 40.0 | 1.94 | 19.5 | 777 | 0.01 | 10.15 | 0.27 | 0.01 |
| TRAIN 3 – GTC 2 | 40.0 | 1.94 | 19.5 | 782 | 0.01 | 9.68 | 0.27 | 0.01 |
| TRAIN 3 – GTC 3 | 40.0 | 1.80 | 22.7 | 767 | 0.01 | 9.81 | 0.27 | 0.01 |
| TRAIN 3 – GTC 4 | 40.0 | 1.80 | 21.7 | 771 | 0.01 | 9.19 | 0.27 | 13.5 |
| TRAIN 3 – GTC 5 | 40.0 | 1.36 | 18.9 | 795 | 0.01 | 3.55 | 0.12 | 0.01 |
| TRAIN 4 – GTC 2 | 40.1 | 3.00 | 23.8 | 811 | 0.01 | 5.79 | 0.64 | 0.01 |
| TRAIN 4 – GTC 1 WHRU1 | 40.1 | 1.45 | 50.9 | 588 | 0.01 | 3.13 | 0.29 | 0.01 |
| TRAIN 4 – GTC 1 WHRU2 | 40.1 | 1.45 | 50.9 | 521 | 0.01 | 3.13 | 0.29 | 0.01 |
| TRAIN 5 – GTC 2 | 40.1 | 3.01 | 23.7 | 811 | 0.01 | 7.18 | 0.64 | 0.01 |
| TRAIN 5 – GTC 1 WHRU 1 | 40.1 | 1.45 | 50.9 | 523 | 0.01 | 3.11 | 0.29 | 0.01 |
| TRAIN 5 – GTC 1 WHRU 2 | 40.1 | 1.45 | 50.9 | 483 | 0.01 | 3.11 | 0.29 | 0.01 |
| Stabiliser 2 Furnace Stack | 33.0 | 0.73 | 39.2 | 699 | 0.01 | 2.56 | 0.01 | 0.01 |
| Stabiliser 4 Furnace Stack | 33.0 | 0.73 | 39.2 | 668 | 0.01 | 2.17 | 0.01 | 0.01 |
| Stabiliser 5 Furnace Stack | 33.0 | 0.73 | 39.2 | 659 | 0.01 | 2.23 | 0.01 | 0.01 |
| Stabiliser 6 Furnace Stack | 32.6 | 0.73 | 39.2 | 630 | 0.01 | 1.98 | 0.01 | 0.01 |
| Power Generation GTG 1 | 40.0 | 1.98 | 20.4 | 681 | 0.01 | 11.58 | 0.24 | 0.01 |
| Power Generation GTG 2 | 40.0 | 1.98 | 21.5 | 681 | 0.01 | 12.21 | 0.24 | 0.01 |
| Power Generation GTG 3 | 40.0 | 1.98 | 20.4 | 675 | 0.01 | 8.63 | 0.24 | 0.01 |
| Power Generation GTG 4 | 40.0 | 1.98 | 21.5 | 681 | 0.01 | 12.21 | 0.24 | 0.01 |
| Power Generation GTG 5 | 40.0 | 1.98 | 20.4 | 675 | 0.01 | 8.63 | 0.24 | 0.01 |
| Power Generation GTG 6 + AGRU 4 & 5 Vent | 40.0 | 1.98 | 20.4 | 675 | 0.02 | 8.63 | 0.24 | 40.6 |
| Power Generation GTG 7 | 40.0 | 1.79 | 22.2 | 751 | 0.01 | 3.00 | 0.22 | 0.01 |
| Power Generation GTG 8 | 40.0 | 1.79 | 17.7 | 751 | 0.01 | 2.66 | 0.22 | 40.6 |
| Power Generation GTG 9 | 40.0 | 1.79 | 34.6 | 751 | 0.01 | 4.45 | 0.22 | 0.01 |
| Power Generation GTG 10 | 40.0 | 1.79 | 31.3 | 745 | 0.01 | 3.64 | 0.22 | 0.01 |
| Domgas-E Flare | 128.5 | 0.51 | 20.0 | 1273 | 0.05 | 0.28 | 0.001 | 0.58 |
| LNG Emergency Flare (representative) | 145.3 | 3.26 | 20.0 | 1273 | 1.95 | 11.32 | 0.044 | 23.42 |
| LNG-SL Flare | 56.9 | 0.28 | 20.0 | 1273 | 0.01 | 0.08 | 0.0003 | 0.17 |
| LPG-SL Flare | 56.5 | 0.21 | 20.0 | 1273 | 0.01 | 0.05 | 0.0002 | 0.10 |

| Emissions Source | Stack Height (m) | Stack Radius (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| Operations Flare | 46.8 | 0.73 | 20.0 | 1273 | 0.10 | 0.56 | 0.002 | 1.17 |
| Emissions Totals (g/s) | | | | | 2.5 | 281.1 | 9.2 | 147.5 |

#Power Generation Turbine 6 is modelled together with the AGRU vent systems 4 & 5 as a single source.

&Flares emissions are represented conservatively with elevated rate applied for KGP LNG Emergency Flare as a constant source in the model to reflect potential for frequent intermittent operation across KGP and PLP. Credible baseload flaring is assumed for other flarepoints.

Flares emissions are represented conservatively with elevated rate applied for KGP LNG Emergency Flare as a constant source in the model to reflect potential for frequent intermittent operation across KGP and PLP. Credible baseload flaring is assumed for other flare points.

### 4.4.2 Woodside Pluto Onshore LNG Plant

The Pluto gas field was discovered in April 2005 and is located on the North West Shelf of WA, approximately 190 km north-west of Dampier. The associated gas processing plant is located on the Burrup Peninsula, approximately 6 km from Dampier.

The Pluto LNG Development was approved by the State and Commonwealth governments following public environment review of the proposal in 2006. The original proposal included the construction, commissioning and operation of the Pluto LNG Development with two LNG processing trains. However, only one train was built, commissioned and operated.

The Woodside PLP air emissions parameters are listed in Table 4-4.

Table 4-4: Pluto Onshore LNG Plant Air Emissions Parameters

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| PLP Train 1 – GTC 1 WHRU 1 | 40.0 | 2.90 | 39.2 | 531.2 | 0.01 | 5.63 | 0.37 | 0.01 |
| PLP Train 1 GTC 1 WHRU 2 | 40.0 | 2.90 | 41.2 | 527.2 | 0.01 | 5.10 | 0.38 | 0.01 |
| PLP Train 1 – GTC 2 | 40.0 | 6.01 | 28.0 | 824.2 | 0.01 | 10.20 | 0.37 | 0.01 |
| PLP GTG 1 | 40.0 | 3.11 | 28.0 | 868.2 | 0.01 | 3.27 | 0.25 | 0.01 |
| PLP GTG 2 | 40.0 | 3.86 | 23.0 | 874.2 | 0.01 | 3.36 | 0.24 | 0.01 |
| PLP GTG 3 | 40.0 | 2.80 | 30.1 | 879.2 | 0.01 | 3.22 | 0.16 | 0.01 |
| PLP GTG 4 | 40.0 | 2.80 | 29.5 | 883.2 | 0.01 | 1.82 | 0.33 | 0.01 |
| PLP Train 1 - Regenerative Thermal Oxidiser | 40.0 | 2.80 | 17.7 | 394.2 | 0.01 | 0.08 | 0.42 | 0.01 |
| Flare Cold Dry | 139.5* | 1.34 | 20.0 | 1273.0 | 0.08 | 0.49 | 0.002 | 1.01 |
| Flare Warm Wet | 139.5* | 1.34 | 20.0 | 1273.0 | 0.08 | 0.49 | 0.002 | 1.013 |
| Storage and Loading Flare | 64.3* | 1.28 | 20.0 | 1273.0 | 0.08 | 0.45 | 0.002 | 0.923 |
| Emissions Totals (g/s) | | | | | 0.32 | 34.1 | 2.53 | 3.03 |

#Calculated 'Effective' stack height for flare sources; USEPA (1992); USEPA (1995).

&Flare emissions are represented conservatively with elevated rate applied for KGP Emergency Flare as a constant source in the model to reflect potential for frequent intermittent operation across the KGP and Pluto LNG Plant. Credible baseload flaring is assumed for other flare points.

### 4.4.3 Other Relevant Emission Sources

The risk assessment determined that point source (stack) emissions of $NO_x$, VOCs and other substances from the following facilities have the potential to make a significant contribution to the ground level concentrations and therefore needed to be considered in any air quality assessment:

- Yara Pilbara Fertilisers and Yara Pilbara Nitrates Technical Ammonium Nitrate (TAN)
- Pilbara Iron Yurralyi Maya Power Station
- Santos Devil Creek Power Station
- ATCO Karratha Power Station
- West Kimberley Power Plant

The Yara Pilbara Fertilisers and Yara Pilbara Nitrates TAN air emissions parameters are listed in Table 4-5.

Table 4-5: Yara Pilbara Fertilisers and Yara Pilbara Nitrates TAN Air Emissions Parameters

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| TAN Plant Stack | 54.0 | 1.4 | 27.5 | 423.0 | 0.00 | 4.2 | 0.0 | 0.0 |
| TAN power generation | 30.0 | 2.6 | 16.9 | 450.0 | 0.06 | 2.1 | 0.0 | 0.0 |
| Fertiliser Reformer | 35.0 | 3.5 | 15.0 | 413.0 | 0.91 | 17.1 | 0.23 | 0.0 |
| Fertiliser Boiler | 30.0 | 3.0 | 4.1 | 450.0 | 0.36 | 6.9 | 0.13 | 0.0 |
| Emissions totals (g/s) | | | | | 1.33 | 30.3 | 0.36 | 0.0 |

The Yurralyi Maya Power Station, owned and operated by Hamersley Iron Pty Ltd, is located approximately 17 km south of the Burrup Hub site. Key air emissions sources of the Yurralyi Maya Power Station are the gas turbines; air emissions parameters are listed in Table 4-6.

Table 4-6: Yurralyi Maya Power Station Emissions Data

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| GTG 1 | 40.0 | 3.57 | 25.7 | 722.0 | 1.0 | 5.63 | 4.0 | 0.04 |
| GTG 2 | 40.0 | 3.57 | 25.7 | 722.0 | 1.0 | 5.63 | 4.0 | 0.04 |
| GTG 3 | 40.0 | 3.57 | 25.7 | 722.0 | 1.0 | 5.63 | 4.0 | 0.04 |
| GTG 4 | 40.0 | 3.57 | 25.7 | 722.0 | 1.0 | 5.63 | 4.0 | 0.04 |
| GTG 5 | 40.0 | 3.57 | 25.7 | 722.0 | 1.0 | 5.63 | 4.0 | 0.04 |
| Emissions totals (g/s) | | | | | 5.0 | 28.2 | 20.0 | 0.20 |

The Devil Creek Gas Plant, operated by Santos (formerly Quadrant Energy), is located 48 km south west of the Burrup hub site. The Devil Creek Gas Plant equipment identified as key air emission sources for the BHSM were:

- two Solar Taurus 60 gas turbine generators of nominal 5000 kW capacity providing electrical power requirements.
- two sales gas compressors power by Solar Taurus 60 gas turbines, fitted with waste heat recovery units;
- waste gas incinerator.
- and an elevated flare and ground flare.

The associated air emissions parameters are listed in Table 4-7.

Table 4-7: Devil Creek Gas Plant Air Emissions Parameters

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| GTG 1 | 13.0 | 1.6 | 23.5 | 783.0 | 0.004 | 0.75 | 0.0 | 0.005 |
| GTG 2 | 13.0 | 1.6 | 23.5 | 783.0 | 0.004 | 0.75 | 0.0 | 0.005 |
| GTC 1 | 13.0 | 1.6 | 16.0 | 633.0 | 0.004 | 0.75 | 0.0 | 0.005 |
| GTC 2 | 13.0 | 1.6 | 16.0 | 633.0 | 0.004 | 0.75 | 0.0 | 0.005 |
| Waste Gas Incinerator | 21.0 | 1.8 | 14.0 | 1073.0 | 0.004 | 0.00 | 11.0 | 0.005 |
| Elevated Flare | 48.0 | 1.6 | 20.0 | 1273.0 | 0.004 | 0.77 | 0.0 | 0.005 |
| Ground Flare | 20.0 | 1.6 | 20.0 | 1273.0 | 0.004 | 0.77 | 0.0 | 0.005 |
| Emissions totals (g/s) | | | | | 0.028 | 4.54 | 11.0 | 0.035 |

The West Kimberley Power Station, operated by EDL Energy, is located approximately 25 km south-west of the Burrup Hub site. Air emissions parameters for the three gas turbines, are listed in Table 4-8.

Table 4-8: West Kimberley Power Project Emissions Data

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| GTG 1 | 10.0 | 1.2 | 26.5 | 700.0 | 0.002 | 0.385 | 0.0006 | 0.0025 |
| GTG 2 | 10.0 | 1.2 | 26.5 | 700.0 | 0.002 | 0.385 | 0.0006 | 0.0025 |
| GTG 3 | 10.0 | 1.2 | 26.5 | 700.0 | 0.002 | 0.385 | 0.0006 | 0.0025 |
| Emissions totals (g/s) | | | | | 0.006 | 1.155 | 0.002 | 0.0075 |

The ATCO Karratha Power station is located 18 km south-east of the Burrup Hub site. Key air emissions sources identified were two LM6000 DP Sprint gas turbines; the air emissions parameters are listed in Table 4-9.

Table 4-9:Karratha Power Station Emissions Data

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| GTG 1 | 18.2 | 3.57 | 26.0 | 723.0 | 0.04 | 6.0 | 0.01 | 0.043 |

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| GTG 2 | 18.2 | 3.57 | 26.0 | 723.0 | 0.04 | 6.0 | 0.01 | 0.043 |
| Emissions totals (g/s) | | | | | 0.08 | 12.0 | 0.02 | 0.086 |

Emissions from shipping were modelled for all (13) berths on the Burrup Peninsula, and five berths at Cape Lambert. A ship was assumed to be docked at all these berths with ancillary engines running continuously; i.e. 24 hours per day, every day of the year. The air emissions parameters assigned for each of the total of 18 berth locations are listed in Table 4-10.

Table 4-10: Air Emissions Data for Shipping

| Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|
| 35.0 | 0.5.0 | 11.9 | 673.0 | 0.25 | 2.0 | 2.0 | 0.12 |
| Burrup Peninsula shipping berths: emissions totals (g/s) | | | | 3.25 | 26.0 | 26.0 | 1.56 |
| Cape Lambert shipping berths: emissions totals (g/s) | | | | 1.25 | 10.0 | 10.0 | 0.60 |

## 4.5 Future Emission Sources

Modelling conducted for the "future" scenarios included emissions from:

- KGP with improvement assumptions
- Pluto LNG Development (Train 1 existing, and proposed Train 2 expansion (preliminary design 2019))
- other current relevant sources, without any expansion
- proposed new facilities (Urea Plant and Methanol Plant).

### 4.5.1 Future Relevant Developments

Woodside, as operator of the Pluto LNG Development, proposes a brownfield expansion as part of the Pluto LNG Development (Pluto Expansion Project). This includes the construction and commissioning of a second LNG processing train, Pluto Train 2.

The construction of Pluto Train 2 as part of the Pluto Expansion Project will comprise six GTCs, one GTG, an AGRU and Nitrogen Rejection Unit (NRU) thermal oxidisers. The purpose of the AGRU is to prevent process blockage (e.g. dry $CO_2$) and meet sales gas specifications for sulfur and carbon dioxide ($CO_2$). Removed gaseous species include $H_2S$ and mercaptans (Mokhatah et al, 2015).

Table 4-11: Pluto LNG Development – Train 2 Air Emissions Parameters (and Train 1 power assumption minor change)

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|
| Train 1 – GTG 3 | 40.1 | 2.80 | 29.1 | 821.0 | 2.98 | 0.07 | 0.01 |
| Train 1 – GTG 4 | 40.1 | 2.80 | 29.5 | 823.0 | 3.53 | 0.06 | 0.01 |
| Train 2 – GTC 1 | 50.7 | 3.06 | 29.6 | 741.0 | 4.55 | 0.002 | 0.01 |
| Train 2 – GTC 2 | 50.7 | 3.06 | 29.6 | 741.0 | 4.55 | 0.002 | 0.01 |

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|
| Train 2 – GTC 3 | 50.7 | 3.6 | 2.4 | 741.0 | 4.55 | 0.002 | 0.01 |
| Train 2 – GTC 4 | 50.7 | 3.06 | 29.6 | 584.0 | 4.55 | 0.002 | 0.01 |
| Train 2 – GTC 5 | 50.7 | 3.6 | 2.4 | 741.0 | 4.55 | 0.002 | 0.01 |
| Train 2 – GTC 6 | 50.7 | 3.06 | 29.6 | 584.0 | 4.55 | 0.002 | 0.01 |
| PLP GTG 5 | 30.0 | 5.7 | 38.3 | 787.0 | 4.88 | 0.003 | 0.01 |
| PLP Train 2 - AGRU Thermal Oxidiser | 16.0 | 0.84 | 13.2 | 962.0 | 0.69 | 0.141 | 0.01 |
| PLP Train 2 - NRU Thermal Oxidiser | 30.5 | 1.07 | 31.0 | 700.0 | 0.70 | 0.040 | 0.01 |
| Emissions Totals (g/s) | | | | | 40.1 | 0.33 | 0.11 |

# Pluto Train 2 emission characteristics are based on early FEED concept reports and subject to change as design matures.

& Emissions parameters add and/or replace equivalent sources of existing air emissions scenario (Section 4.4).

While the modelling scenarios include emissions from the other relevant current emissions, future developments at these industrial facilities are excluded. The scenarios do, however, include two new representative facilities located within the Burrup Strategic Industrial Area, near the Proposal:

- a urea plant with a production capacity of approximately 2 Mtpa
- a methanol plant with production capacity of approximately 5,000 tpd

Air emissions parameters used in the modelling for the Urea Proposal are set out in Table 4-12, and for the Methanol Proposal in Table 4-13.

Table 4-12: Air Emissions Data for Urea Proposal

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|
| Fired Heater H201 | 75.0 | 2.5 | 15.3 | 423.0 | 6.68 | 0.04 | 0.02 |
| GTG 1 | 30.0 | 3.0 | 20.8 | 378.0 | 2.25 | 0.07 | 0.01 |
| Urea Train 1 Absorber vent | 40.0 | 6.5 | 19.6 | 320.0 | 0.0 | 0.0 | 0.0 |
| Urea Train 2 Absorber vent | 40.0 | 6.5 | 19.6 | 320.0 | 0.0 | 0.0 | 0.0 |
| Emissions Totals (g/s) | | | | | 8.93 | 0.11 | 0.03 |

Table 4-13: Air Emissions Data for Methanol Proposal

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|
| Flue Gas Stack | 35.0 | 3.7 | 20.0 | 433.0 | 20.8 | 0.001 | 0.01 |
| Process Condensate Stripper | 8.3 | 0.5 | 20.0 | 343.0 | 0.0 | 0.001 | 0.01 |
| Flare Stack (with effective diameter) | 35.0 | 1.4 | 20.0 | 1273.0 | 0.03 | 0.001 | 0.01 |
| Gas Turbine Stack | 20.0 | 3.0 | 8.0 | 753.0 | 0.83 | 0.001 | 0.01 |

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|
| Auxiliary Boiler Stack | 30.0 | 3.7 | 6.0 | 463.0 | 6.39 | 0.001 | 0.01 |
| Emissions Totals (g/s) | | | | | 28.05 | 0.005 | 0.05 |

### 4.5.2 Karratha Gas Plant – Improvement Opportunities

The NWS Project Extension Proposal includes a staged reduction of NOx emissions. The improvement opportunities modelling scenario emissions estimates listed in Table 4-14 were based on representative concepts of feasible and significant $NO_x$ reductions as determined by Woodside engineering investigations. These KGP data were relevant for the scenarios: KIO, FBSIA-KIO, and FBSIA E&A.

Table 4-14: Changes to Karratha Gas Plant emissions to reflect potential improvement opportunities

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| Domgas GTC 1 | 24.0 | 1.0 | 42.3 | 815.0 | 0.01 | 3.81 | 0.12 | 0.01 |
| Domgas GTC 2 | 24.0 | 1.4 | 43.4 | 764.0 | 0.01 | 4.47 | 0.25 | 0.01 |
| Domgas GTC 3 | 24.0 | 1.0 | 42.3 | 815.0 | 0.01 | 3.81 | 0.12 | 0.01 |
| Domgas GTC 4 | 24.0 | 1.4 | 43.4 | 764.0 | 0.01 | 4.47 | 0.25 | 0.01 |
| TRAIN 1 – GTC 1 | 40.0 | 1.9 | 23.1 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 1 – GTC 2 | 40.0 | 1.9 | 23.1 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 1 – GTC 3 | 40.0 | 1.8 | 26.9 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 1 – GTC 4 | 40.0 | 1.8 | 26.9 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 1 – GTC 5 | 40.0 | 1.4 | 18.9 | 795.0 | 0.01 | 3.55 | 0.12 | 0.01 |
| TRAIN 2 – GTC 1 | 40.0 | 1.9 | 23.1 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 2 – GTC 2 | 40.0 | 1.9 | 23.1 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 2 – GTC 3 | 40.0 | 1.8 | 26.9 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 2 – GTC 4 | 40.0 | 1.8 | 26.9 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 2 – GTC 5 | 40.0 | 1.4 | 18.9 | 795.0 | 0.01 | 3.55 | 0.12 | 0.01 |
| TRAIN 3 – GTC 1 | 40.0 | 1.9 | 23.1 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 3 – GTC 2 | 40.0 | 1.9 | 23.1 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 3 – GTC 3 | 40.0 | 1.8 | 26.9 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 3 – GTC 4 | 40.0 | 1.8 | 26.9 | 764.0 | 0.01 | 4.47 | 0.27 | 0.01 |
| TRAIN 3 – GTC 5 | 40.0 | 1.4 | 18.9 | 795.0 | 0.01 | 3.55 | 0.12 | 0.01 |
| TRAIN 4 – GTC 2 | 40.1 | 3.0 | 23.8 | 811.0 | 0.01 | 5.79 | 0.64 | 0.01 |
| TRAIN 4 – GTC 1 WHRU1 | 40.1 | 1.5 | 50.9 | 588.0 | 0.01 | 3.13 | 0.29 | 0.01 |
| TRAIN 4 – GTC 1 WHRU2 | 40.1 | 1.5 | 50.9 | 521.0 | 0.01 | 3.13 | 0.29 | 0.01 |

| Emissions Source | Stack Height (m) | Stack Diameter (m) | Exit Velocity (m/s) | Temp. (K) | $PM_{10}$ (g/s) | $NO_x$ (g/s) | $SO_2$ (g/s) | VOC (g/s) |
|---|---|---|---|---|---|---|---|---|
| TRAIN 5 – GTC 2 | 40.1 | 3.0 | 23.7 | 811.0 | 0.01 | 7.18 | 0.64 | 0.01 |
| TRAIN 5 – GTC 1 WHRU 1 | 40.1 | 1.5 | 50.9 | 523.0 | 0.01 | 3.11 | 0.29 | 0.01 |
| TRAIN 5 – GTC 1 WHRU 2 | 40.1 | 1.5 | 50.9 | 483.0 | 0.01 | 3.11 | 0.29 | 0.01 |
| Stabiliser 2 Furnace Stack | 33.0 | 0.7 | 39.2 | 699.0 | 0.01 | 2.56 | 0.01 | 0.01 |
| Stabiliser 4 Furnace Stack | 33.0 | 0.7 | 39.2 | 668.0 | 0.01 | 2.17 | 0.01 | 0.01 |
| Stabiliser 5 Furnace Stack | 33.0 | 0.7 | 39.2 | 659.0 | 0.01 | 2.23 | 0.01 | 0.01 |
| Stabiliser 6 Furnace Stack | 32.6 | 0.7 | 39.2 | 630.0 | 0.01 | 1.98 | 0.01 | 0.01 |
| Power Generation GTG1 | 40.0 | 2.0 | 17.1 | 814.0 | 0.01 | 2.01 | 0.24 | 0.01 |
| Power Generation GTG2 | 40.0 | 2.0 | 17.1 | 814.0 | 0.01 | 2.01 | 0.24 | 0.01 |
| Power Generation GTG3 | 40.0 | 2.0 | 17.1 | 814.0 | 0.01 | 2.01 | 0.24 | 0.01 |
| Power Generation GTG4 | 40.0 | 2.0 | 17.1 | 814.0 | 0.01 | 2.01 | 0.24 | 0.01 |
| Power Generation GTG5 | 40.0 | 2.0 | 17.1 | 814.0 | 0.01 | 2.01 | 0.24 | 0.01 |
| Power Generation GTG6 | 40.0 | 2.0 | 17.1 | 814.0 | 0.02 | 2.01 | 0.24 | 40.61 |
| Power Generation 7 | 40.0 | 1.8 | 22.2 | 751.0 | 0.01 | 3.00 | 0.22 | 0.01 |
| Power Generation 8 | 40.0 | 1.8 | 17.7 | 751.0 | 0.01 | 2.66 | 0.22 | 40.60 |
| Power Generation 9 | 40.0 | 1.8 | 34.6 | 751.0 | 0.01 | 4.45 | 0.22 | 0.01 |
| Power Generation 10 | 40.0 | 1.8 | 31.3 | 745.0 | 0.01 | 3.64 | 0.22 | 0.01 |
| Domgas-E Flare | 128.5 | 0.5 | 20.0 | 1273.0 | 0.05 | 0.28 | 0.00 | 0.58 |
| LNG Emergency Flare (representative source) | 145.3 | 3.3 | 20.0 | 1273.0 | 1.95 | 11.32 | 0.04 | 23.42 |
| LNG-SL Flare | 56.9 | 0.3 | 20.0 | 1273.0 | 0.01 | 0.08 | 0.00 | 0.17 |
| LPG-SL Flare | 56.5 | 0.2 | 20.0 | 1273.0 | 0.01 | 0.05 | 0.00 | 0.10 |
| Operations Flare | 46.8 | 0.7 | 20.0 | 1273.0 | 0.10 | 0.56 | 0.00 | 1.17 |
| Emissions Totals (g/s) | | | | | 2.5 | 153.3 | 9.2 | 107.0 |

# Emissions parameters add and/or replace equivalent sources of existing air emissions scenario (Section 4.4).

# 5. Modelling Methodology

## 5.1 Overview

The modelling used the CSIRO-developed 'TAPM' meteorological and air dispersion model (Hurley, 2008a; Hurley et al., 2008). The model was chosen for consistency with previous air quality modelling studies for the Burrup Peninsula completed by CSIRO atmospheric scientists; e.g. Hurley et al. (2004); Physick et al. (2004). The latest version of TAPM (V.4.0.5) was used for the modelling.

The modelling methodology was discussed with EPA Services air quality specialists prior to the commencement of modelling (Jacobs, 2019b). At the EPA Services meeting, it was proposed to use TAPM for the project primarily due to the legacy of TAPM modelling for the Pilbara environment and simulating the potential effects of annual variations in meteorology. Subsequent meetings to discuss methodology model development findings, and preliminary outcomes were held with EPA Services and DWER between on 28 March and 13 May 2019. Several aspects about the model were raised including which version of the model to use for the project, and alternative modelling options were discussed; however, TAPM has been found, from the current and historical modelling, to provide an accuracy appropriate for the assessment of the Proposal.

## 5.2 Review of Scientific Literature

Between 2000 and 2010 the air pollution sources on the Burrup Peninsula and the dispersion of pollutants was a focus of intense study including meteorological modelling, air emissions inventory, and air dispersion modelling. These studies included several TAPM modelling studies by the CSIRO Division of Atmospheric Research, SKM (now Jacobs), and other specialist air quality consultants. This section sets out the main findings from a review of those previous studies, important for establishing the modelling methods for this project.

Physick (2001) published a TAPM-Generic Reaction Set (GRS) modelling study on the meteorology and air quality of the Pilbara region, including comparisons with observations at six monitoring sites; this study found:

- There was strong seasonal variation of the monthly averaged winds at each site.
- There was little difference in the winds between the sites for any given month, especially for wind direction.
- Three dominant wind patterns were identified in the coastal region between Karratha and Port Hedland:
  - An easterly pattern in which winds varied between northeast and southeast over the diurnal period;
  - A westerly pattern in which the winds varied from northwest to southwest; and
  - A wind direction rotation anti-clockwise through 360 degrees over 24 hours.
- The rotation pattern was assessed as being likely to be important for the recirculation of pollutants, (therefore causing higher air pollutant concentrations around Burrup Peninsula).
- The rotation prevailed on some days throughout the year, but more frequently in March, April, August and September.

Apart from the importance of recirculation, Physick (2001) found that emissions from the Burrup Peninsula can meander up the coast to Port Hedland, moving onshore and offshore with sea breezes and nocturnal flows off the land. Thus, in this early phase of studying the atmospheric environment of the Burrup Peninsula, TAPM-GRS was found to be a suitable model to apply to the Pilbara region.

In relation to emissions from the Woodside gas processing facilities, Hurley et al. (2004) determined that buoyancy enhancement of the plumes from the Woodside facilities were important – the effect of plumes combining is to enhance the buoyancy of each individual plume ('plume merging'). The reactivity of the hydrocarbons known as VOCs emitted from several Woodside facility stacks was found to be important, and reactivity coefficients for the VOCs were updated. Biogenic emissions were an important consideration, with databases created to address this using a WA Department of Environmental Protection (DEP) gridded emission inventory (DEP, 2002).

Hurley et al. (2004) advised against assimilation of local wind observations due to the complexity of the region, the sparsity of the wind observations data (two stations only), and local influences such as trees on the wind measurements at Dampier.

Hurley et al. (2008b) reported the following improvements to TAPM V4 over V3:

- better performance for a number of annual meteorological verification datasets;
- better prediction of wind speed average;
- better prediction of temperature standard deviation;
- lower root mean square error (RMSE) for all variables;
- high index of agreement (IOA) for all variables; and
- good prediction of extreme pollution concentrations for several high-quality datasets in regions of varying complexity.

Hurley et al. (2009) provided a summary of some of the improvements in V.4 from V.3:

- Land surface parameterisation, nocturnal, low wind conditions, turbulence in the convective boundary layer, “in particular has resulted in improvements in prediction of near surface meteorology.”
- Wind and temperature performance for a number of regions of varying complexity—e.g. Kwinana, Kalgoorlie, Perth—"have shown consistently good performance for annual statistics with little mean bias, low RMSE and high IOA.”

In summary, in the 2000s the comparisons of TAPM results with monitoring data indicated TAPM was performing well given the complexity of the coastal meteorology of the Burrup Peninsula region (e.g. Physick et al., 2002), and the complexity of the emissions inventories used (e.g. Hurley et al., 2004).

The previous TAPM modelling and input data used were used as the basis for the modelling for the Proposal detailed in the next section.

## 5.3 Model configuration

### 5.3.1 Grid Resolution and Vertical Levels

Horizontal and vertical spatial resolution (and time resolution), are key factors that impact on computer speed for a meteorological and air dispersion modelling run. The TAPM modelling for the Proposal drew on previous TAPM set-ups described in this section. Using TAPM, Physick and Blockley (2001) carried out simulations for the Burrup Peninsula with three grids centred near Dampier (each 21 x 21 x 20 grid points), with grid spacings of 10 km, 3 km and 1 km for the meteorology. The grid spacings for the corresponding air quality simulations over the same domains were 5 km, 1.5 km and 0.5 km.

Physick et al. (2004) completed simulations for only one month in the summer (January 1999), winter (July 1998) and the transition season (April 1998). These simulations were carried out on three nests (each 40 x 40 x 20 grid-points) with grid spacings of 30 km, 10 km and 3 km, centred on Karratha. Vertical grid levels were at heights above the ground of 10, 50, 100, 150, 200, 300, 400, 500, 750, 1000, 1250, 1500, 2000, 2500, 3000, 4000, 5000, 6000, 7000 and 8000 m. Terrain elevation data were obtained from Geoscience Australia’s gridded 9-second DEM data (approximately 250 m).

For the Proposal, sensitivity tests were undertaken by comparisons of TAPM-predicted winds at Karratha Aerodrome with the Bureau of Meteorology (BoM) measurements of wind speed and wind direction at Karratha Aerodrome and Roebourne. Inclusion of an additional grid with finer horizontal resolution of 400m led to only a small improvement in the accuracy of TAPM-predicted winds. However, the added computational time expense of the additional grid was significant; i.e. weeks, given several scenarios required testing, with many model runs required. As such 1 km resolution modelling was selected for the assessment (meteorological modelling run-times were approximately less than 40 hours for a simulated year).

Assimilation of local wind observational data was not used in TAPM to enable proper comparisons of results from modelling and monitoring, and to avoid the formation of unrealistic wind vector fields. Hurley et al. (2004) advised that meteorological data assimilation was not advisable for the Burrup Peninsula due to the complexity of the region, the sparsity of (quality) wind data (primarily BoM Karratha Aerodrome), and the local influences on observed wind speeds at Dampier such as trees.

For the current Proposal assessment, a balance between computing speed and accuracy of results was achieved using the TAPM settings set out in Table 5-1.

Table 5-1: Model Configuration

| TAPM Modelling Parameter | Input data | Notes / references |
|---|---|---|
| Grid centre coordinates | Lat. S. 20° 40'; Long. 116° 43' | MGA94 co-ordinates: East 470,489 m; North 7,714,717 m |
| Number of grids | 3 | Grid Spacings (10 km, 3 km, 1 km) |
| Outer grid spacing | 10 km | Nil |
| Number of grid points | 51 (west-east) x 51 (north-south) x 25 (vertical) | Total 2601 ground level grid receptors (inner grid). |
| Advanced/Experimental Options | Default settings | All defaults as 'Recommended' (Hurley, 2008a). |
| Modelling year | 2014 selected due typical wind pattern as determined from analysis of Bureau of Met. Karratha Aerodrome observational data 2010-2018, and good examples of $NO_2$ and $O_3$ measurements at Karratha. | 2014 was selected to support model verification of current routine operations against ambient air monitoring records representative of recent plant 'full rate' operations.<br>2012 was a back-up year due good examples of $NO_2$ and $O_3$ measurements, and typical wind pattern. |
| Vertical Layers (m) | 25 vertical layers including: 10, 50, 100, 150, 200, 300, 400, 500, 750, 1000, 1250, 1500, 2000… up to 8000 m. | Not fully operational |

### 5.3.2 Land Use

TAPM uses terrain elevations and land use data to describe the geography of a study area that underlies the fields of three-dimensional meteorological data computed and allowed to evolve over the modelled study area. Land use data include parameters important for boundary layer meteorological computations, where the meteorology makes contact with the land surface. One of these parameters is surface roughness, which influences turbulence in the atmospheric boundary layer or mixing layer, which in turn influences the dispersion of air pollutants.

Parameters for vegetation types defined in the TAPM model are set out in Table 5-2 (Hurley 2008a).

Table 5-2: TAPM Vegetation Characteristics

| Type | Height (m) | Surface fraction ($s_f$) | Leaf Area Index | Minimum stomatal resistance ($s^{-1}$) |
|---|---|---|---|---|
| Forest - low dense | 9.00 | 0.75 | 3.9 | 200 |
| Shrubland - tall mid-dense scrub | 3.00 | 0.50 | 2.6 | 160 |
| Shrubland - low mid-dense | 1.00 | 0.50 | 1.4 | 90 |
| Shrubland - low sparse | 0.60 | 0.25 | 1.5 | 90 |
| Grassland - mid-dense tussock | 0.60 | 0.50 | 1.2 | 80 |
| Pasture mid-dense | 0.45 | 0.50 | 1.2 | 40 |
| Urban and Industrial | 10.00 | 0.75 | 2.0 | 100 |

The TAPM land use settings for the Burrup Peninsula were based on those of Physick and Blockley (2001). For the 1km grid, land-use classification in the data set accompanying the TAPM modelling package was changed from a land category to water for grid points corresponding to the Dampier Salt Farm at the lower end of the Burrup Peninsula. A roughness length of 0.9 m was assigned to Burrup Peninsula grid points by changing the land-use category in that region to low dense forest, which simulates the rough rocky landscape. The final two nested grids (3 km and 1 km) used for the modelling are illustrated in the image extracts from the TAPM Graphical User Interface in Figure 5-1.

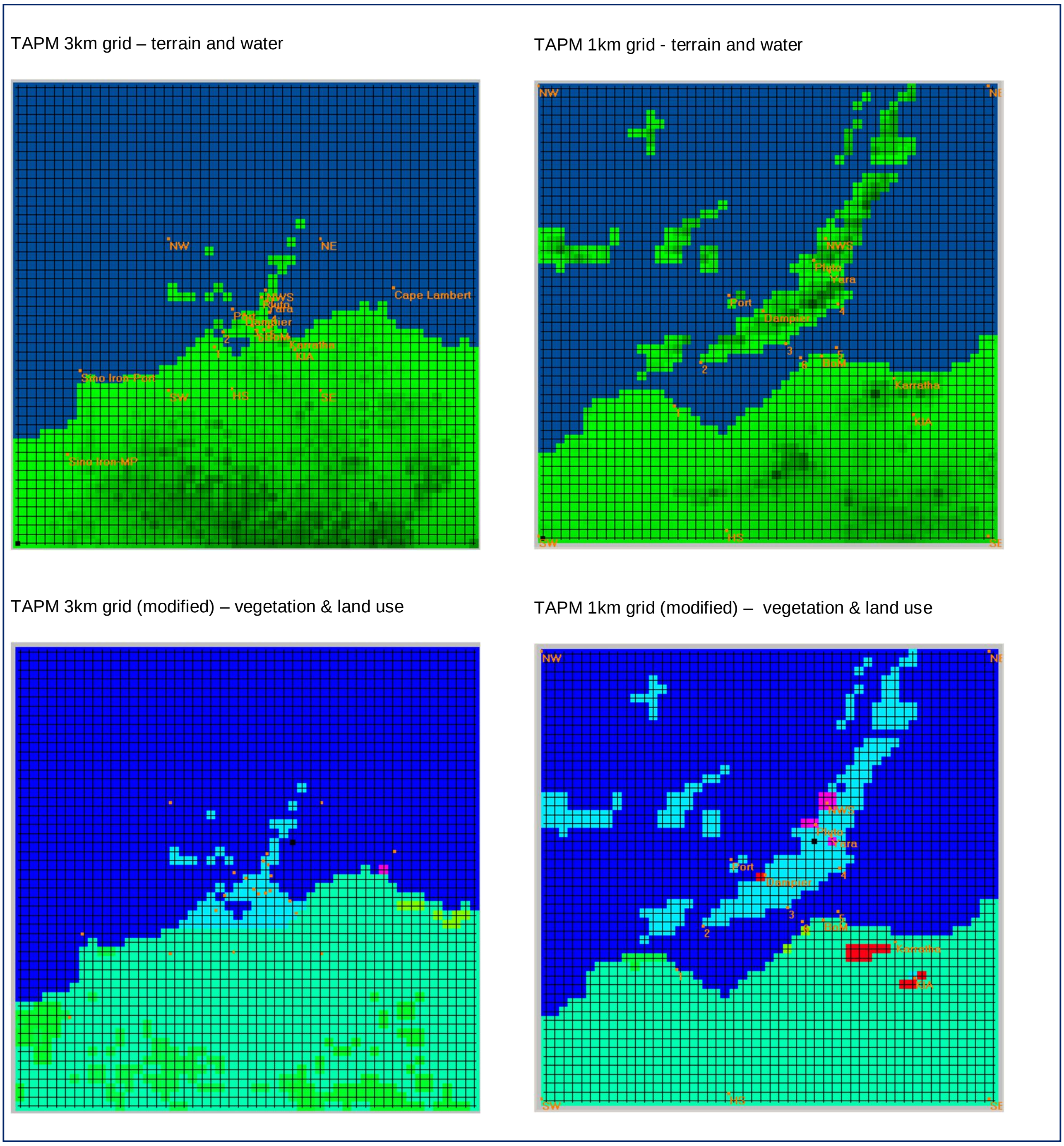



Figure 5-1: TAPM 3km and 1km Grids – Terrain, Vegetation and Land Use

### 5.3.3 Deep Soil Moisture Content

Estimates for monthly varying Deep Soil Moisture Content (DSMC) were interpolated linearly based on tests by Physick et al. (2004) that showed best agreement with wind data obtained using: DSMC 0.05 $m^3$ $m^{-3}$ for January and April; and DSMC 0.15 $m^3$ $m^{-3}$ for July. The modified DSMC values used for the modelling assessment are shown in Figure 5-2 .

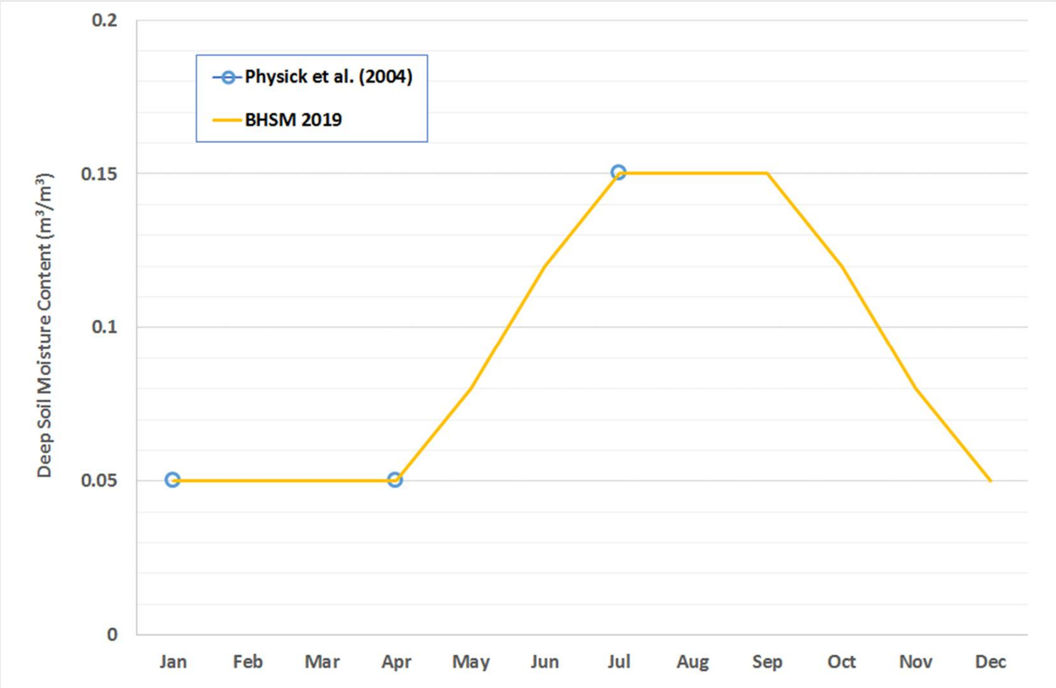



Figure 5-2: Deep Soil Moisture Content Settings

### 5.3.4 Photochemical Modelling

TAPM's in-built photochemical modelling scheme was used for this modelling assessment for consistency with previous CSIRO and SKM modelling studies. In TAPM, gas-phase photochemical modelling is based on the Generic Reaction Set (GRS) semi-empirical mechanism of Azzi et al. (1992) and the hydrogen peroxide modification of Venkatram et al. (1997). TAPM also includes gas-phase and aqueous-phase reactions of $SO_2$ and particles. Aqueous-phase reactions were based on Seinfeld and Pandis (1998).

TAPM simulates 10 chemical reactions for 13 species in GRS mode including: smog reactivity ($R_{smog}$), the radical pool (RP), hydrogen peroxide ($H_2O_2$), nitric oxide (NO), $NO_2$, $O_3$, sulfur dioxide ($SO_2$). Further details are provided in Hurley (2008a).

More complex photochemical modelling could be undertaken for the Burrup Peninsula; e.g., using TAPM-CTM (Cope and Lee, 2009). However, the selection of TAPM-GRS provided an appropriate balance between model accuracy (as determined by comparisons with monitoring results) and computational time cost. The use of TAPM-GRS also allowed for the efficient modelling of multiple year-long simulations, a feature important to make comparisons between annual averages for each scenario.

Comparisons of TAPM-GRS results with monitoring data obtained on the Burrup Peninsula, were the key tests of model accuracy. The current application of TAPM-GRS to the Pilbara indicated the most substantial gains towards model accuracy were through improvements to the air emissions inventories used as input.

Using the previous CSIRO studies as the main foundational guides, inputs required at the user interface for the photochemical modelling included the following estimates for background air pollutant levels: $NO_x$ (1 ppb), background smog reactivity or the so-called '$R_{smog}$' parameter (0.2 ppb), and background $O_3$ (25 ppb). Values for $R_{smog}$ were calculated for every modelled source using estimates for the total VOC emission rate (g/s) and an estimate of reactivity associated with the source type. Air Assessments (2010b) stated that generally it is the boundary (background) condition of $R_{smog}$ that is most important, with 'surface sources contributing little $R_{smog}$'. Initially the estimate for background $R_{smog}$ (0.2 ppb) was selected by Hurley et al. (2004).

TAPM also allows for the input of large-scale area emissions of air pollutants to include as background. Again, using the previous CSIRO studies as a guide, the CSIRO biogenic emissions databases used with TAPM are illustrated in Figure 5-3 ($NO_x$), and Figure 5-4 ($R_{smog}$). The figures are overlaid on the base map image of the Burrup Peninsula study area, representing the TAPM inner-grid.

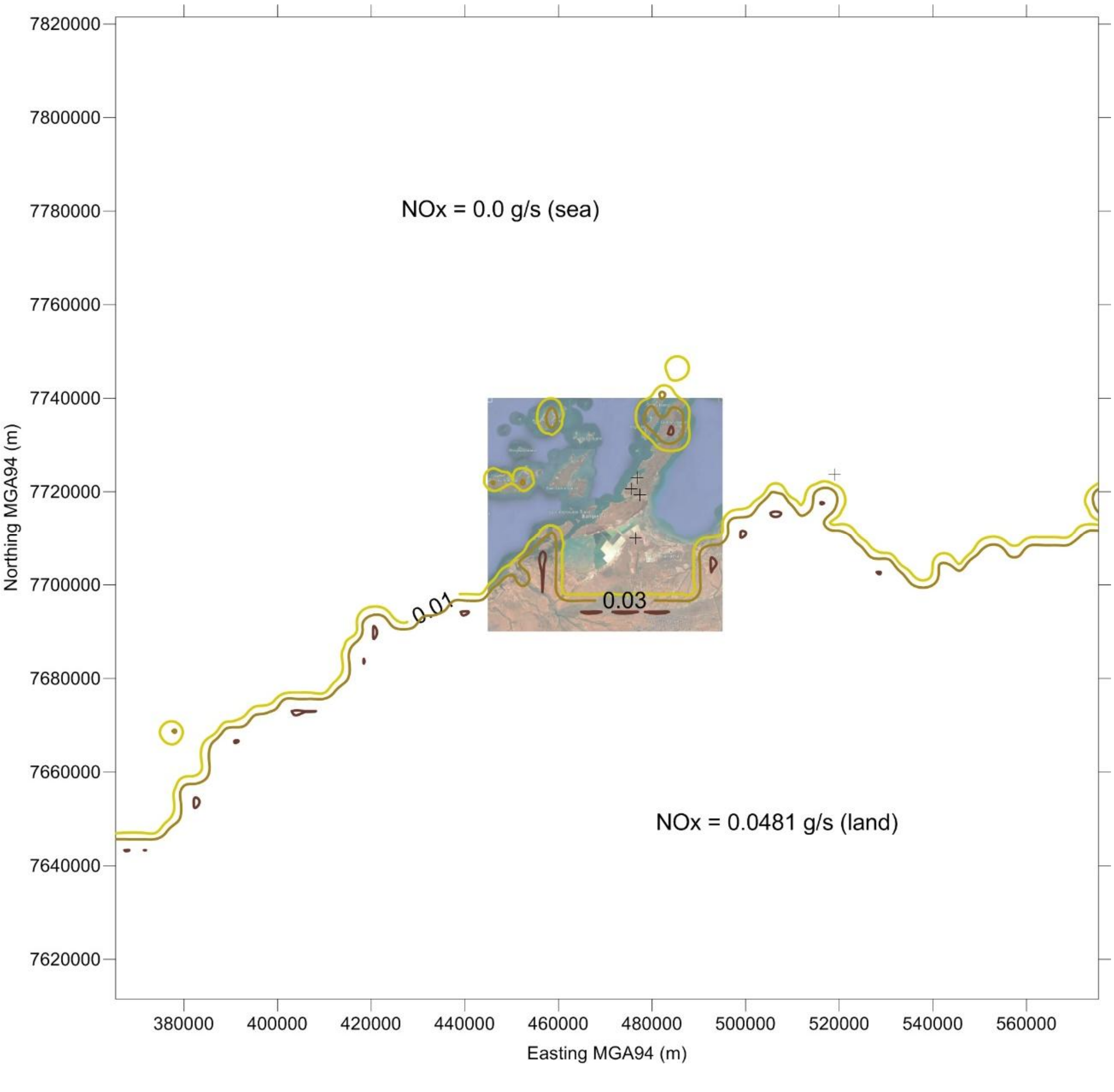



Figure 5-3: CSIRO Biogenic $NO_x$ Area Emissions Database and Current Study Area (Inset)

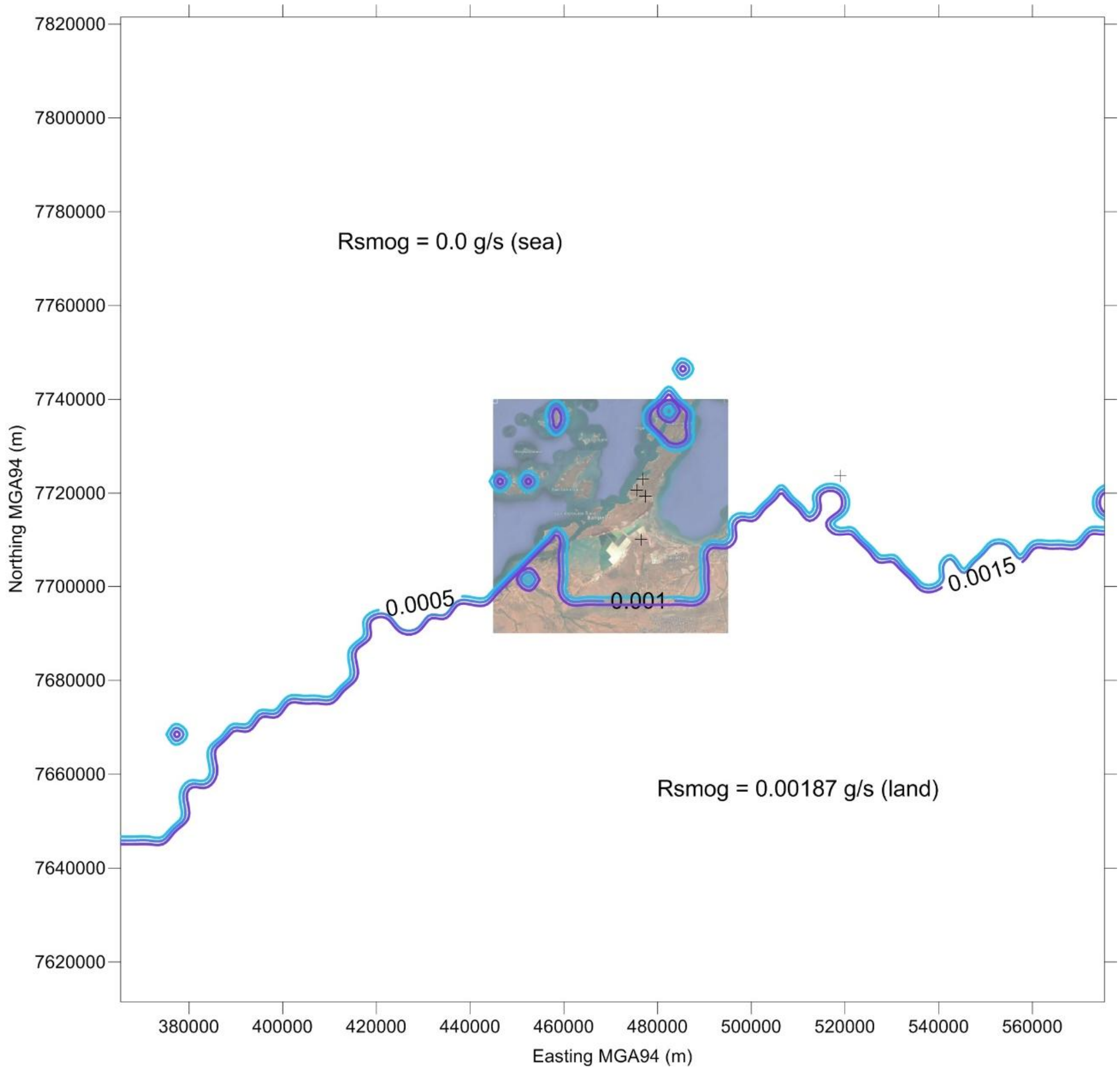



Figure 5-4: CSIRO Biogenic Area $R_{smog}$ Emissions Database and Current Study Area (Inset)

Another area source file used with previous TAPM modelling included emissions from shipping and the relatively small townships of Dampier (population approximately 1,100), and Karratha (population approximately 15,800). A weakness of this database was overestimating the effects of the shipping emissions by excluding the effects of hot (buoyant) exhausts from ship engines. This weakness in the emissions estimates was recognised by Air Assessments (2010). For this project, the effects of shipping were modelled by including ship engines running continuously throughout a year at every available berth in the Burrup Peninsula and Cape Lambert.

Area emissions from Dampier and Karratha were also excluded from the modelling because the small amounts of emissions from road traffic from these towns were insignificant relative to the industrial sources. In any case, by including background levels of $NO_x$, O3, particles and hydrocarbons in the modelling, the emissions from Dampier and Karratha were included implicitly.

### 5.3.5 Deposition flux of Nitrogen and Sulfur – $NO_2$ and $SO_2$ Contribution

The deposition flux of nitrogen and sulfur on Burrup Peninsula may be relevant for effects on rock art, and a summary of results for the $NO_2$ and $SO_2$ deposition components obtained from measurements was set out in Section 3.7. TAPM-GRS modelling outputs were obtained for the $NO_2$ and $SO_2$ deposition components of these fluxes for the purpose of further analysis and in the absence of a relevant standard (an assessment of the impacts on rock art was outside the scope of this assessment).

The model results for $NO_2$ deposition were illustrated as contour plots in a similar way to the standard presentation of results for (airborne) GLCs. The results were provided in units of kg/ha/year to enable comparisons with previous assessment results; e.g. SKM (2009); and in units of meq/$m^2$/year to enable comparisons with previous monitoring results; e.g., Gillet (2008).

It is noted the TAPM calculations for dry and wet deposition of $NO_2$ and $SO_2$, which are detailed in Hurley (2008), use a similar method to that adopted by Gillett (2008) and Gillett (2014). The results may differ slightly between the methods depending on parameters such as, deposition velocities of the gases, and various resistance parameters used in the calculations by each study. Measured airborne concentrations are used to calculate dry deposition of a gas. Variability in the input parameters of approximately 10% (Gillett, 2008), means the TAPM calculations of deposition could differ from the 'measured' values by approximately 10% or slightly greater.

The conversion of the TAPM results for gaseous $NO_2$ deposition in units of mg/$m^2$/year to meq/$m^2$/year was calculated using the equation, $D = m/M \times z$, where $m$ is the deposition mass (mg) predicted by TAPM, $M$ is the molecular mass of $NO_2$ (46 g/mol), and $z$ is the charge (see Gillett, 2014). The value of $z$ was one with the assumption that all the deposited $NO_2$ formed nitric acid ($HNO_3$), with the charge on the nitrate ion ($NO_3$) being (minus) one.

### 5.3.6 Selection of Year for Modelling

The TAPM meteorological simulation year 2014 was selected as the basis for the air quality assessment supporting the Proposal. The process for selecting this representative year included a review of 9 years of hourly-average meteorological observations data from BoM Karratha Aerodrome (2010-2018). Annual statistics for wind speed and wind direction were examined for any annual meteorological variations in the Burrup region. This included a review of cyclones in the Pilbara to check the potential effects on Karratha wind speed (Appendix C. Results – Meteorological Modelling).

The completeness and representativeness of air quality monitoring data was considered. The selection for the simulation was 2014, which was considered to be representative of meteorological conditions, combined with an annual air quality monitoring dataset that best represented the existing industrial air emissions situation.

PLP was commissioned in 2012, ramped up in the later half 2012, and was at full production in 2013, although with some variability in the 2013 operations. The year 2014 was determined to be a good record of high KGP and PLP production rates and overlapped with a solid ambient air quality monitoring record. All factors combined, the year 2014 was selected as the best meteorological simulation year for TAPM.

TAPM was used to produce modelling results for wind speed and wind direction for 2014. The predicted meteorological outputs were compared with the 2014 hourly datasets from the Bureau of Meteorology (BoM) weather stations at Karratha, Roebourne and Legendre Island to assess the model's suitability for dispersion modelling. This comparison is outlined in Appendix C. Results – Meteorological Modelling.

### 5.3.7 Consideration of Climate Change

Meteorological simulation of a climate change scenario was considered for the Project, however the uncertainties associated with creating an annual database of hourly average meteorological parameters were considered to be too high for input to modelling. It is acknowledged that Australian Government (2019) predicts future climate scenarios for areas within Australia; of these areas. the Proposal is located approximately between the 'Rangelands north' and 'Monsoonal NorthWest clusters. This adds to the uncertainties of climate change predictions for the Burrup region.

# 6. Comparisons with 2014 Monitoring Results

The purpose of this section is to compare key statistical results from the current TAPM-GRS modelling with corresponding statistics from the 2014 monitoring results; 2014 was the simulated meteorological year for modelling; see Section 5.3.6.

Comparisons of the TAPM results for hourly average $NO_2$ GLCs (ppb) with monitoring data are set out in Table 6-1. The plots provide statistical summaries of the 8760 one-hour average $NO_2$ GLCs predicted by TAPM-GRS for three grid point locations representative of the Karratha (left), Dampier (middle) and Burrup Road (right) monitoring locations. The TAPM 'CLOC' parameter captures the maximum grid point concentration surrounding the selected point, so provides a better indication of the broader model results for each location.

A similar comparison of modelling vs. monitoring results (2014) is provided in Table 6-2 for $O_3$–in 2014, $O_3$ monitoring data were obtained from Karratha and Dampier monitoring stations only.

The Robust Highest Concentration (RHC) is an estimate of the maximum, which attempts to minimise over-estimates or under-estimates in a dataset; e.g., see Hurley (2008a). Estimates for the RHCs are also provided in the following tables. The hourly average statistics plotted (left-to-right) in each chart are: maximum, RHC, 99.9$^{th}$ percentile, 99$^{th}$ percentile, 70$^{th}$ percentile, 50$^{th}$ percentile (i.e. median), and annual average. An analysis of the comparisons is provided below each chart.

The reliability of the TAPM-GRS results was determined primarily by comparisons of model results with monitoring records. These comparisons of statistical results indicated TAPM-GRS was performing well in terms of being able to accurately predict a variety of statistical results for $NO_2$ and $O_3$ as measured by Woodside at the Burrup, Dampier and Karratha monitoring stations.

Table 6-1: Comparisons of TAPM Results with 2014 Monitoring Results for Hourly Average $NO_2$

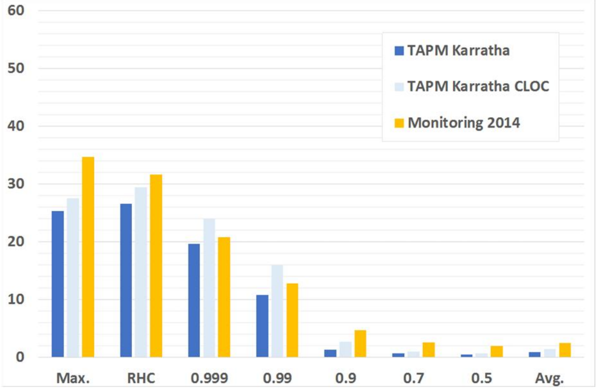
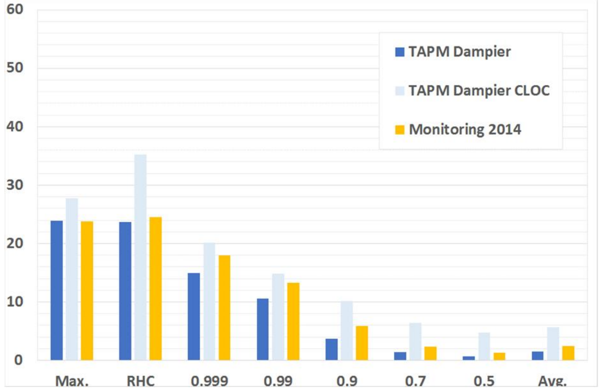
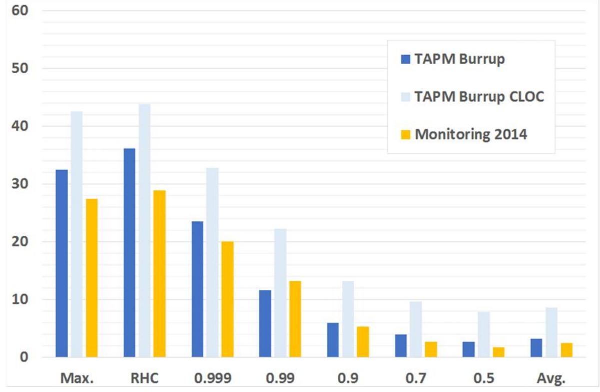
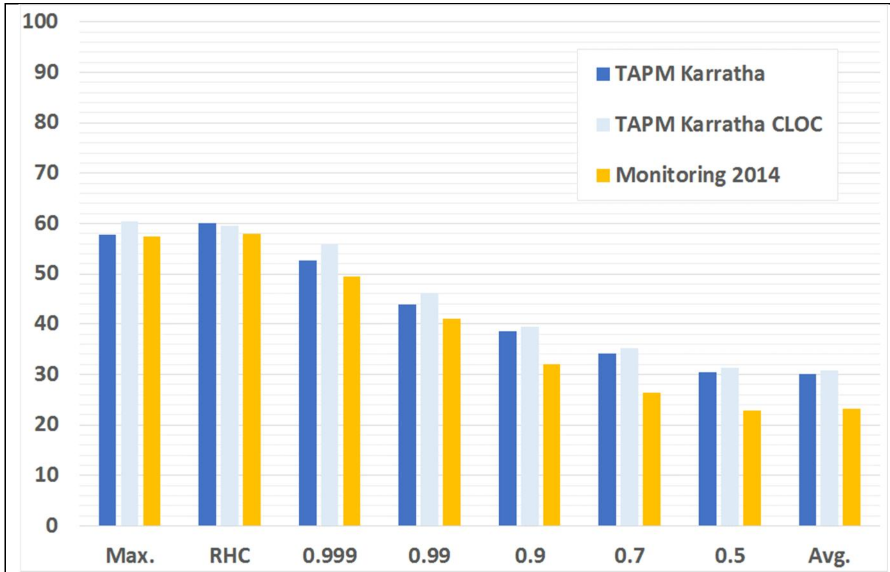
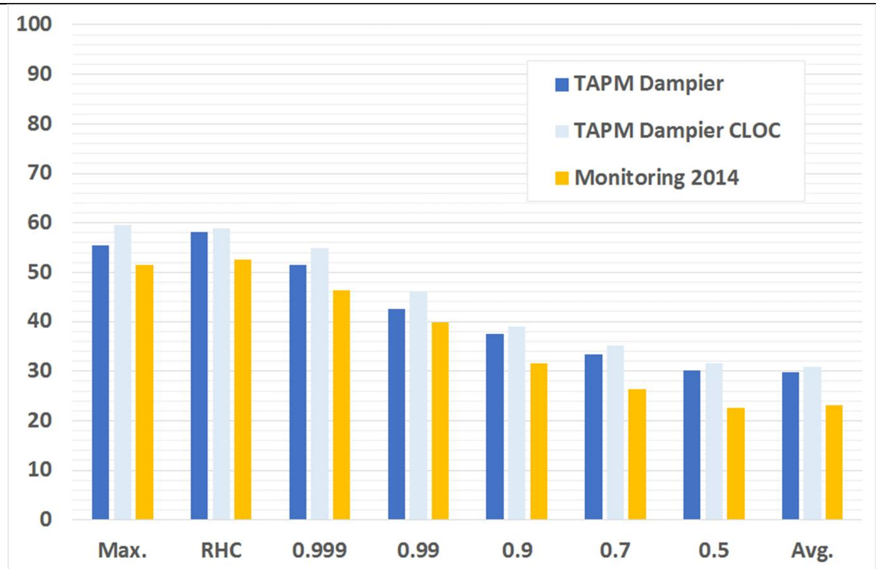
| | | |
|---|---|---|
|  |  |  |
| · Karratha 2014: 1-Hour Average $NO_2$ (ppb)<br>· TAPM (blue) and monitoring (yellow)<br>· Plotted range is 0-60 ppb<br>· NEPM (Ambient Air Quality) standard 120 ppb | · Dampier 2014: 1-Hour Average $NO_2$ (ppb)<br>· TAPM (blue) and monitoring (yellow)<br>· Plotted range is 0-60 ppb<br>· NEPM (Ambient Air Quality) standard 120 ppb | · Burrup 2014: 1-Hour Average $NO_2$ (ppb)<br>· TAPM (blue) and monitoring (yellow)<br>· Plotted range is 0-60 ppb<br>· NEPM (Ambient Air Quality) standard 120 ppb |
| Analysis:<br><br>Generally good agreement between the TAPM results and monitoring for the higher $NO_2$ concentrations in Karratha; e.g., the 99.9$^{th}$ percentile for the grid point selected to represent Karratha is almost an exact match.<br><br>TAPM slightly underestimating annual average $NO_2$ for both point 'Karratha' and 'CLOC'. | Analysis:<br><br>Excellent agreement between the TAPM results and monitoring for the higher $NO_2$ concentrations in Dampier.<br><br>CLOC parameter indicates the TAPM results are conservative, high.<br><br>Excellent agreement for annual average $NO_2$ at Dampier, and TAPM slightly overestimating (conservative, high). | Analysis:<br><br>Excellent agreement between the TAPM results (blue) and monitoring (yellow) for the higher $NO_2$ concentrations for Burrup Road; parameter 'CLOC' indicates the TAPM results are conservative, high).<br><br>Good agreement for annual average $NO_2$ at Dampier, with TAPM overestimating (conservative, high). |

Table 6-2: Comparisons of TAPM Results with 2014 Monitoring Results for Hourly Average $O_3$

<table>
<tr>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>· Karratha 2014: 1-Hour Average $O_3$ (ppb)<br>· TAPM (blue) and monitoring (yellow)<br>· Plotted range is 0-100 ppb<br>· NEPM (Ambient Air Quality) standard 100 ppb</td>
<td>· Dampier 2014: 1-Hour Average $O_3$ (ppb)<br>· TAPM (blue) and monitoring (yellow)<br>· Plotted range is 0-100 ppb<br>· NEPM (Ambient Air Quality) standard 100 ppb</td>
</tr>
<tr>
<td>Excellent overall agreement between the TAPM results for hourly average $O_3$ concentrations and monitoring across the whole range of statistics. The comparisons of RHCs are aligned, with TAPM slightly conservative (slightly higher).<br><br>TAPM overestimating annual average $O_3$ (conservative).</td>
<td>Excellent overall agreement between the TAPM results for hourly average $O_3$ concentrations and monitoring across the whole range of statistics. The comparisons of RHCs is perfect, with TAPM slightly conservative (slightly higher).<br><br>TAPM overestimating annual average $O_3$ (conservative).</td>
</tr>
</table>

# 7. Results

## 7.1 Overview

Modelled concentrations of pollutants of concern are presented in the following sections. Contour plots for each species and averaging period provide comparison between the modelled scenarios and give indications of the concentration trends over the wider region.

## 7.2 $NO_2$ Concentrations

The maximum 1-hour averaged $NO_2$ GLCs for the five modelled air emissions scenarios at the three sensitive receptor locations, Karratha, Burrup and Dampier, and the maxima anywhere on the grid, are presented in Table 7-1. Contour plots of the GLCs are provided in Figure 7-1 (Current Baseline) through to Figure 7-5 (scenario FBSIA E&A). There were no predicted exceedances of the corresponding NEPM standard of 120 ppb for any of the five air emissions scenarios tested by modelling.

Table 7-1: Maximum 1-hour Average $NO_2$ Concentrations (ppb)- Grid Receptors

| Receptor | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| Karratha | 24.8 | 16.1 | 28.3 | 20.9 | 17.5 |
| Burrup | 33.4 | 22.4 | 34.2 | 25.4 | 22.9 |
| Dampier | 24.8 | 18.2 | 25.8 | 19.5 | 19.0 |
| Maximum on Grid | 42.6 | 29.1 | 43.9 | 32.4 | 30.7 |
| **NEPM Standard** | **120** | **120** | **120** | **120** | **120** |

The modelled maxima of the annual average $NO_2$ concentrations for the air emissions scenarios at the sensitive receptor locations, and the grid receptor maxima, are presented in Table 7-2. Contour plots of the GLCs are provided in Figure 7-6 (Current Baseline) through to Figure 7-10 (scenario FBSIA E&A). There were no predicted exceedances of the corresponding NEPM standard of 30 ppb for any of the five air emissions scenarios tested by modelling.

Table 7-2: Annual Average $NO_2$ concentrations (ppb)- Grid Receptors

| Receptor | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| Karratha | 0.9 | 0.8 | 1.0 | 0.9 | 0.8 |
| Burrup | 3.2 | 3.0 | 4.0 | 3.8 | 3.3 |
| Dampier | 1.7 | 1.6 | 1.8 | 1.7 | 1.6 |
| Maximum on Grid | 5.0 | 4.9 | 5.6 | 5.7 | 5.0 |
| **NEPM Standard** | **30** | **30** | **30** | **30** | **30** |

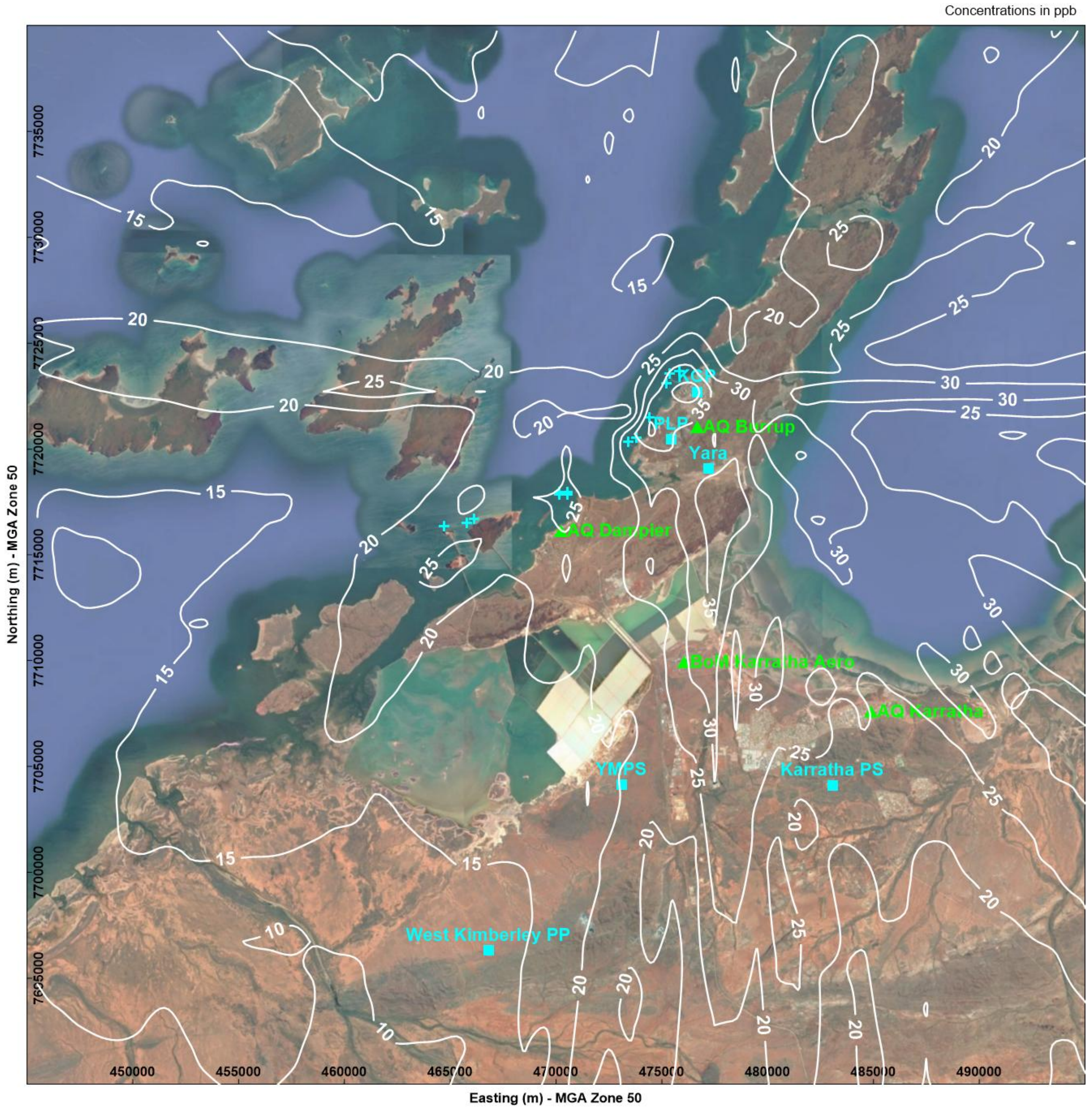



Figure 7-1: CBM – Maximum 1h $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 42.6 ppb.
- NEPM (Ambient Air Quality) standard, 120 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

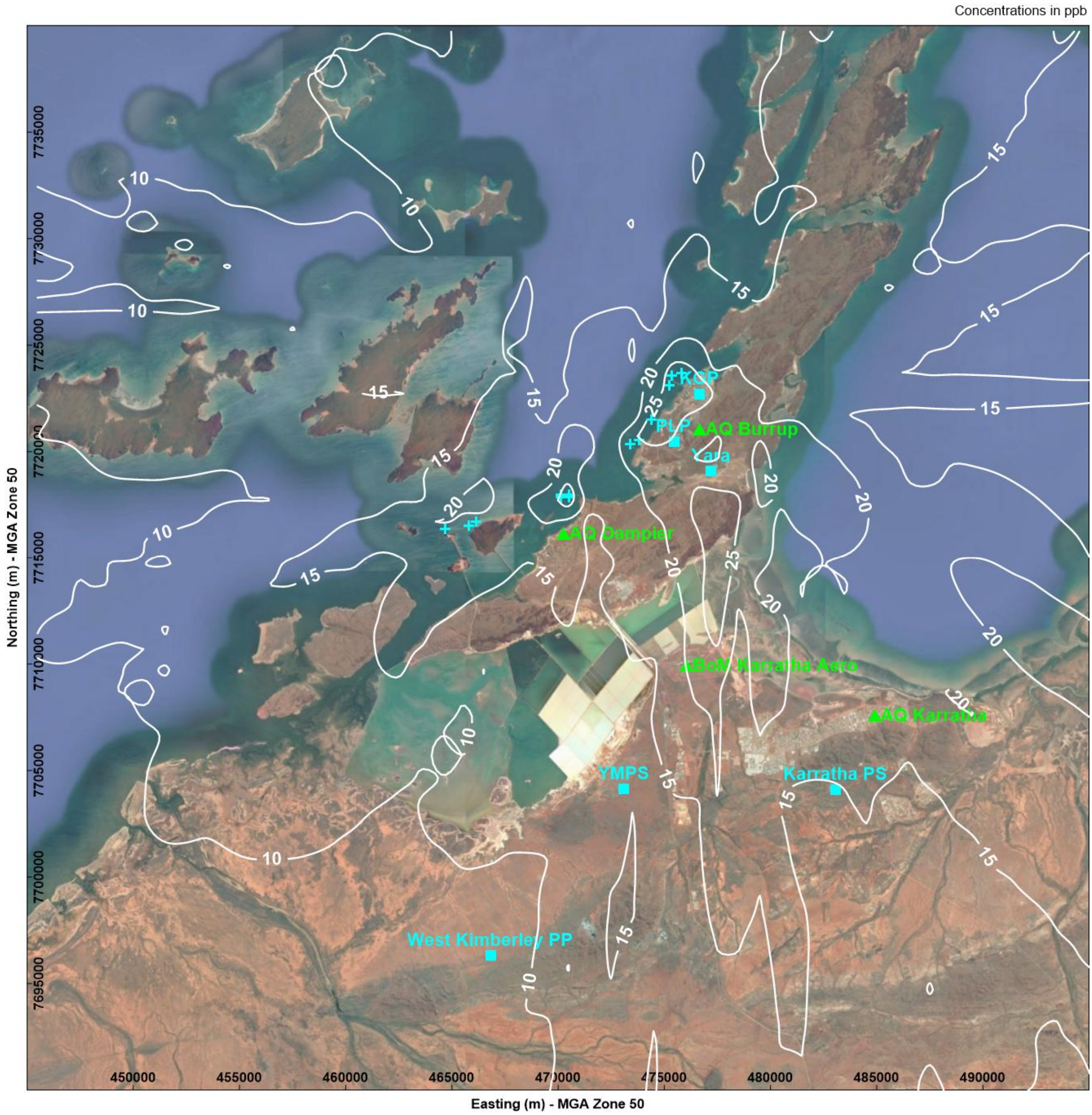



Figure 7-2: KIO – Maximum 1h $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 29.1 ppb.
- NEPM (Ambient Air Quality) standard, 120 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

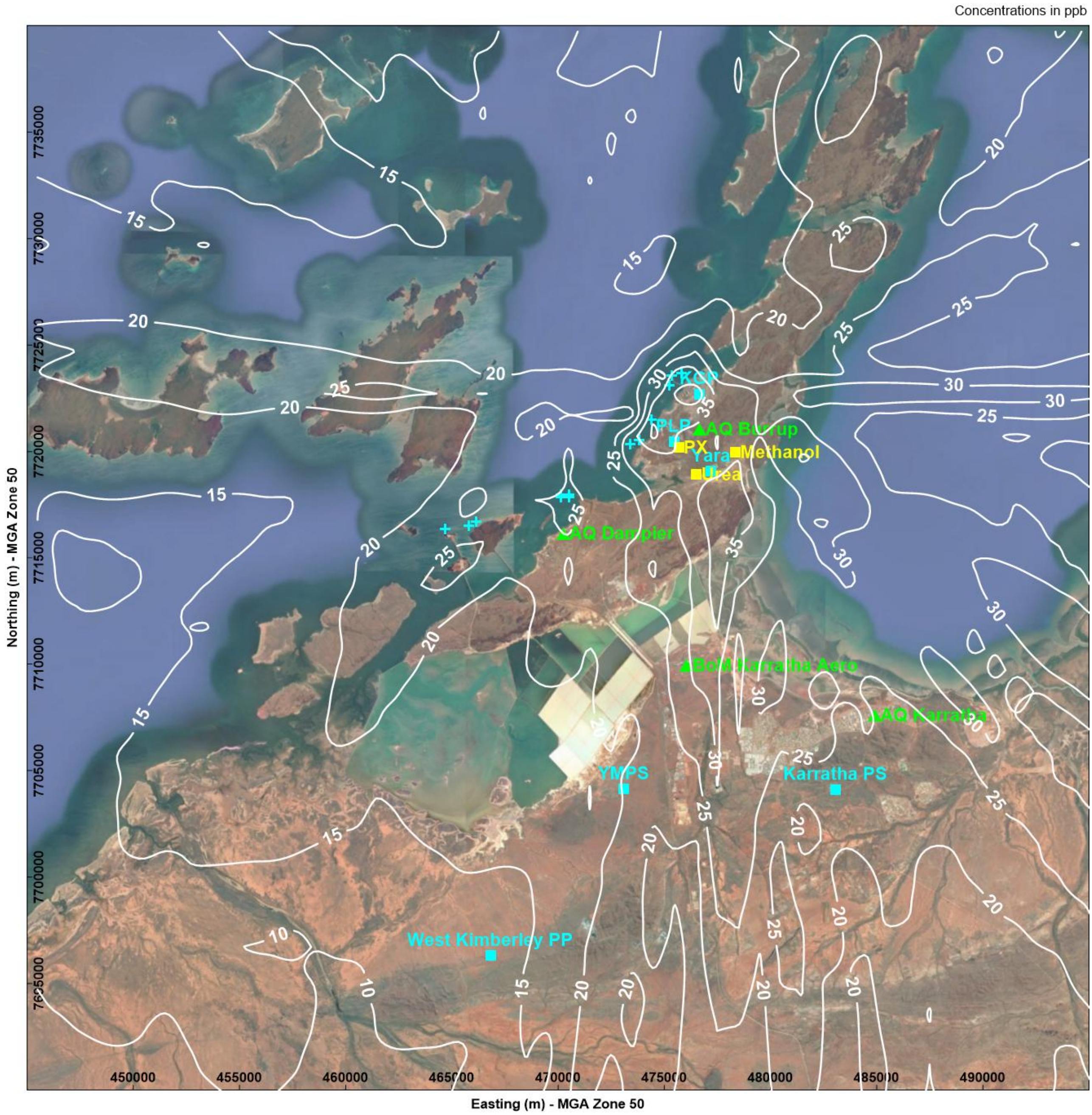



Figure 7-3: FBSIA – Maximum 1h $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 43.9 ppb.
- NEPM (Ambient Air Quality) standard, 120 ppb.
- Result of cumulative air quality impact assessment: no exceedances

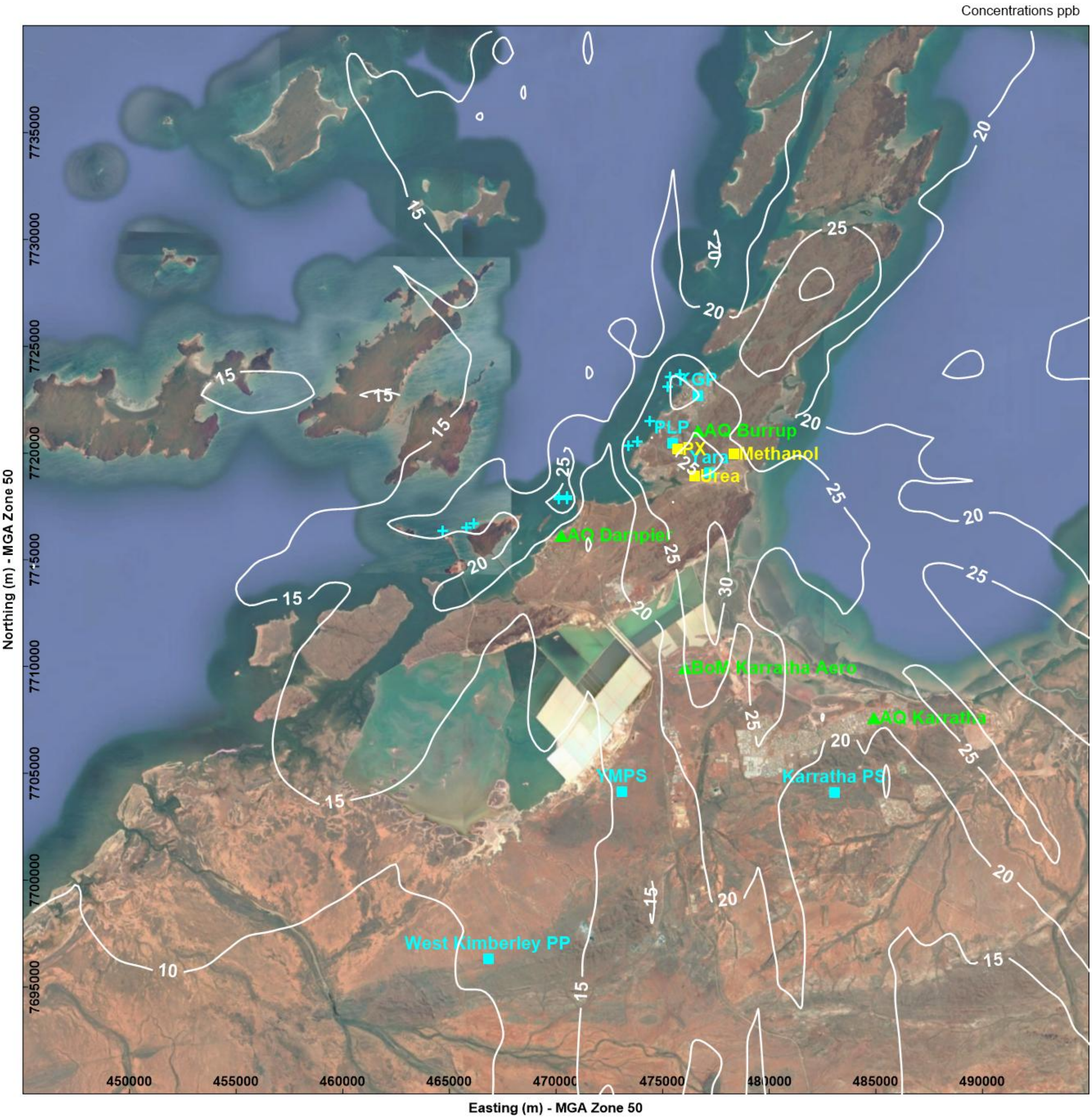



Figure 7-4: FBSIA-KIO – Maximum 1h $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 32.4 ppb.
- NEPM (Ambient Air Quality) standard, 120 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

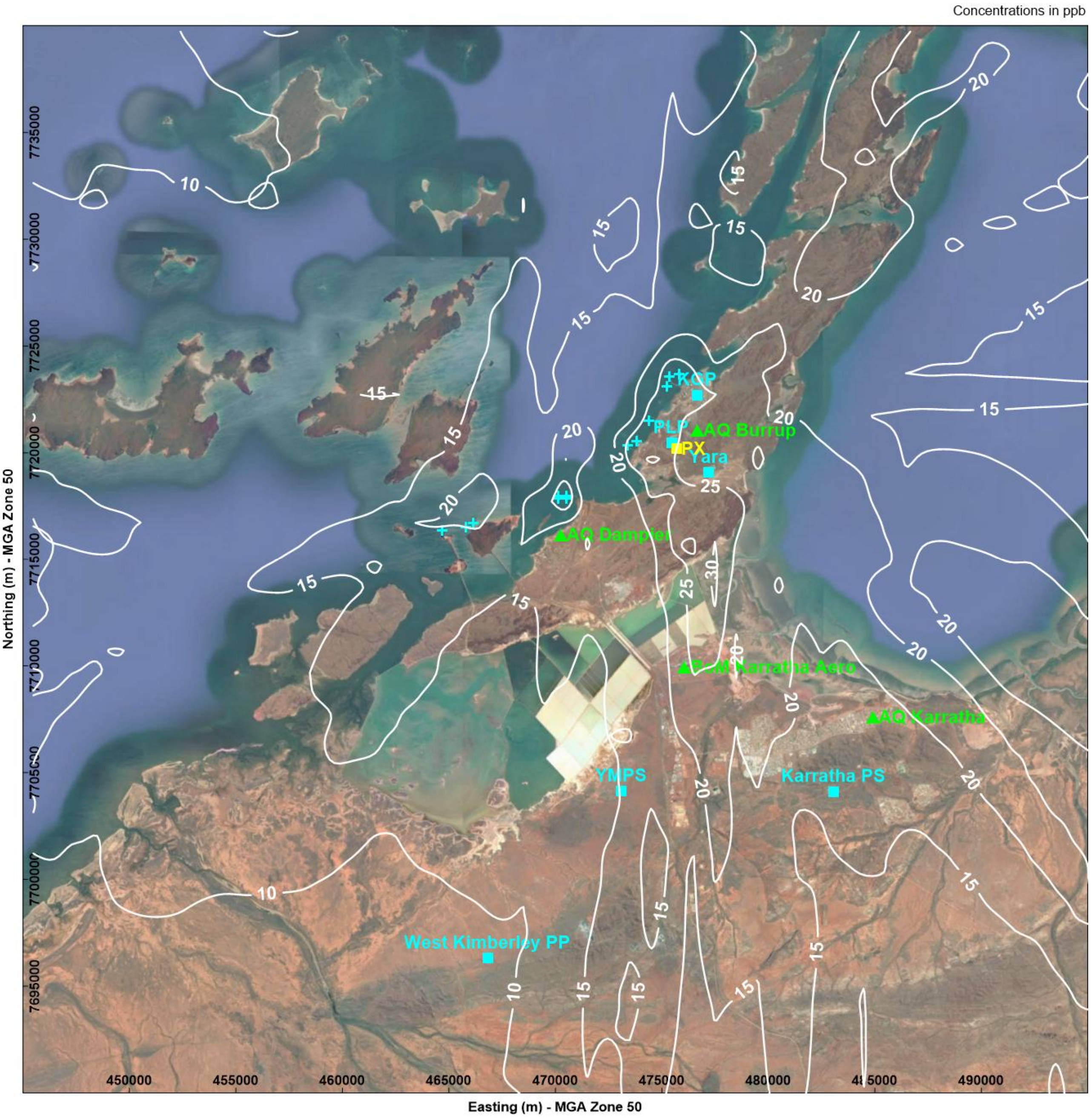



Figure 7-5: FBSIA E&A – Maximum 1h $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 30.7 ppb.
- NEPM (Ambient Air Quality) standard, 120 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

Concentrations in ppb

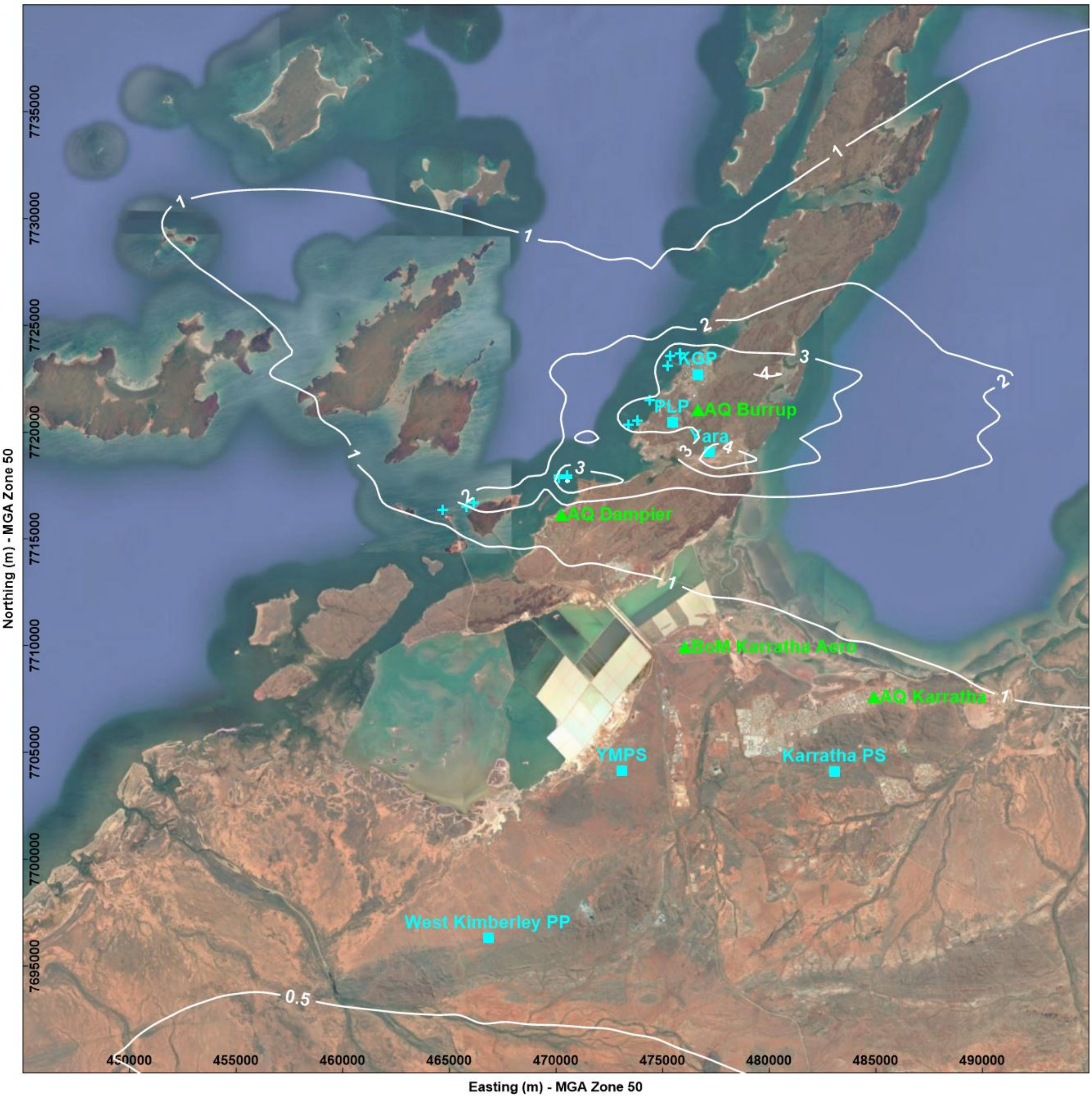



Figure 7-6: CBM – Annual Average $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 5.0 ppb.
- NEPM (Ambient Air Quality) standard, 30 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

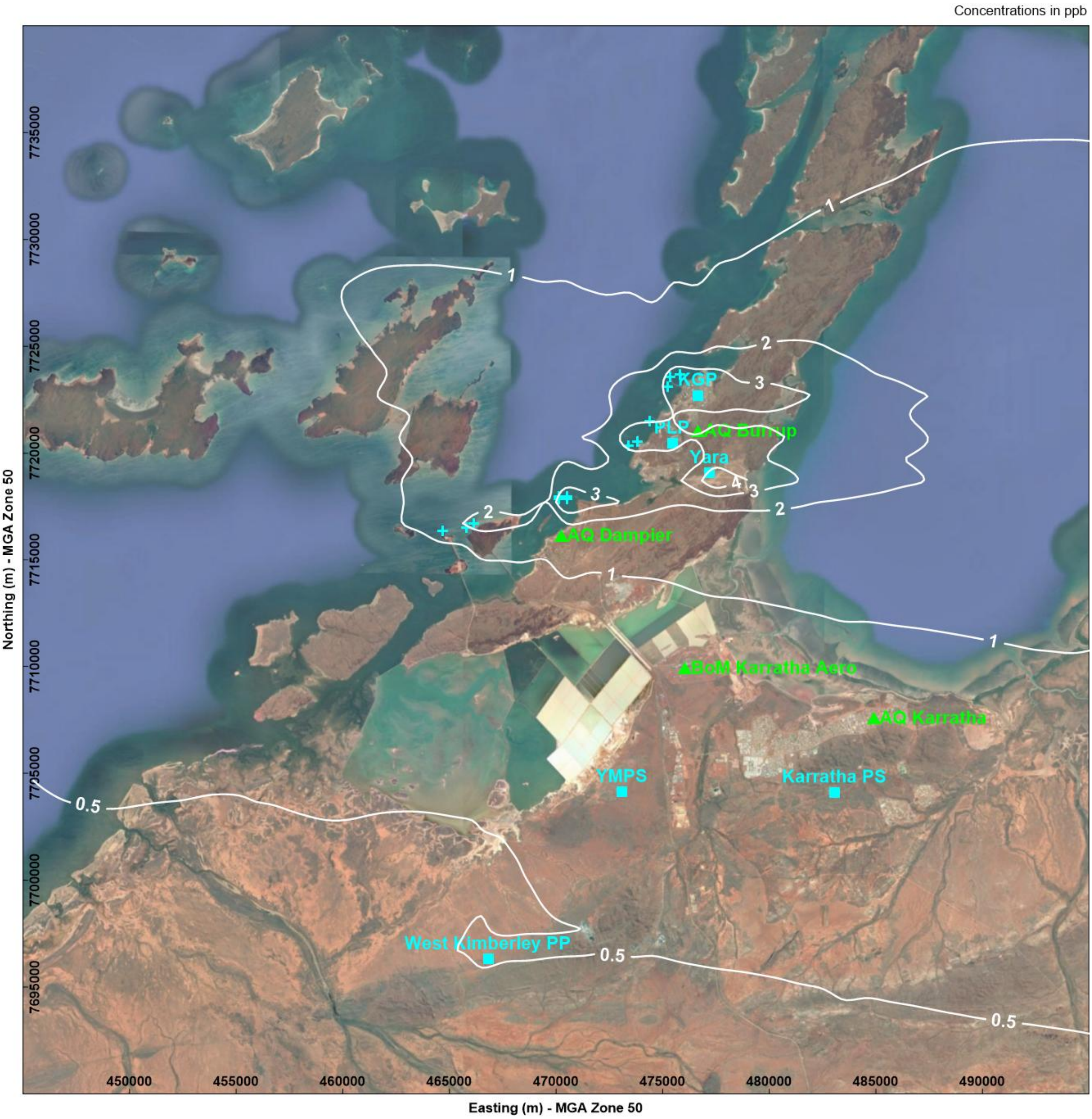



Figure 7-7: KIO – Annual Average $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 4.9 ppb.
- NEPM (Ambient Air Quality) standard, 30 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

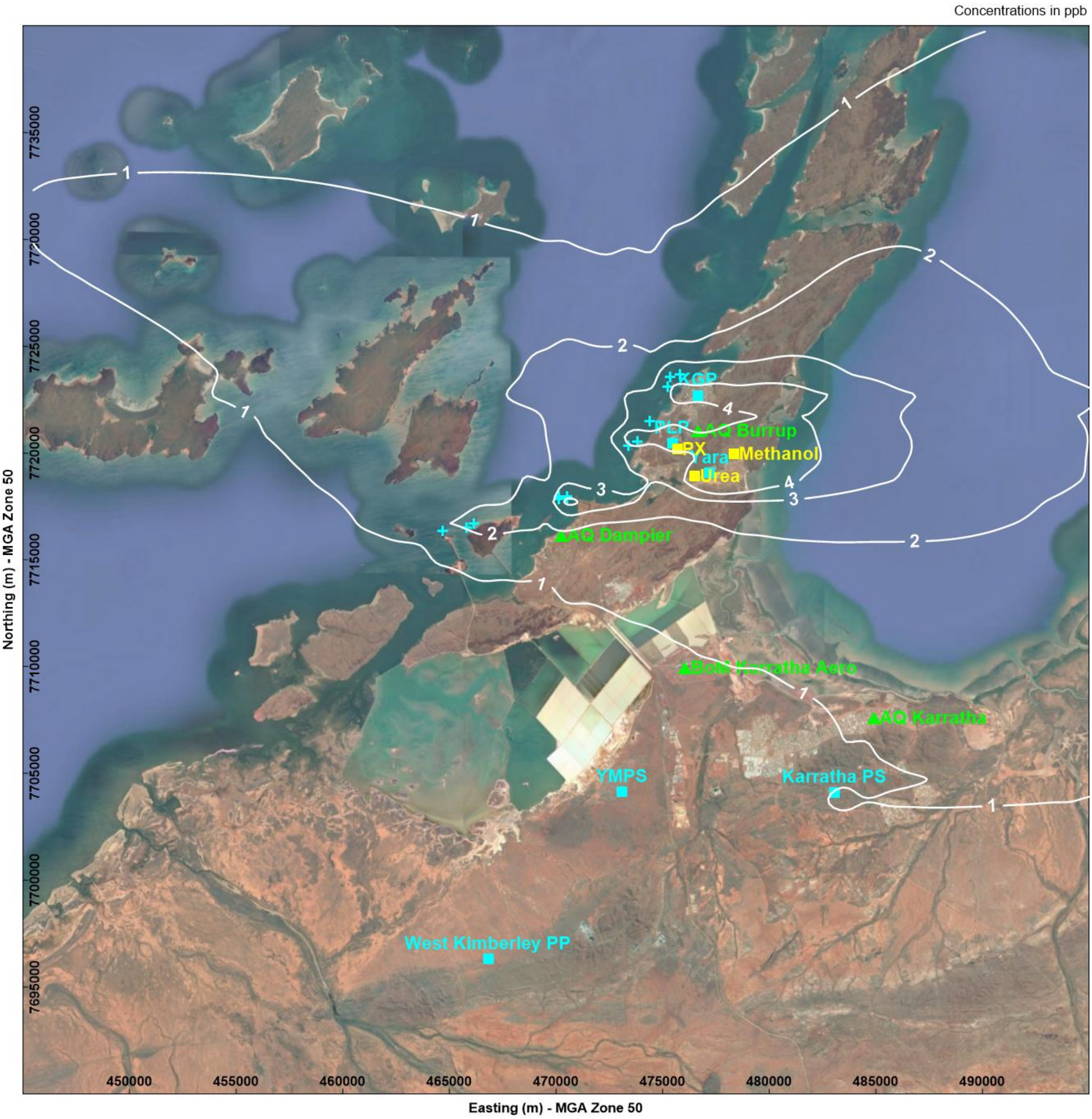



Figure 7-8: FBSIA – Annual Average $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 5.6 ppb.
- NEPM (Ambient Air Quality) standard, 30 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

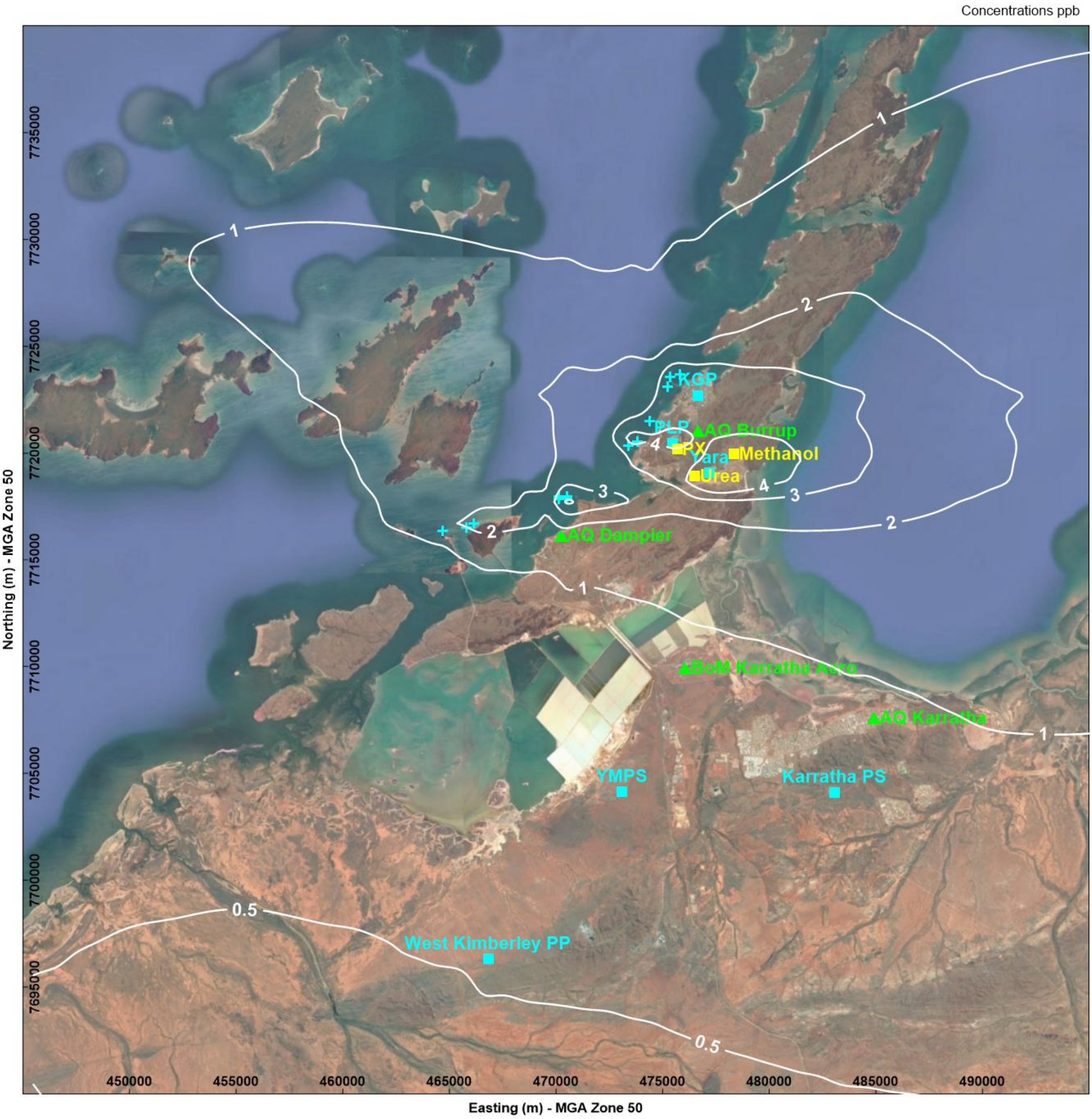



Figure 7-9: FBSIA-KIO – Annual Average $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 5.7 ppb.
- NEPM (Ambient Air Quality) standard, 30 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

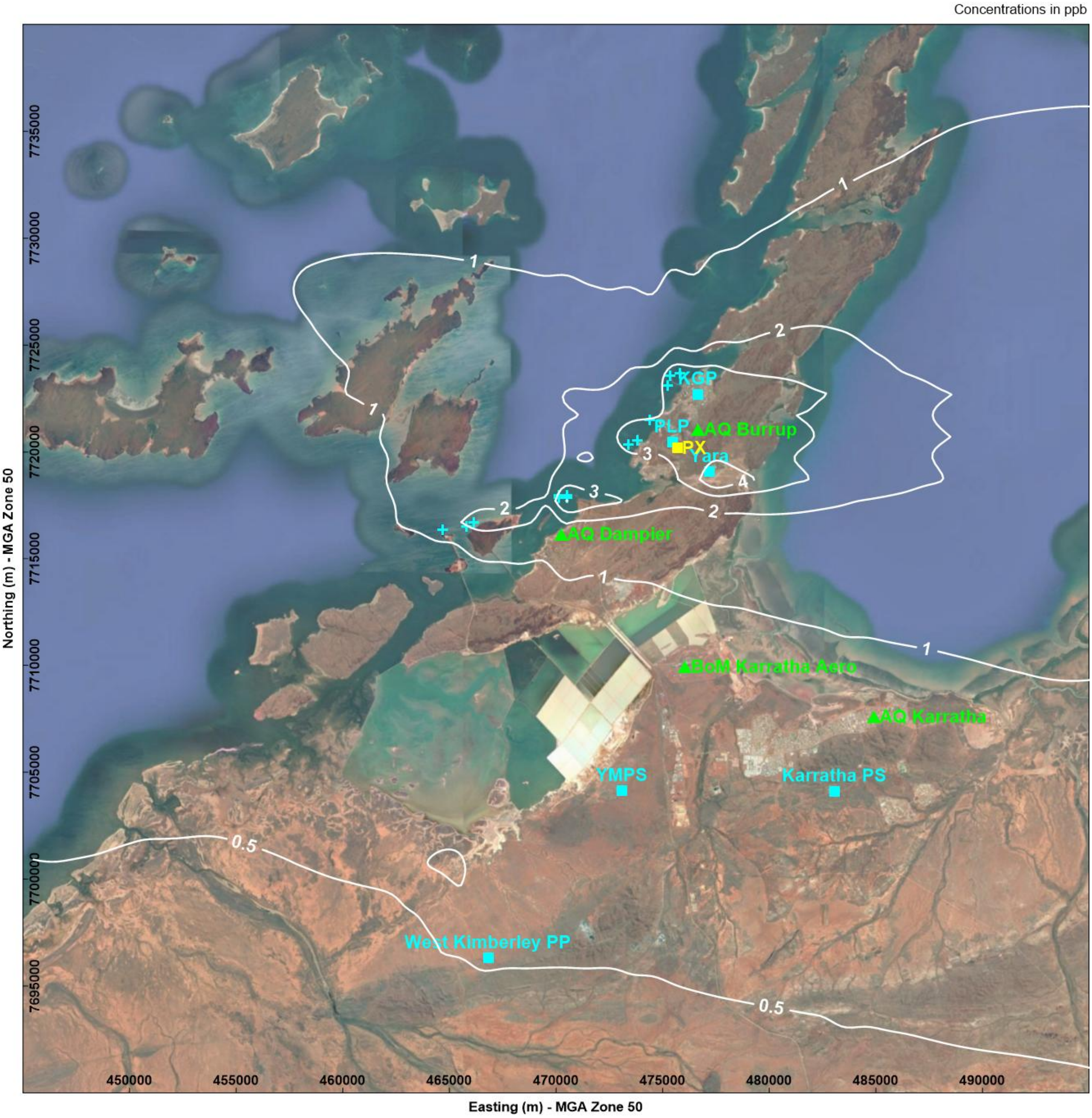



Figure 7-10: FBSIA E&A – Annual Average $NO_2$ concentrations (ppb)

- Maximum grid receptor concentration, 5.0 ppb.
- NEPM (Ambient Air Quality) standard, 30 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

## 7.3 $O_3$ Concentrations

The maximum 1-hour average $O_3$ concentrations for the five modelled air emissions scenarios at the sensitive receptors, and the grid maxima, are presented in Table 7-3. Contour plots of the maximum hourly average $O_3$ GLCs for the five scenarios are provided in Figure 7-11 (Current Baseline) through to Figure 7-15 (FBSIA E&A). All the results are less than the corresponding NEPM standard of 100 ppb.

Table 7-3: Maximum 1-hour Average $O_3$ Concentrations (ppb)- Grid Receptors

| Receptor | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| Karratha | 57.9 | 55.0 | 61.2 | 55.8 | 55.2 |
| Burrup | 58.7 | 55.4 | 58.4 | 55.6 | 55.6 |
| Dampier | 55.4 | 53.2 | 56.5 | 54.4 | 53.7 |
| Maximum on Grid | 61.8 | 59.2 | 63.0 | 61.0 | 60.0 |
| **NEPM Standard** | **100** | **100** | **100** | **100** | **100** |

It is noted the TAPM output for 4-hour average $O_3$ is not the 'rolling average' needed for assessment against the relevant NEPM standard (80 ppb). Therefore the 4-hour average results provided here are indicative. However, the step-wise 4-hour average $O_3$ results; i.e., the standard TAPM output, should provide a reasonable indication of the rolling 4-hour averages. The maximum 4-hour average $O_3$ concentrations for the three modelling scenarios at the sensitive receptors and anywhere on the grid are presented in Table 7-4.

Table 7-4: Maximum 4-hour Average $O_3$ Concentrations (ppb)- Grid Receptors

| Receptor | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| Karratha | 56.3 | 51.2 | 59.1 | 53.8 | 51.8 |
| Burrup | 54.3 | 51.7 | 53.7 | 51.7 | 51.9 |
| Dampier | 52.5 | 50.5 | 53.6 | 51.8 | 51.0 |
| Maximum on Grid | 58.2 | 55.3 | 59.7 | 57.4 | 56.1 |
| **NEPM Standard** | **80** | **80** | **80** | **80** | **80** |

The results for maximum 1-hour and maximum 4-hour average $O_3$ GLCs show relevant NEPM standards are unlikely to be exceeded anywhere in the study area; at least in relation to the industrial $NO_x$ sources. Other 'natural' sources of $O_3$, such as bushfires, were not included in the modelling, and potentially these could cause exceedances of $O_3$ standards.

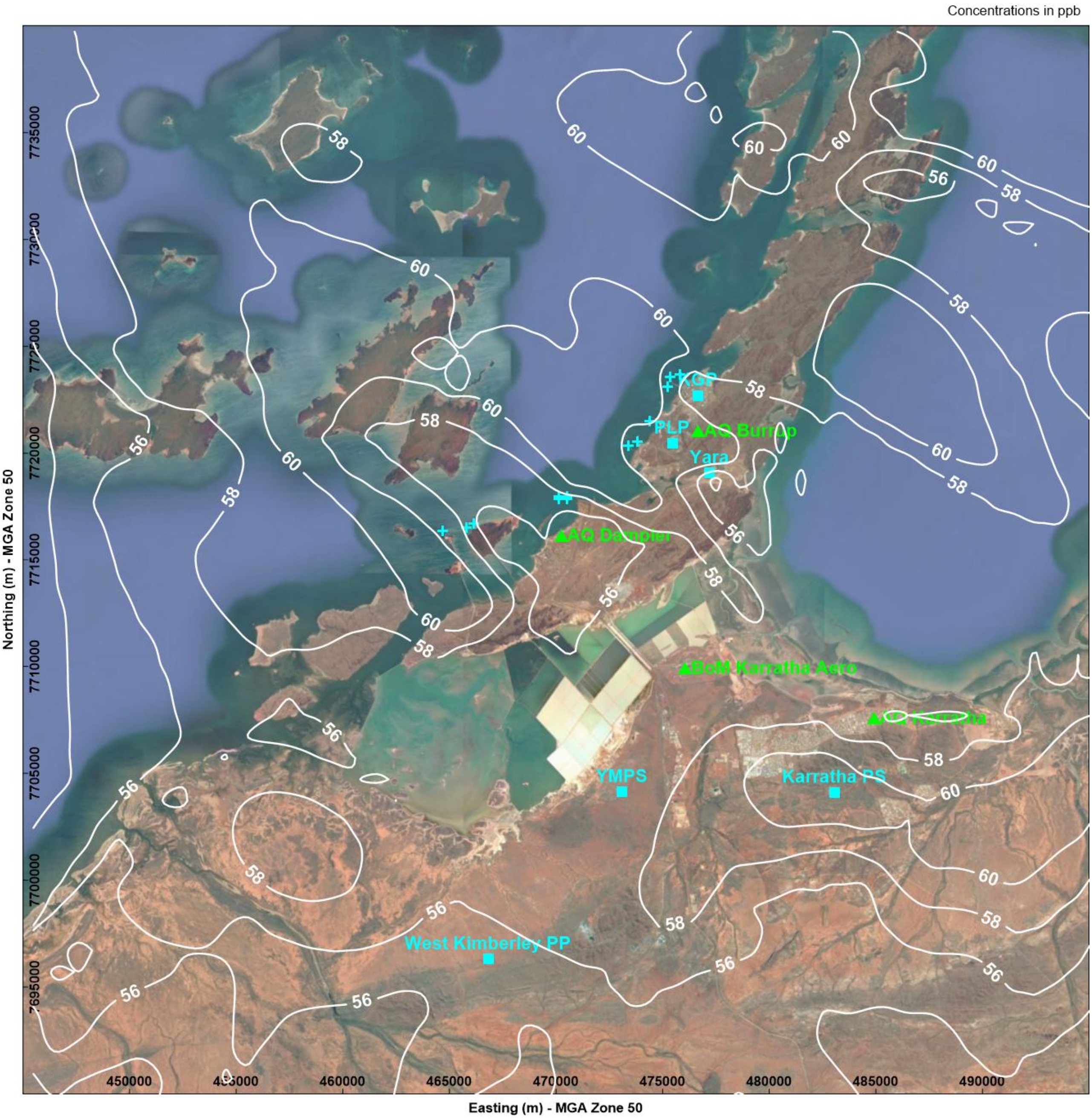



Figure 7-11: CBM – Maximum 1-hour Average $O_3$ Concentrations (ppb)

- Maximum grid receptor concentration, 61.8 ppb.
- NEPM (Ambient Air Quality) standard, 100 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

Concentrations in ppb

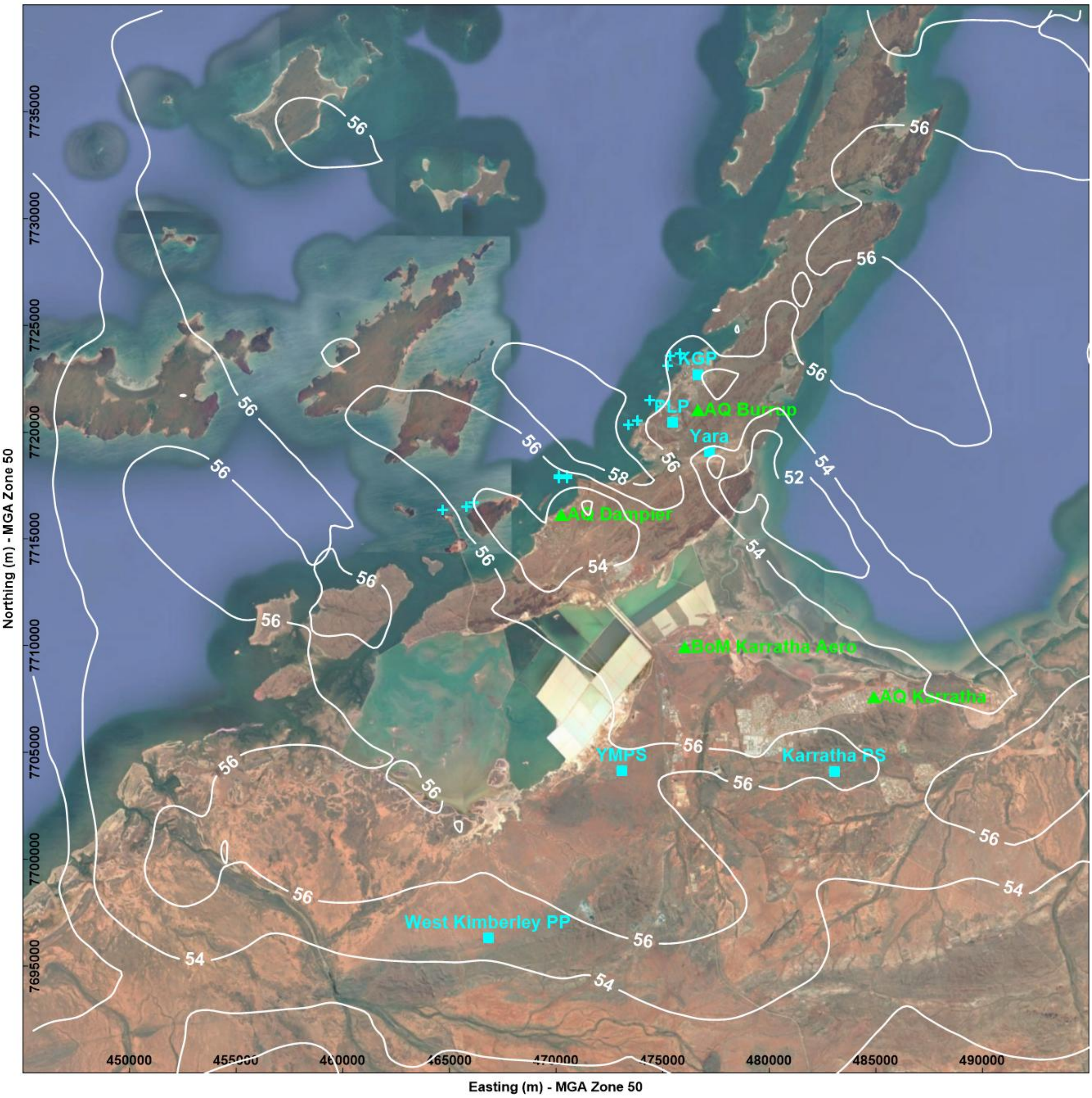



Figure 7-12: KIO – Maximum 1-hour Average $O_3$ Concentrations (ppb)

- Maximum grid receptor concentration, 59.2 ppb.
- NEPM (Ambient Air Quality) standard, 100 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

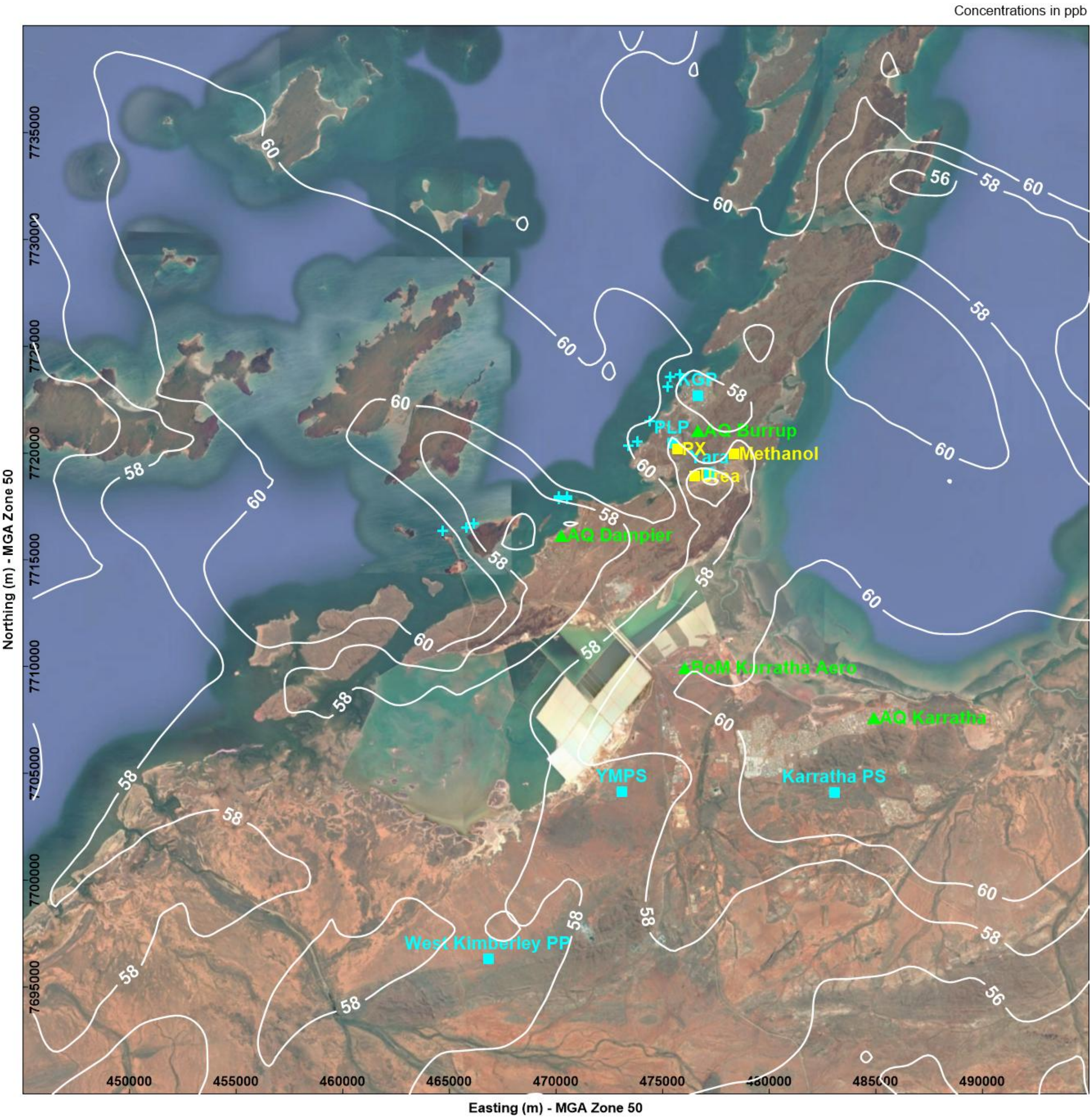



Figure 7-13: FBSIA – Maximum 1-hour Average $O_3$ Concentrations (ppb)

- Maximum grid receptor concentration, 63.0 ppb.
- NEPM (Ambient Air Quality) standard, 100 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

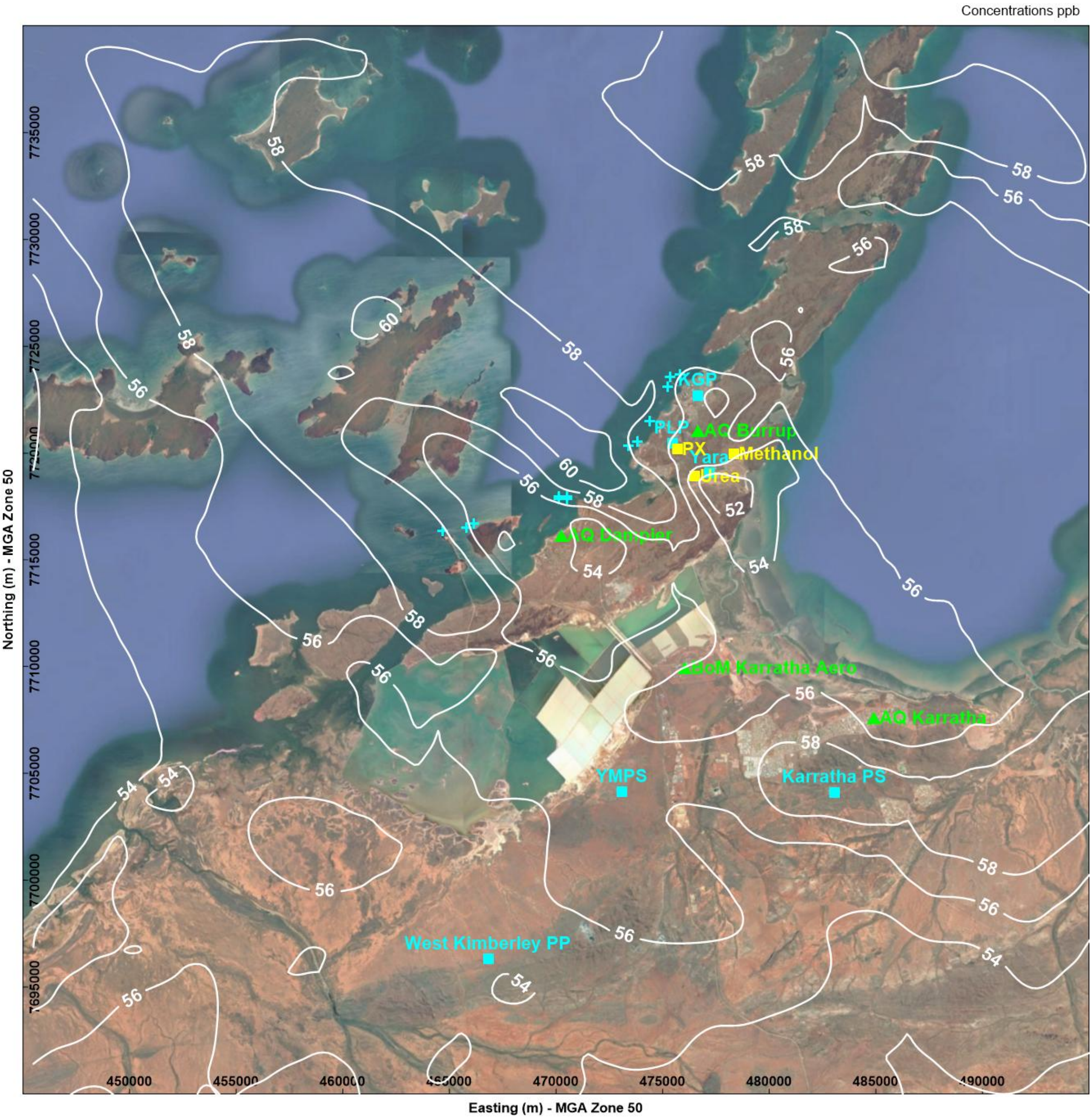



Figure 7-14: FBSIA-KIO – Maximum 1-hour Average $O_3$ Concentrations (ppb)

- Maximum grid receptor concentration, 61.0 ppb.
- NEPM (Ambient Air Quality) standard, 100 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

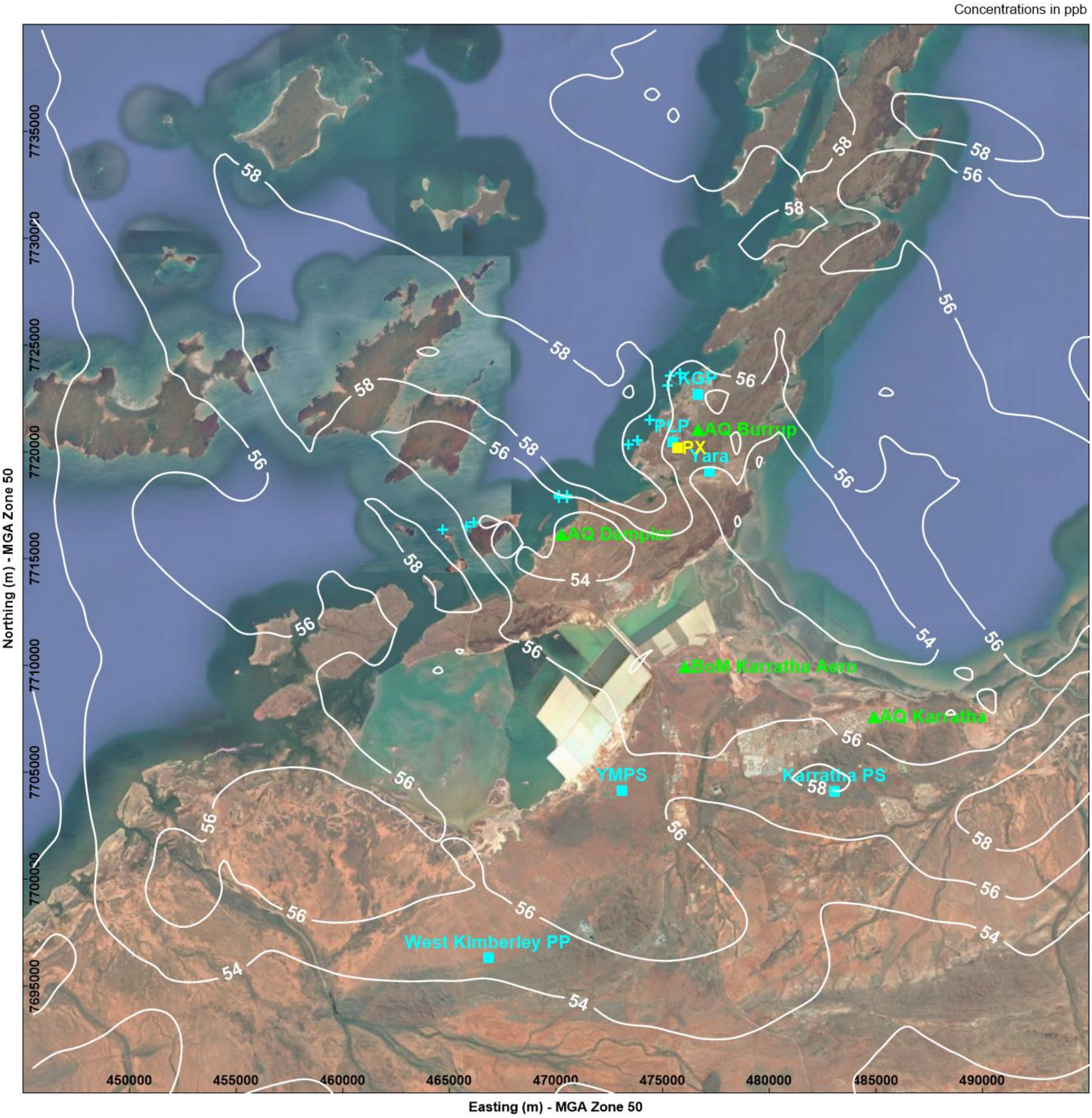



Figure 7-15: FBSIA E&A – Maximum 1-hour Average $O_3$ Concentrations (ppb)

- Maximum grid receptor concentration, 60.0 ppb.
- NEPM (Ambient Air Quality) standard, 100 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

## 7.4 $SO_2$ Concentrations

The model results for the $SO_2$ GLCs for the five modelled air emissions scenarios at the three sensitive receptor locations, Karratha, Burrup and Dampier, and the grid maxima, are presented in Table 7-5 (maximum 1-hour averages), Table 7-6 (maximum 24-hour averages), and Table 7-7 (annual averages). These results show that the relevant NEPM standards are not expected to be exceeded anywhere in the study area. It is noted that $SO_2$ concentrations are expected to decrease from 1 January 2020 with the introduction of low sulfur fuel requirements for ships by the International Maritime Organization (IMO) (section 7.5). However, this emissions reduction was not factored into the modelling scenarios.

Table 7-5: Maximum 1-hour Average $SO_2$ Concentrations (ppb)

| Receptor | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| Karratha | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 |
| Burrup | 11.3 | 11.2 | 11.4 | 11.3 | 11.3 |
| Dampier | 12.9 | 13.3 | 12.9 | 13.3 | 13.3 |
| Maximum on Grid | 18.1 | 18.2 | 18.1 | 18.2 | 18.2 |
| **NEPM Standard** | **200** | **200** | **200** | **200** | **200** |

Table 7-6: Maximum 24-hour Average $SO_2$ Concentrations (ppb)

| Receptor | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| Karratha | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| Burrup | 4.7 | 4.7 | 4.8 | 4.7 | 4.7 |
| Dampier | 4.6 | 4.5 | 4.6 | 4.5 | 4.5 |
| Maximum on Grid | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 |
| **NEPM Standard** | **80** | **80** | **80** | **80** | **80** |

Table 7-7: Annual Average $SO_2$ Concentrations (ppb)

| Receptor | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| Karratha | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| Burrup | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Dampier | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Maximum on Grid | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| **NEPM Standard** | **20** | **20** | **20** | **20** | **20** |

The $SO_2$ emission rates varied by very little between the scenarios. As such, only one set of contour plots is provided for the Current Baseline scenario, which is representative of all five model scenarios. The results are provided in Figure 7-16 (maximum 1-hour average $SO_2$), Figure 7-17 (maximum 24-hour average $SO_2$), and Figure 7-18 (annual average $SO_2$).

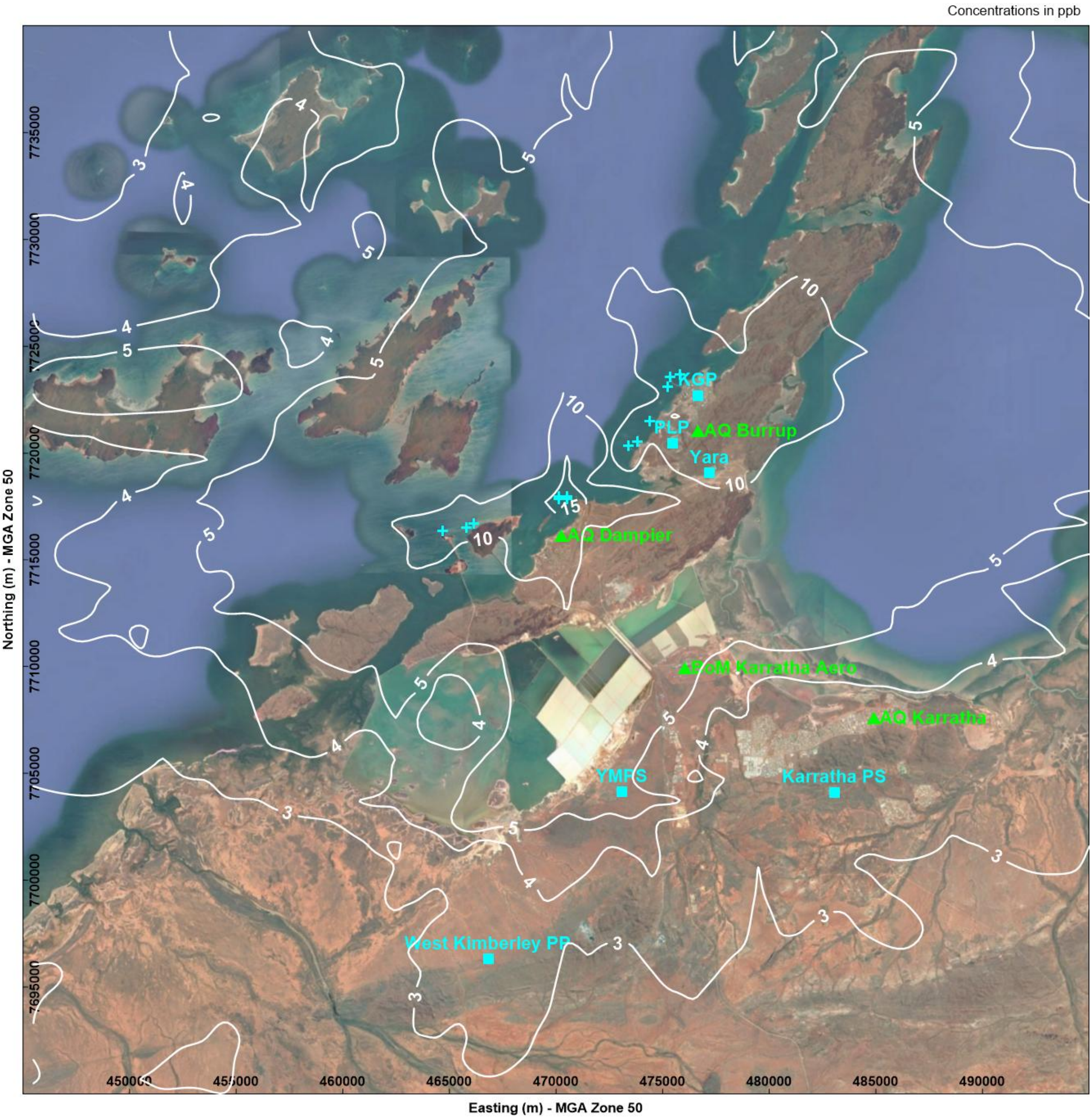



Figure 7-16: CBM – Maximum 1-hour Average $SO_2$ Concentrations (ppb)

- Maximum grid receptor concentration, 18.1 ppb.
- NEPM (Ambient Air Quality) standard, 200 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

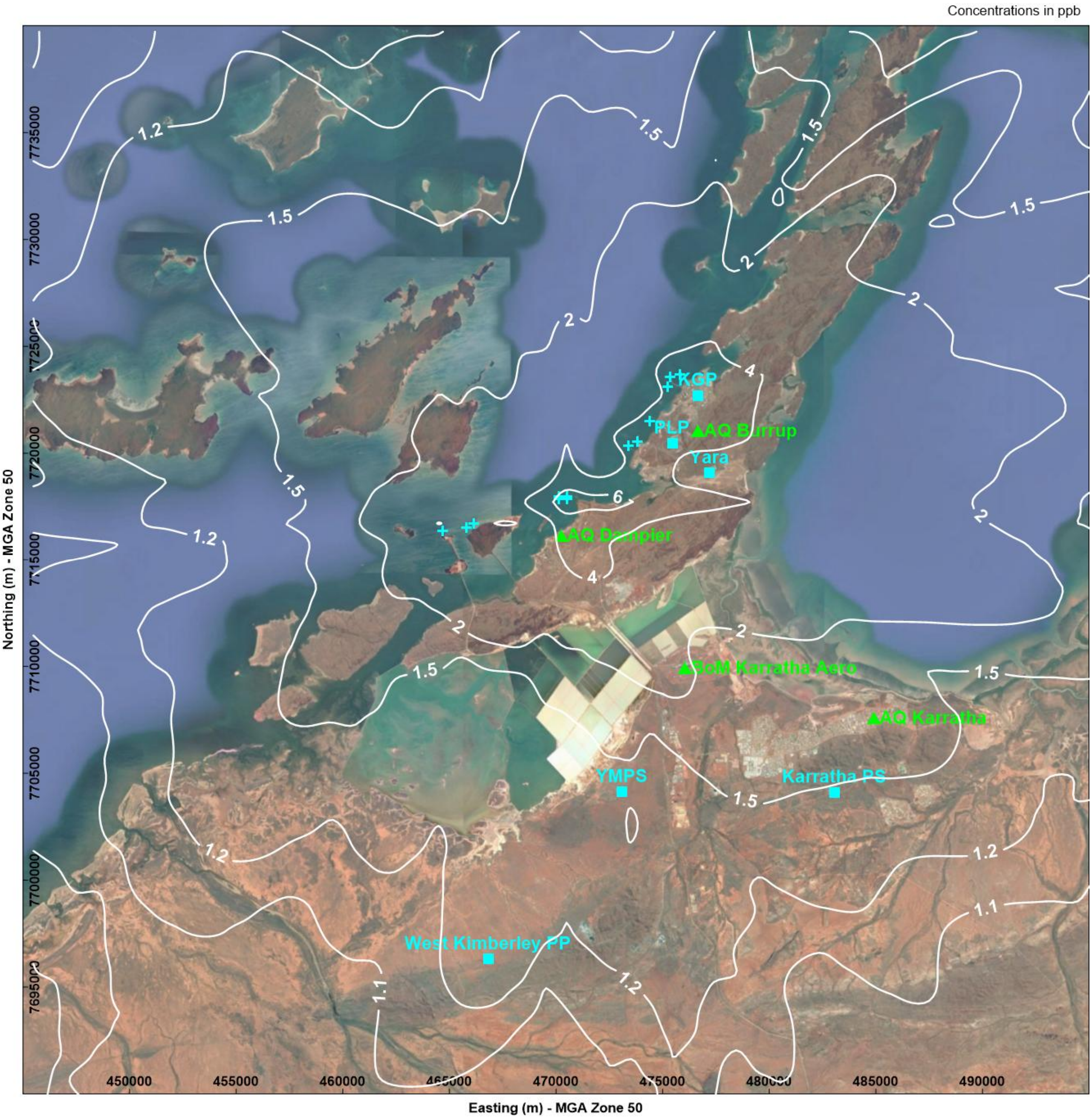



Figure 7-17: CBM – Maximum 24-hour Average $SO_2$ Concentrations (ppb)

- Maximum grid receptor concentration, 7.0 ppb.
- NEPM (Ambient Air Quality) standard, 80 ppb.
- Result of cumulative air quality impact assessment: no exceedances

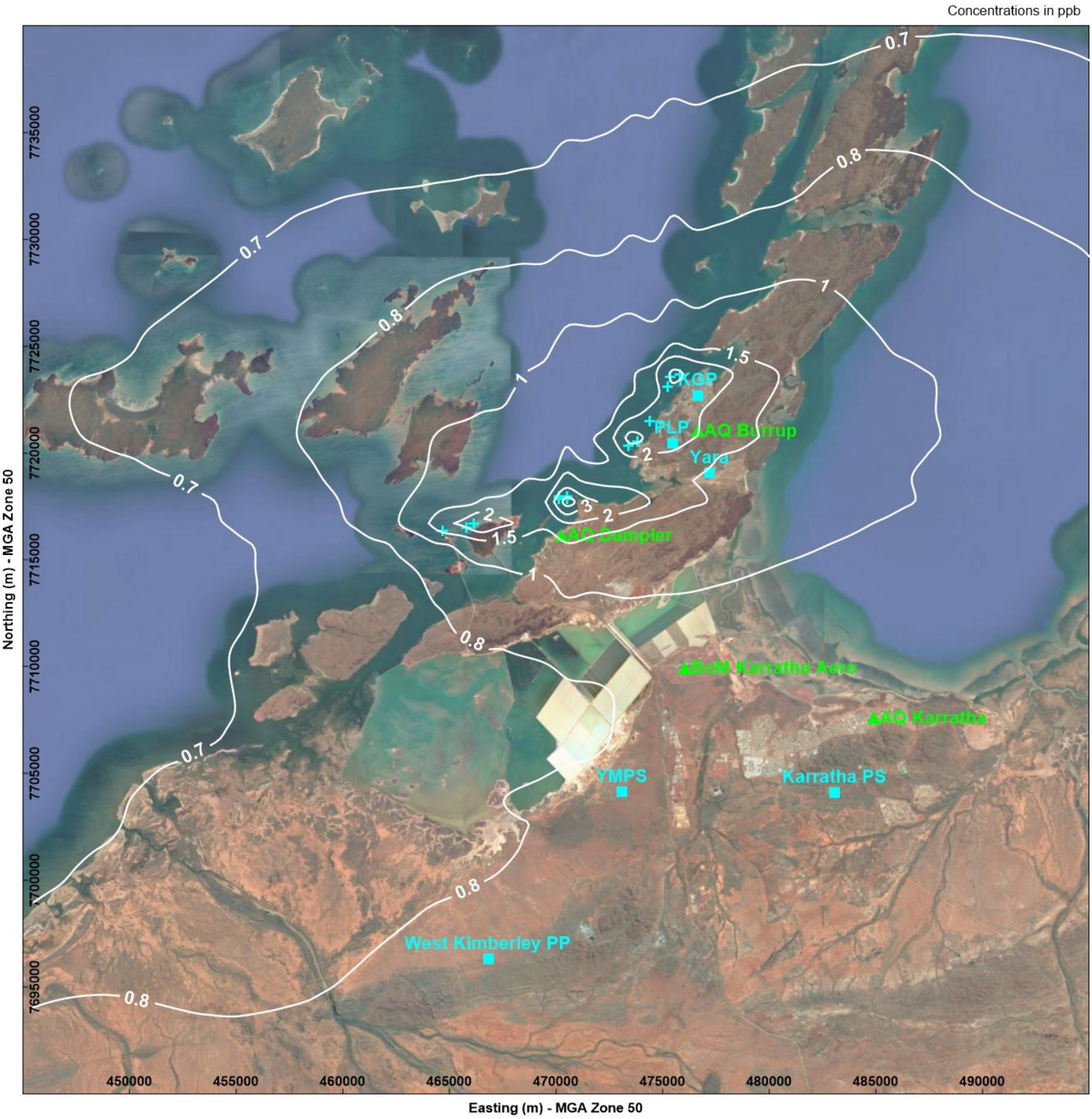



Figure 7-18: CBM – Annual Average $SO_2$ Concentrations (ppb)

- Maximum grid receptor concentration, 4.5 ppb.
- NEPM (Ambient Air Quality) standard, 20 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

## 7.5 Potential Effects on Vegetation

The purpose of this section is to provide the results of an assessment on the potential effects on vegetation health due to airborne $NO_x$ and $SO_2$ emissions. The relevant standards for assessment are the project standards detailed in Section 2.4; these are also listed in Table 7-8.

The maximum annual average $NO_x$ results (ppb) for each of the five scenarios are provided in Table 7-8. All values are less than 16 ppb, which is well below the relevant EU (2008) standard of 16 ppb (we have converted the EU standard of 20 µg/m$^3$ to 16 ppb using the temperature 30$^o$C).

Also, the maximum annual average $SO_2$ results (ppb) for each of the five scenarios are provided in Table 7-8. All values are less than 5 ppb, which is well below the relevant EU (2008) standard of 8 ppb. For all five scenarios, the highest concentrations were predicted for locations adjacent to the shipping berths, which were conservatively modelled as continuous sources; e.g., see Figure 7-18, provided in the preceding Section 7.4. It is noted that the future IMO requirements to reduce the sulfur content of fuel for shipping (Section 7.4), is likely to lower the future risk of impact on vegetation from $SO_2$ emissions (AMSA, 2018). However, this emissions reduction was not factored into the modelling scenarios.

Results for the two new Proposal scenarios for annual $NO_x$ are provided in Figure 7-22 (FBSIA-KIO) and Figure 7-23 (FBSIA E&A); for annual $SO_2$ results, see the CBM results in Figure 7-18.

Table 7-8: Maximum Grid concentrations for the three scenarios for Assessment of Vegetation Effects

| Assessment Parameter | EU 2008 Veg. Standard (ppb) | CBM (ppb) | KIO (ppb) | FBSIA (ppb) | FBSIA-KIO (ppb) | FBSIA E&A (ppb) | Max. Fraction of Standard |
|---|---|---|---|---|---|---|---|
| Annual average $NO_x$ | 16.2 ppb (from 30 µg/m$^3$ as $NO_2$ at 30$^o$C) | 7.7 | 7.4 | 9.0 | 8.8 | 7.7 | 56% |
| Annual average $SO_2$ | 7.8 ppb (from 20 µg/m$^3$ at 30$^o$C) | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 58% |

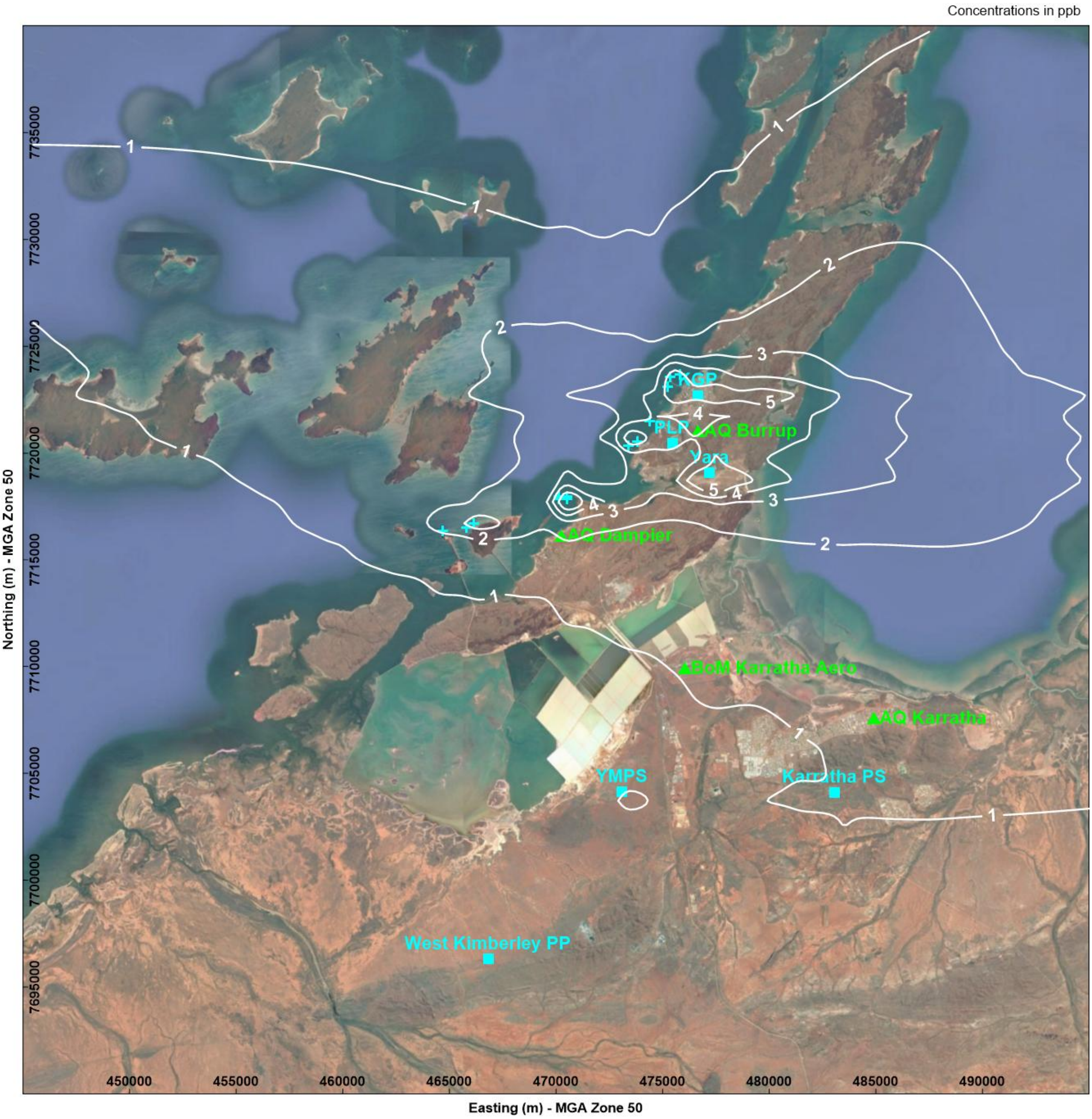



Figure 7-19: CBM- Annual Average $NO_X$ Concentrations (ppb)

- Maximum grid receptor concentration, 7.7 ppb.
- EU (2008) standard for protection of vegetation, 16.2 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

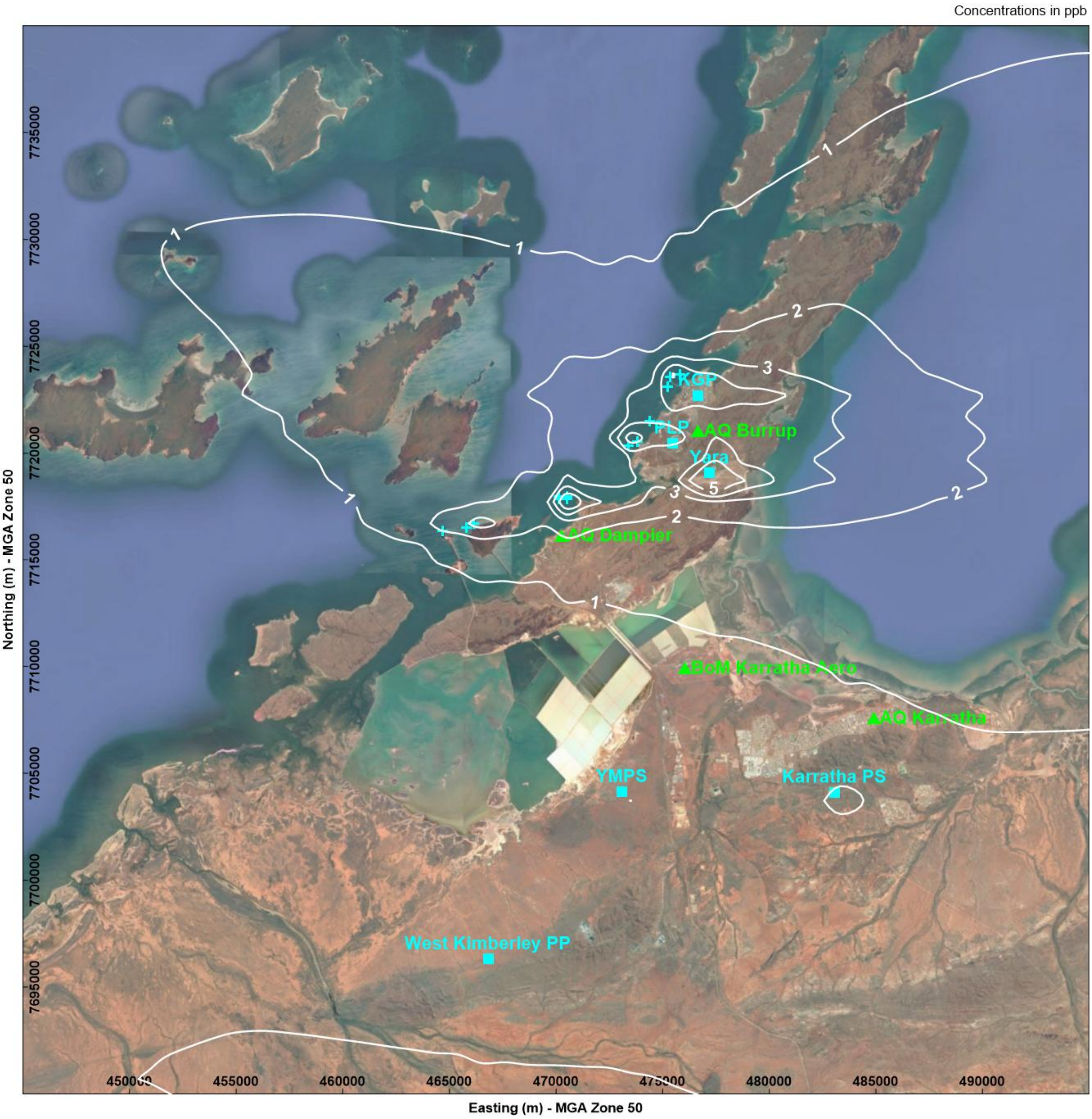



Figure 7-20: KIO- Annual Average $NO_X$ Concentrations (ppb)

- Maximum grid receptor concentration, 7.4 ppb.
- EU (2008) standard for protection of vegetation, 16.2 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

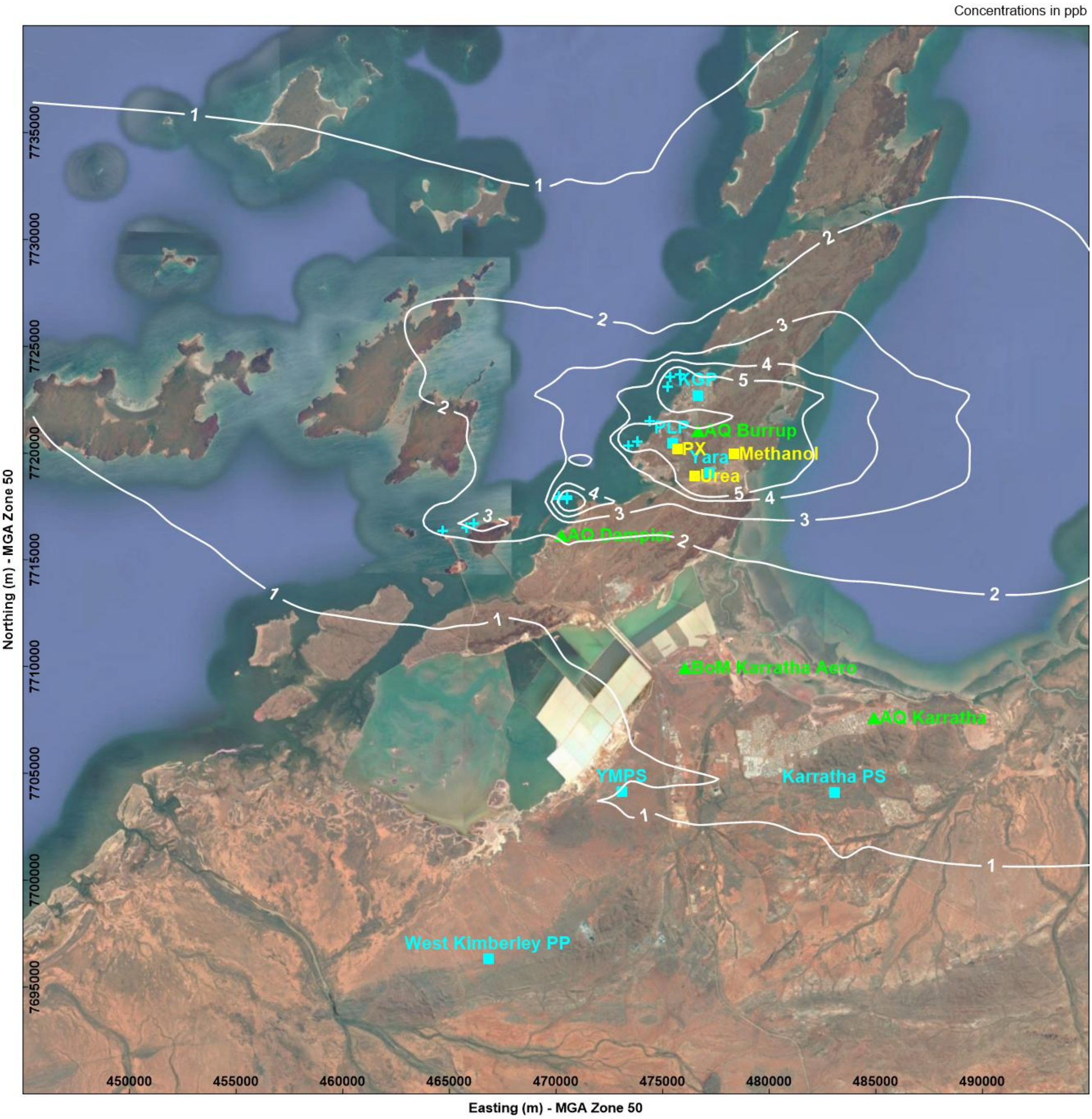



Figure 7-21: FBSIA- Annual Average $NO_X$ Concentrations (ppb)

- Maximum grid receptor concentration, 9.0 ppb.
- EU (2008) standard for protection of vegetation, 16.2 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

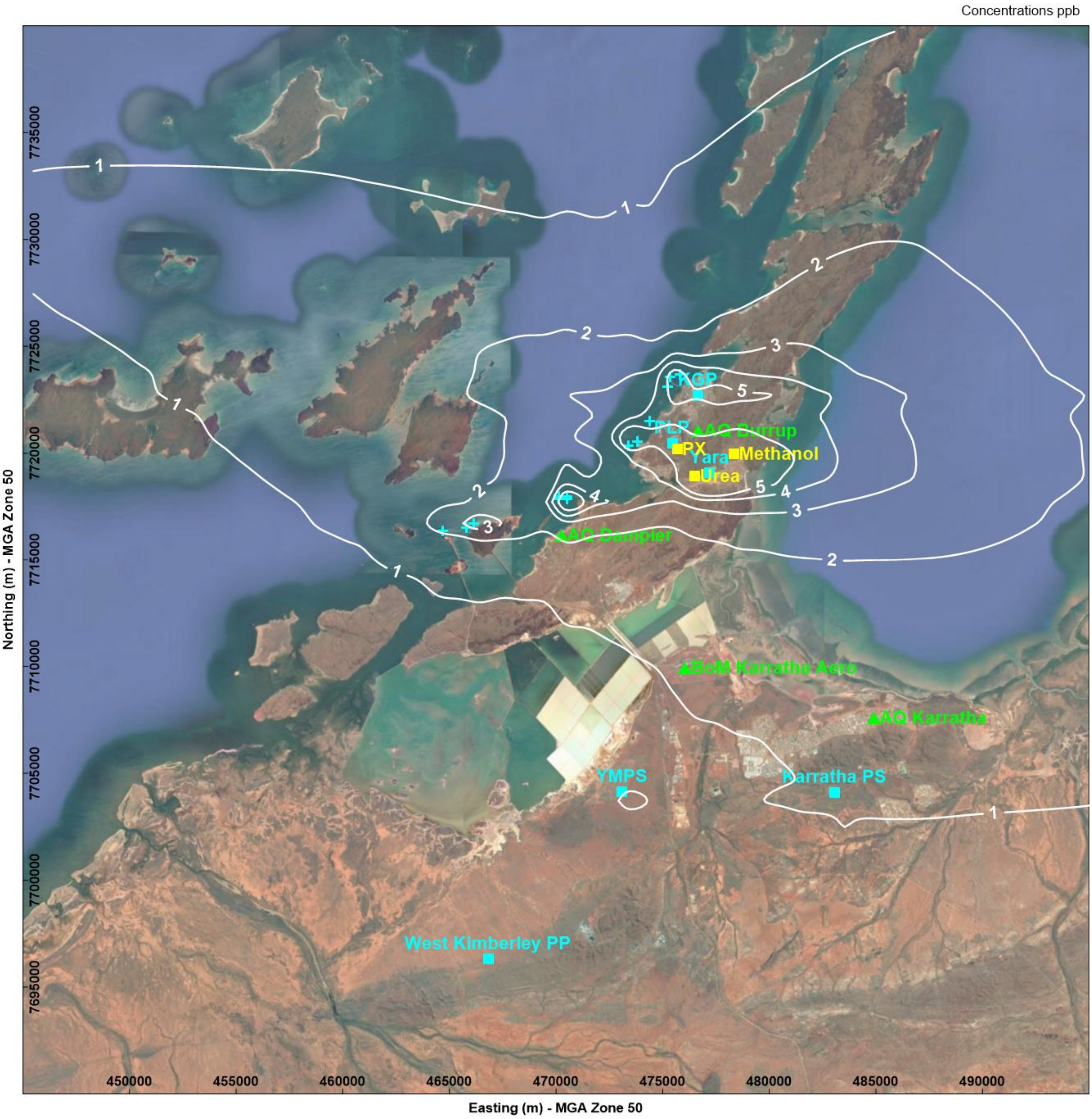



Figure 7-22: FBSIA- KIO- Annual Average $NO_X$ Concentrations (ppb)

- Maximum grid receptor concentration, 8.8 ppb.
- EU (2008) standard for protection of vegetation, 16.2 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

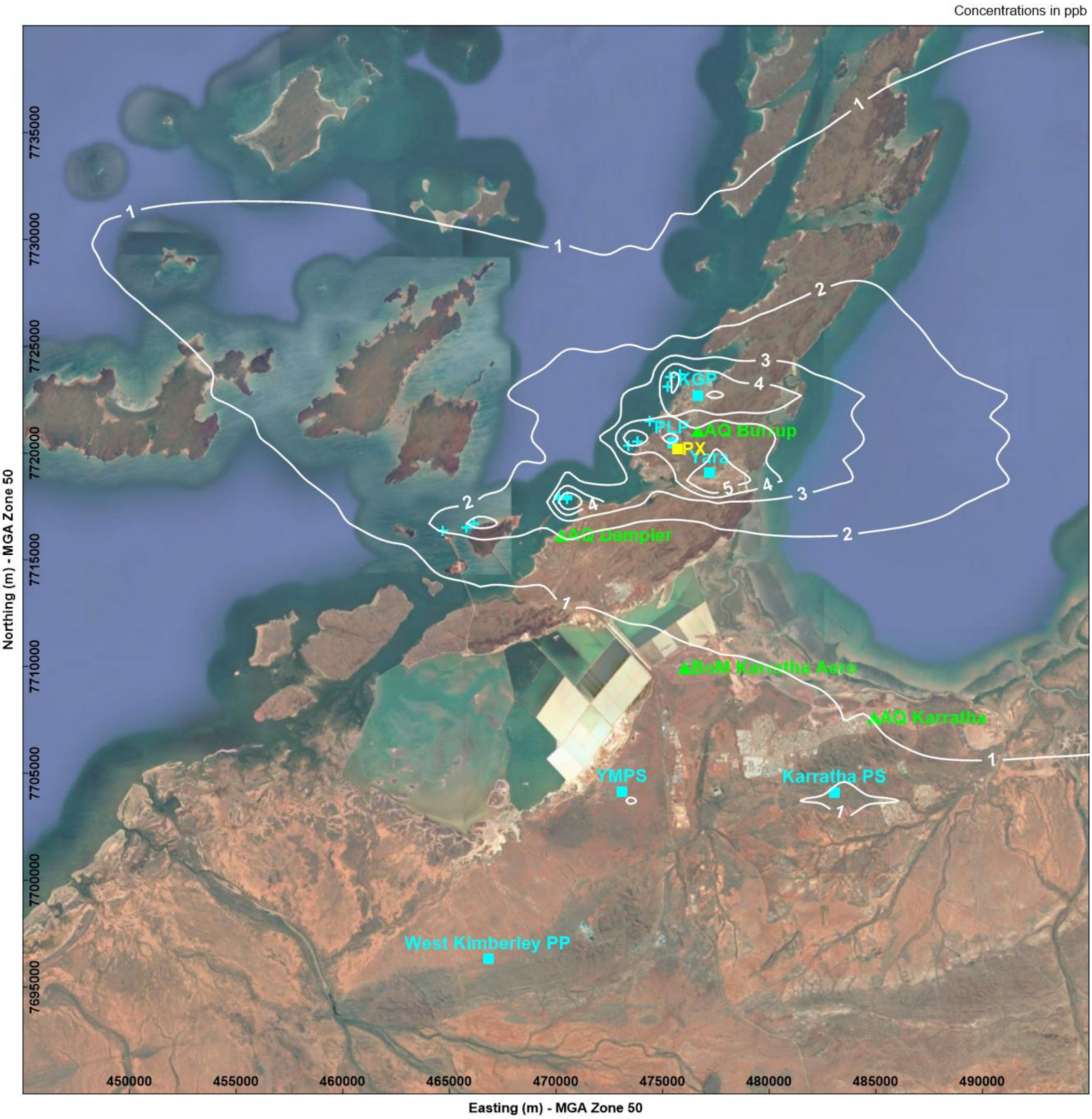



Figure 7-23: FBSIA E&A- Annual Average $NO_X$ Concentrations (ppb)

- Maximum grid receptor concentration, 7.7 ppb.
- EU (2008) standard for protection of vegetation, 16.2 ppb.
- Result of cumulative air quality impact assessment: no exceedances.

## 7.6 Deposition of $NO_2$ and $SO_2$

This section provides a summary of modelling results for the deposition of $NO_2$ and $SO_2$. The scope of works excludes an impact assessment or analysis of these results as there are no approved deposition standards for the assessment of environmental impacts on land surfaces. (For the assessment of effects on vegetation health, see the results for annual average $NO_x$ and $SO_2$ provided in the previous section).

Results for modelled deposition for the five air emissions scenarios are provided in the following series of plots:

- Annual average $NO_2$ deposition (kg/ha/year); Figure 7-24 through to Figure 7-28.
- Annual average $NO_2$ deposition (meq/m$^2$/year); Figure 7-29 through to Figure 7-33.
- Annual average $SO_2$ deposition (kg/ha/year); Figure 7-34. It is relevant to note that the $SO_2$ deposition rates varied by very little between the scenarios. As such, only one set of contour plots is provided for the Current Baseline scenario, which is representative of all five model scenarios.

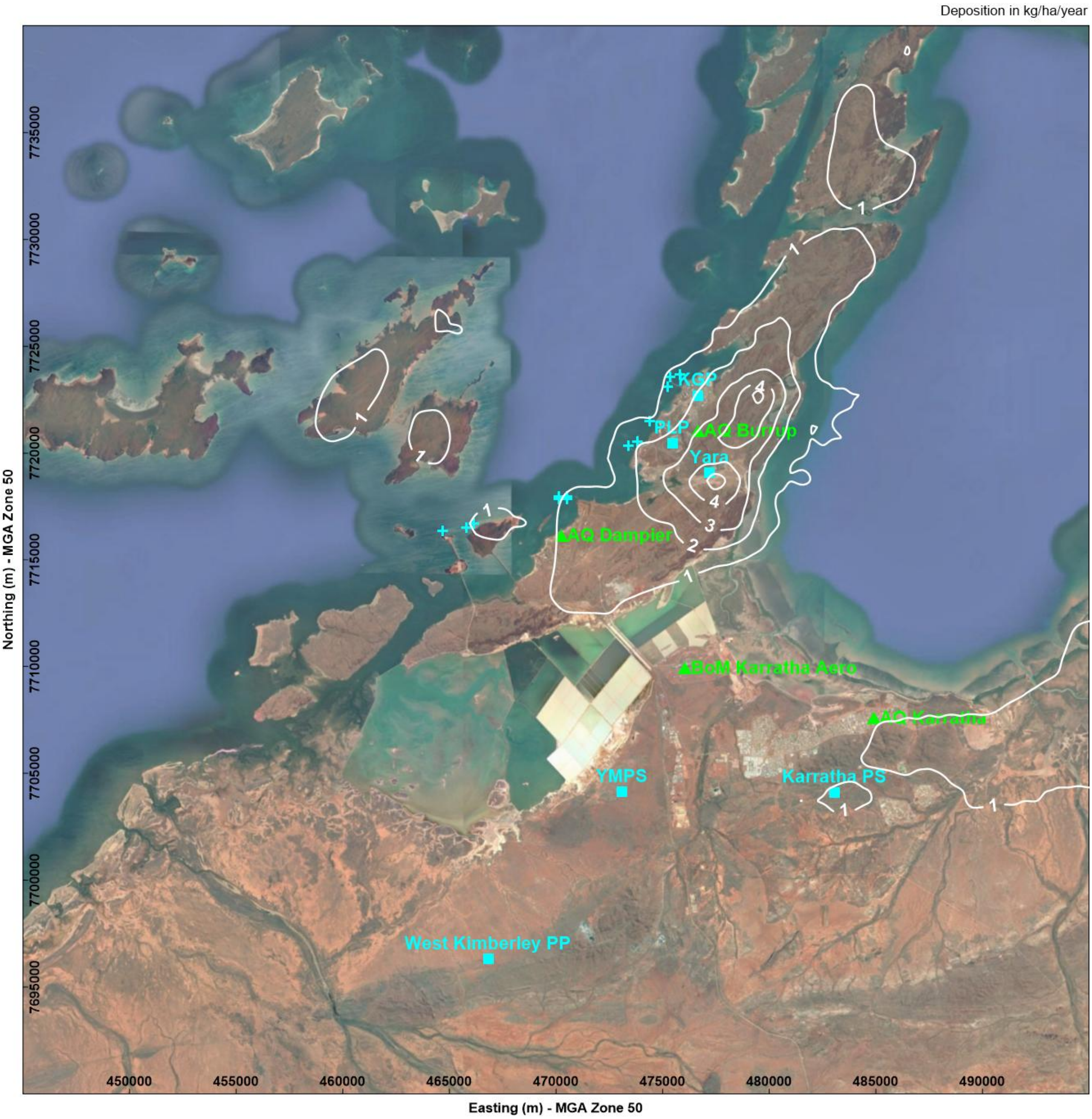



Figure 7-24: CBM – $NO_2$ deposition (kg/ha/year)

- Maximum grid receptor deposition, 5.7 kg/ha/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

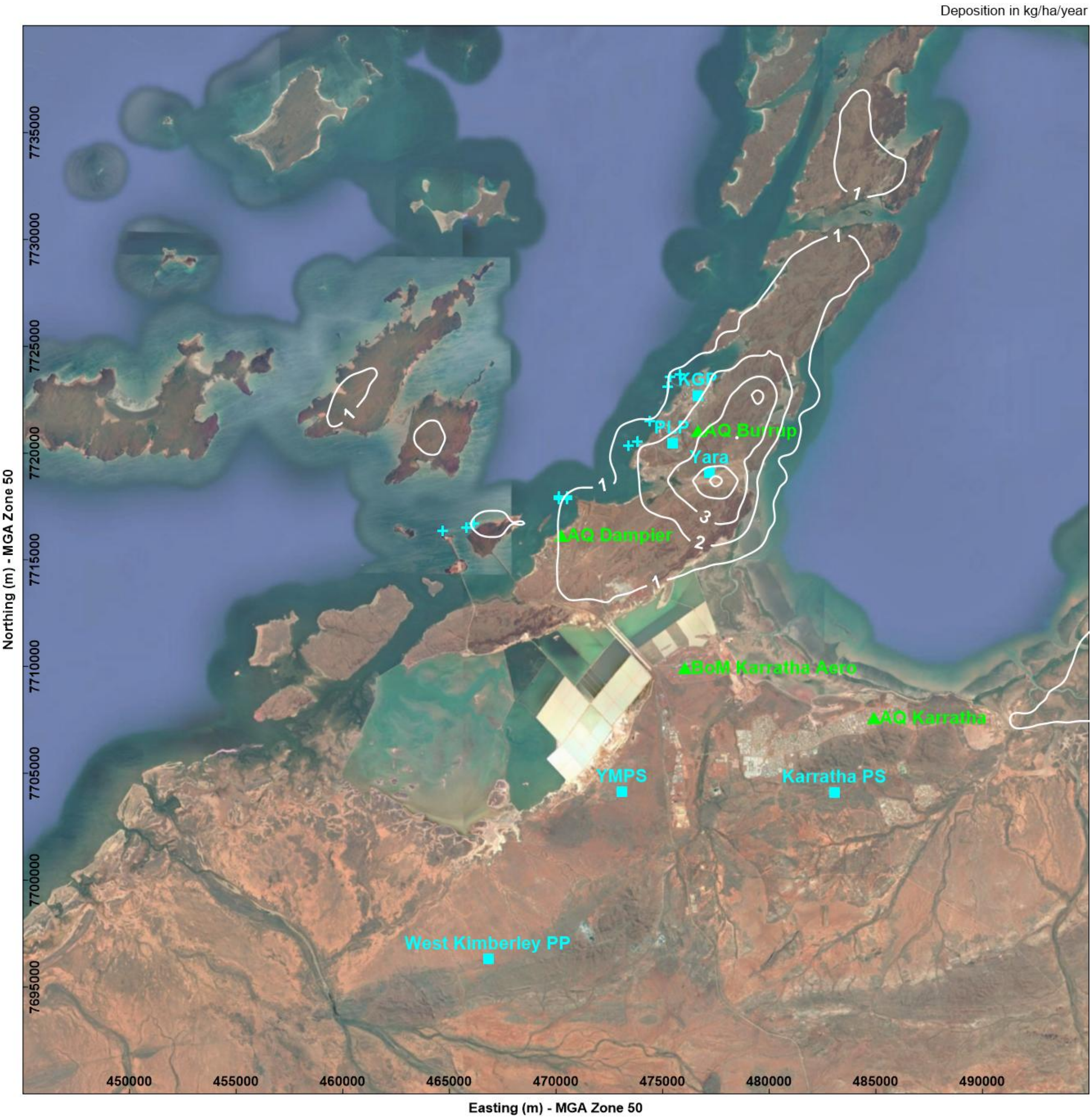



Figure 7-25: KIO – $NO_2$ deposition (kg/ha/year)

- Maximum grid receptor deposition, 5.5 kg/ha/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

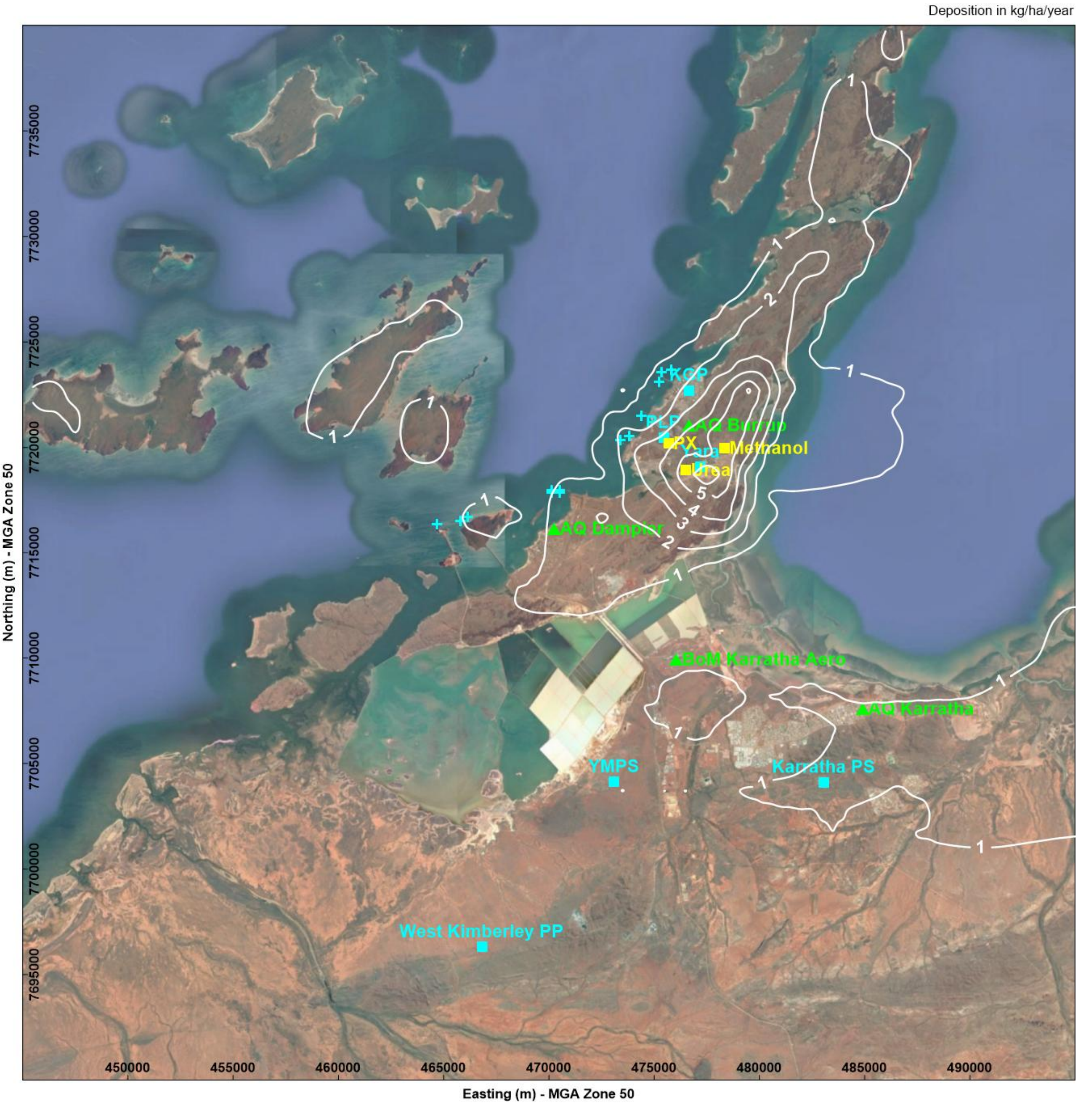



Figure 7-26: FBSIA – $NO_2$ deposition (kg/ha/year)

- Maximum grid receptor deposition, 6.8 kg/ha/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

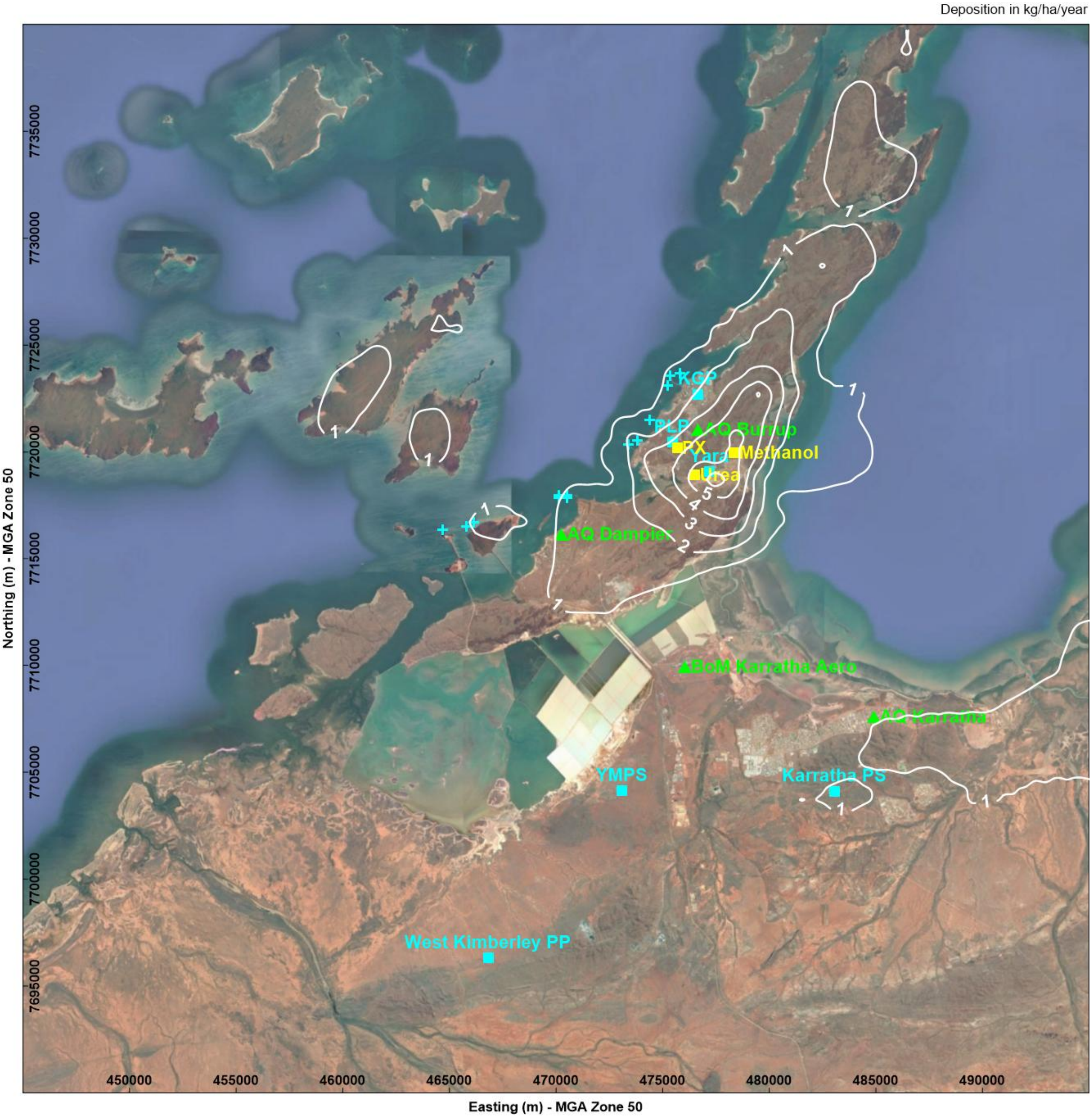



Figure 7-27: FBSIA-KIO – $NO_2$ deposition (kg/ha/year)

- Maximum grid receptor deposition, 6.6 kg/ha/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

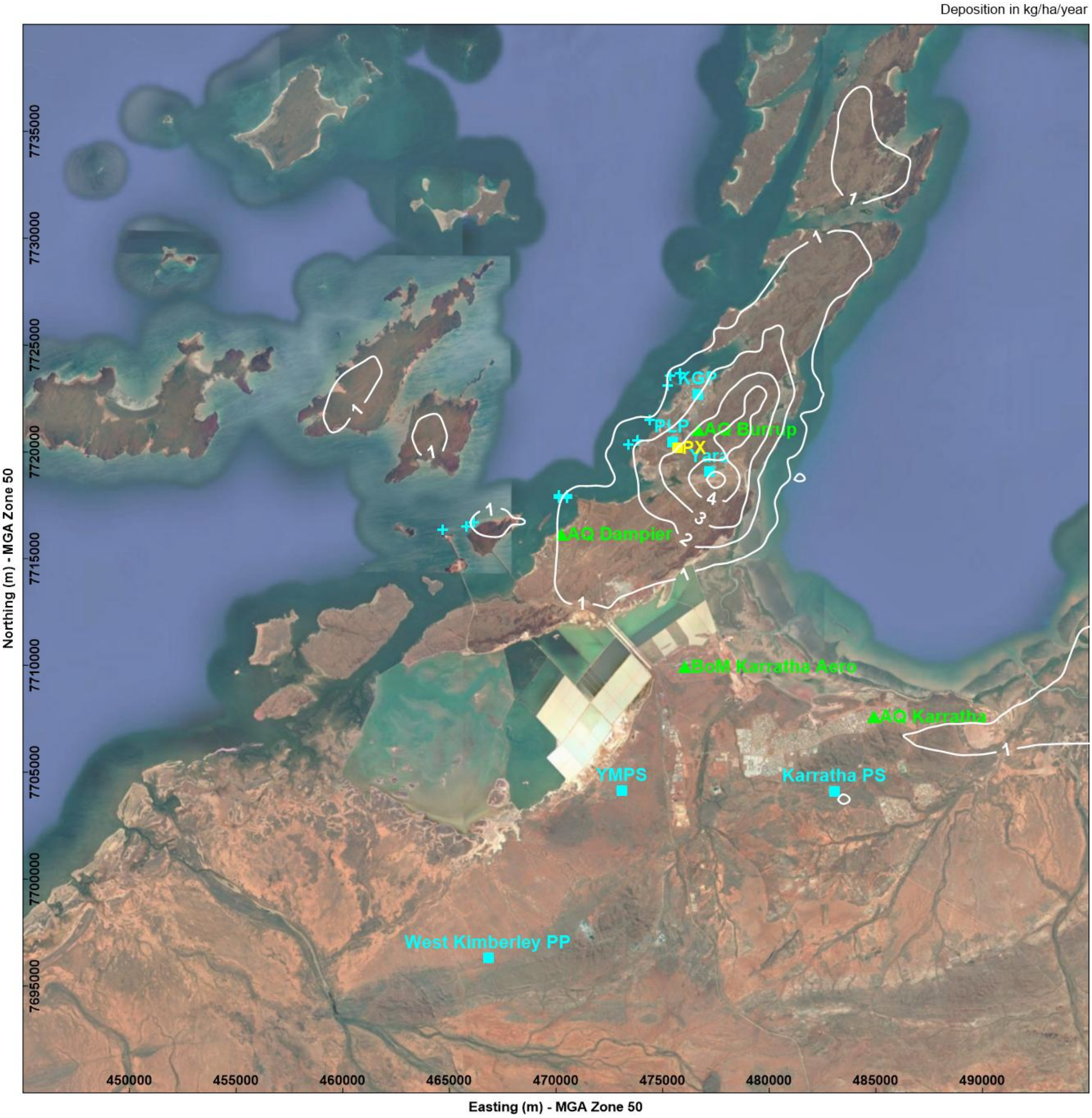



Figure 7-28: FBSIA E&A – $NO_2$ deposition (kg/ha/year)

- Maximum grid receptor deposition, 5.7 kg/ha/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

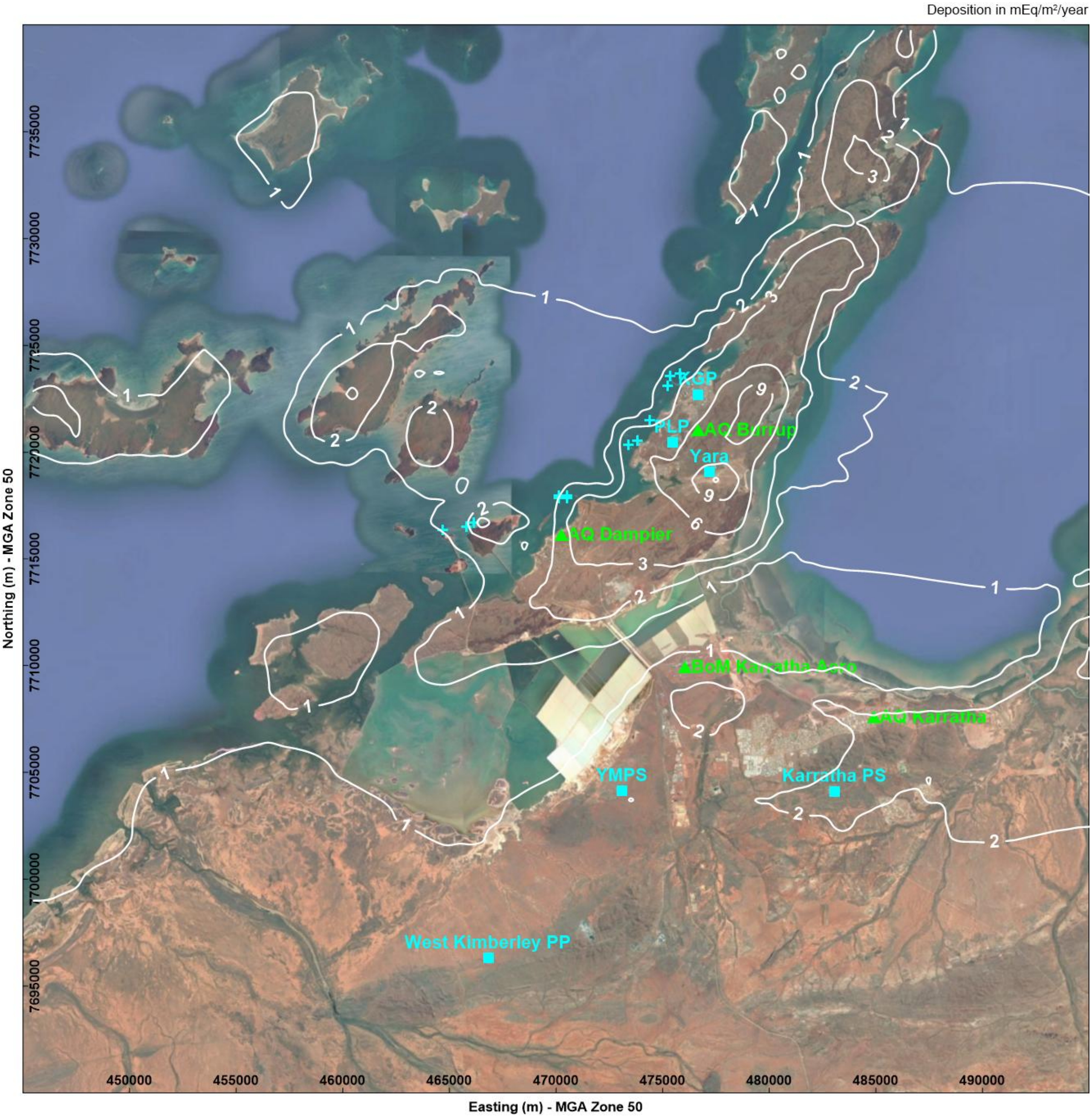



Figure 7-29: CBM – $NO_2$ deposition (meq/m²/year)

- Maximum grid receptor deposition, 12.4 meq/m²/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

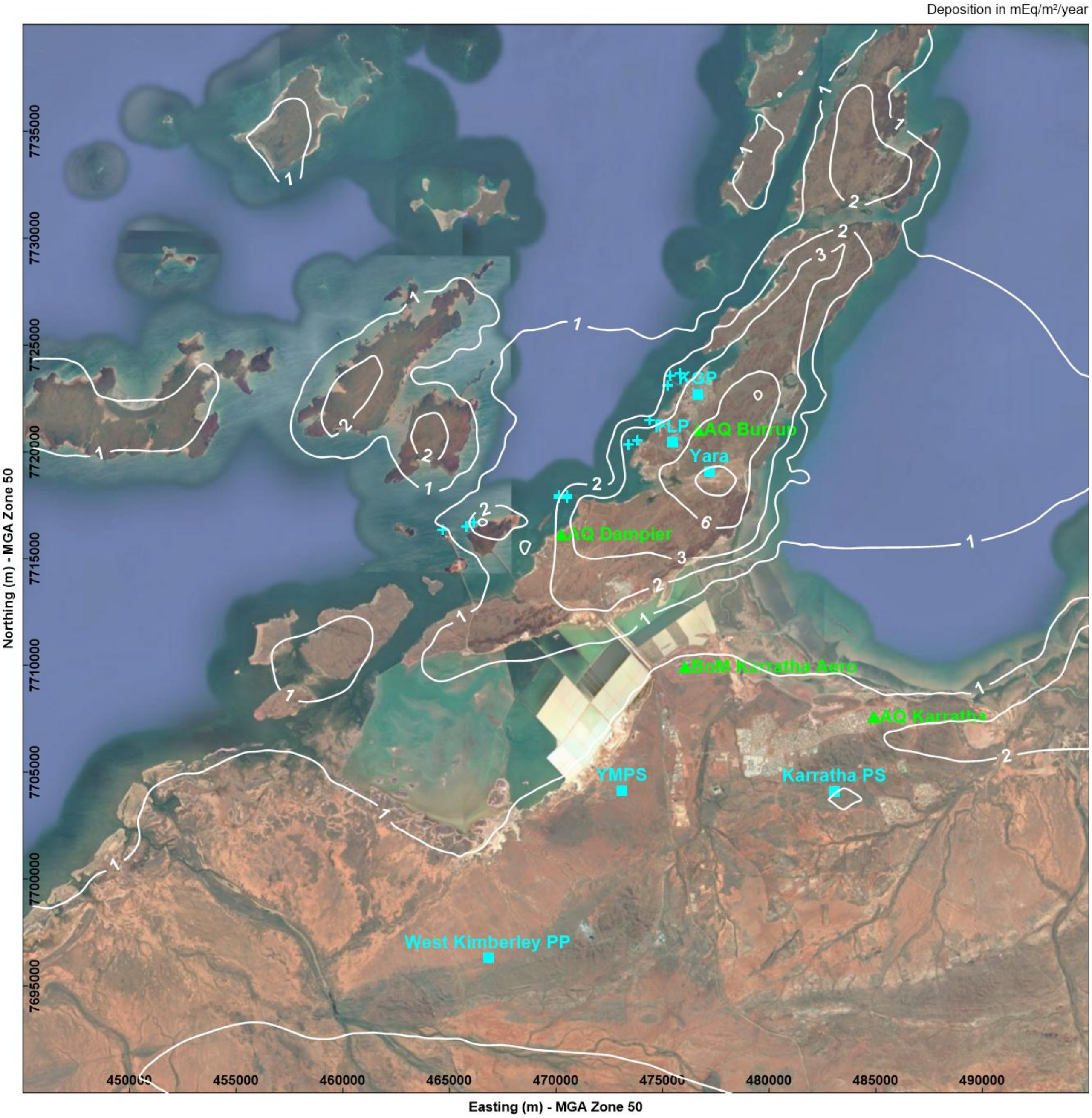



Figure 7-30: KIO – $NO_2$ deposition (meq/m²/year)

- Maximum grid receptor deposition, 11.9 meq/m²/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

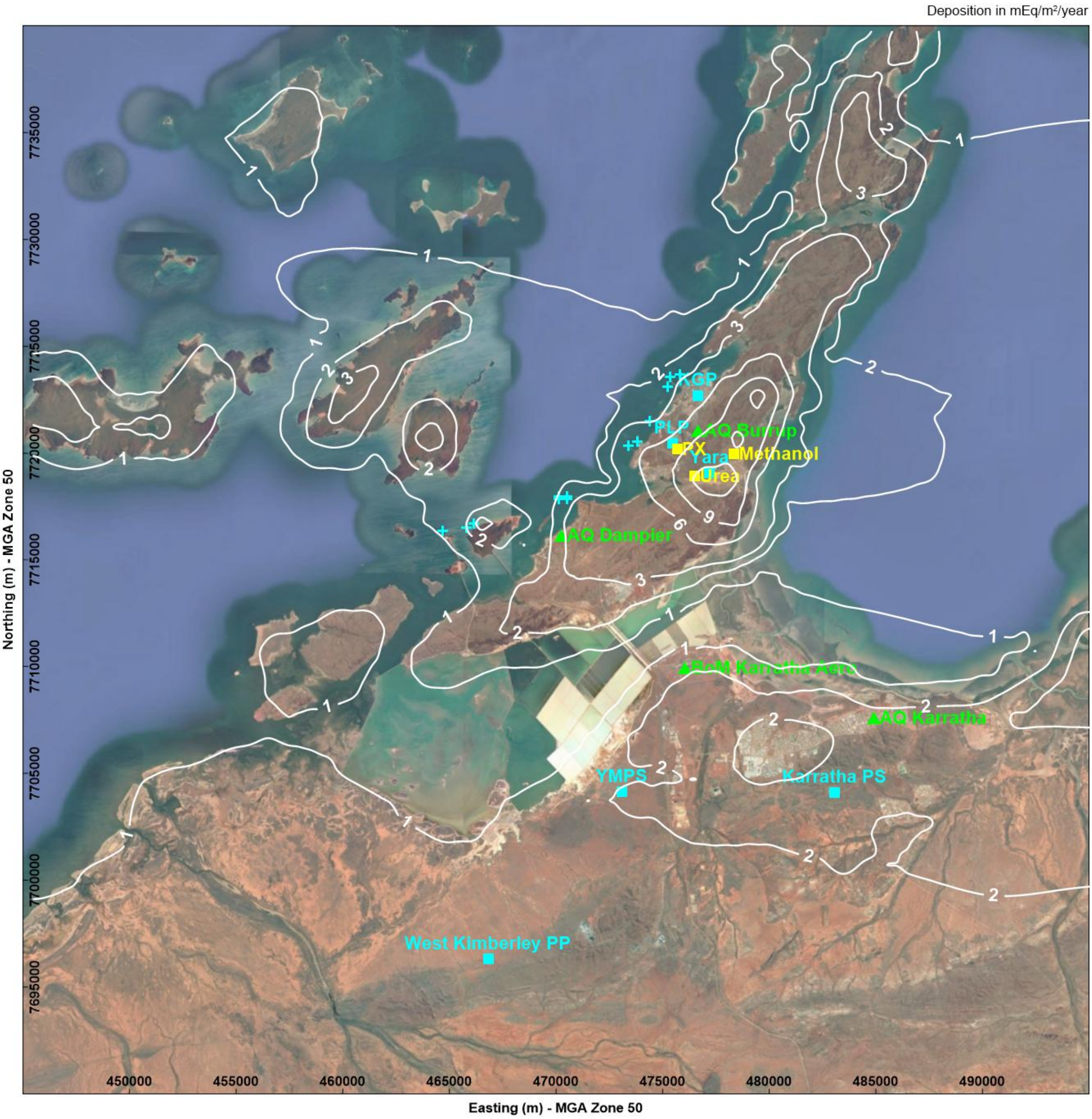



Figure 7-31: FBSIA – $NO_2$ deposition (meq/m$^2$/year)

- Maximum grid receptor deposition, 14.8 meq/m$^2$/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

Deposition in mEq/m²/year

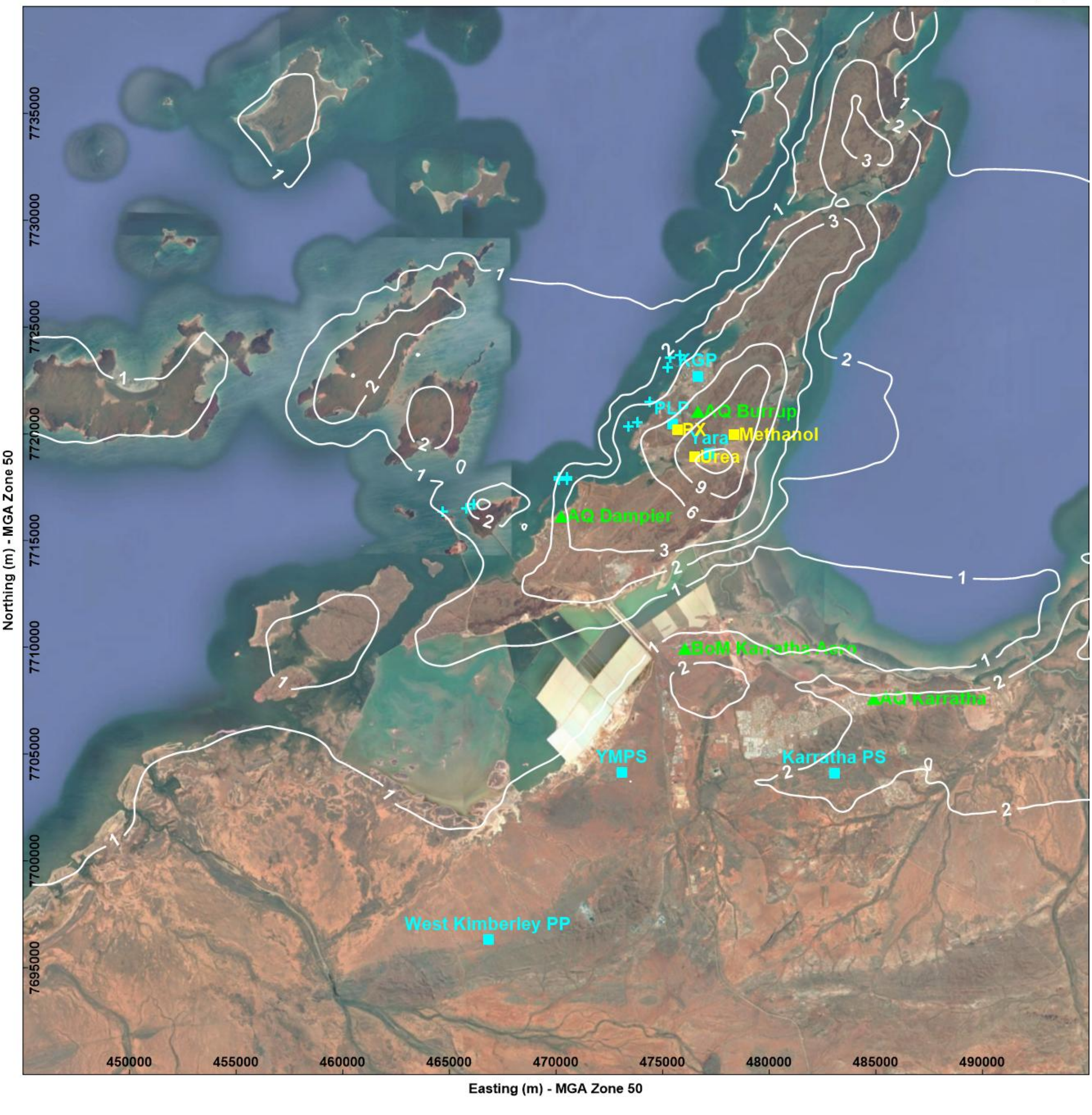



Figure 7-32: FBSIA-KIO – $NO_2$ deposition (meq/m²/year)

- Maximum grid receptor deposition, 14.3 meq/m$^2$/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

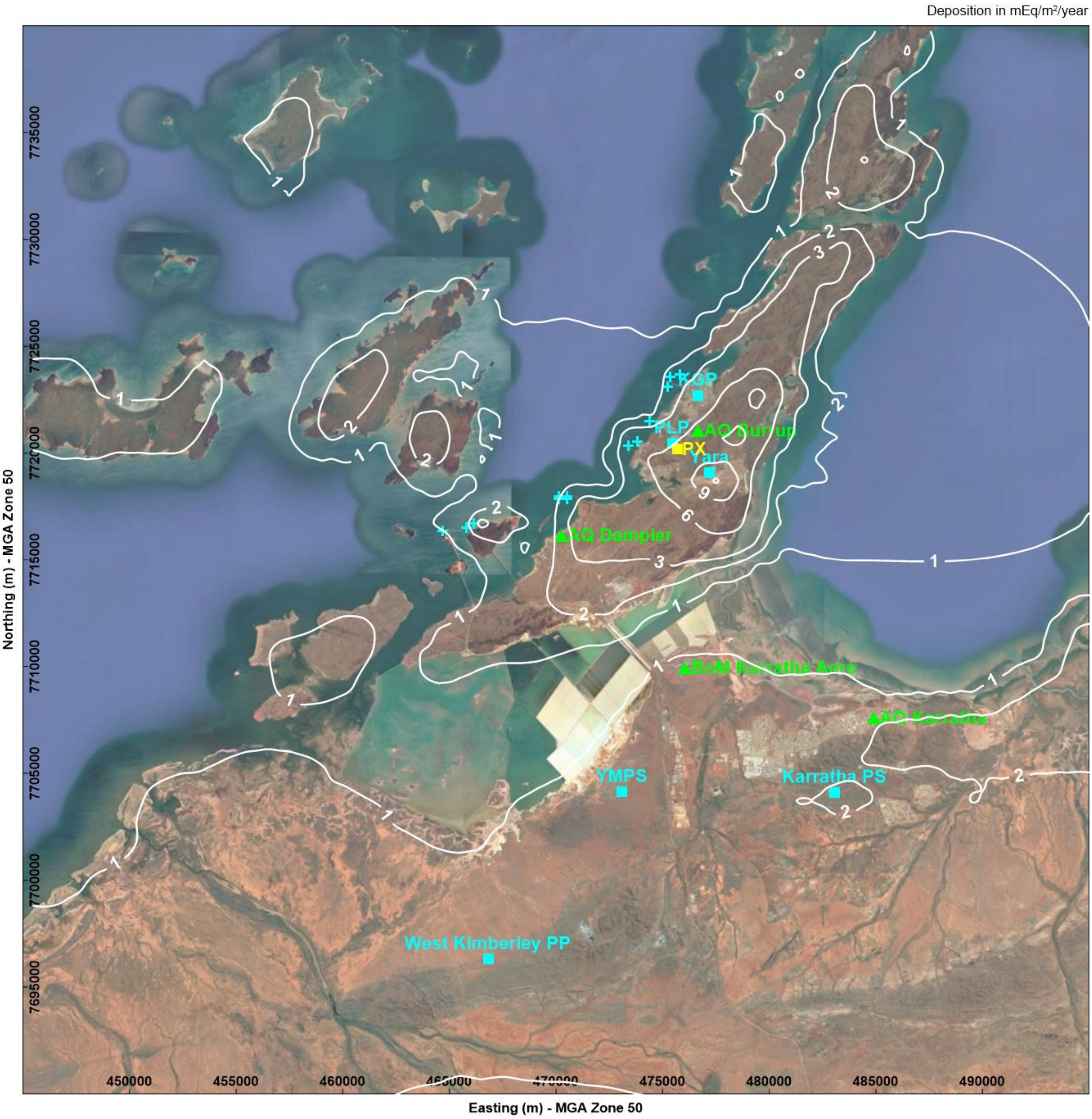



Figure 7-33: FBSIA E&A – $NO_2$ deposition (meq/m2/year)

- Maximum grid receptor deposition, 12.4 meq/m$^2$/year.
- For assessment of effects on vegetation health; see annual average $NO_x$.

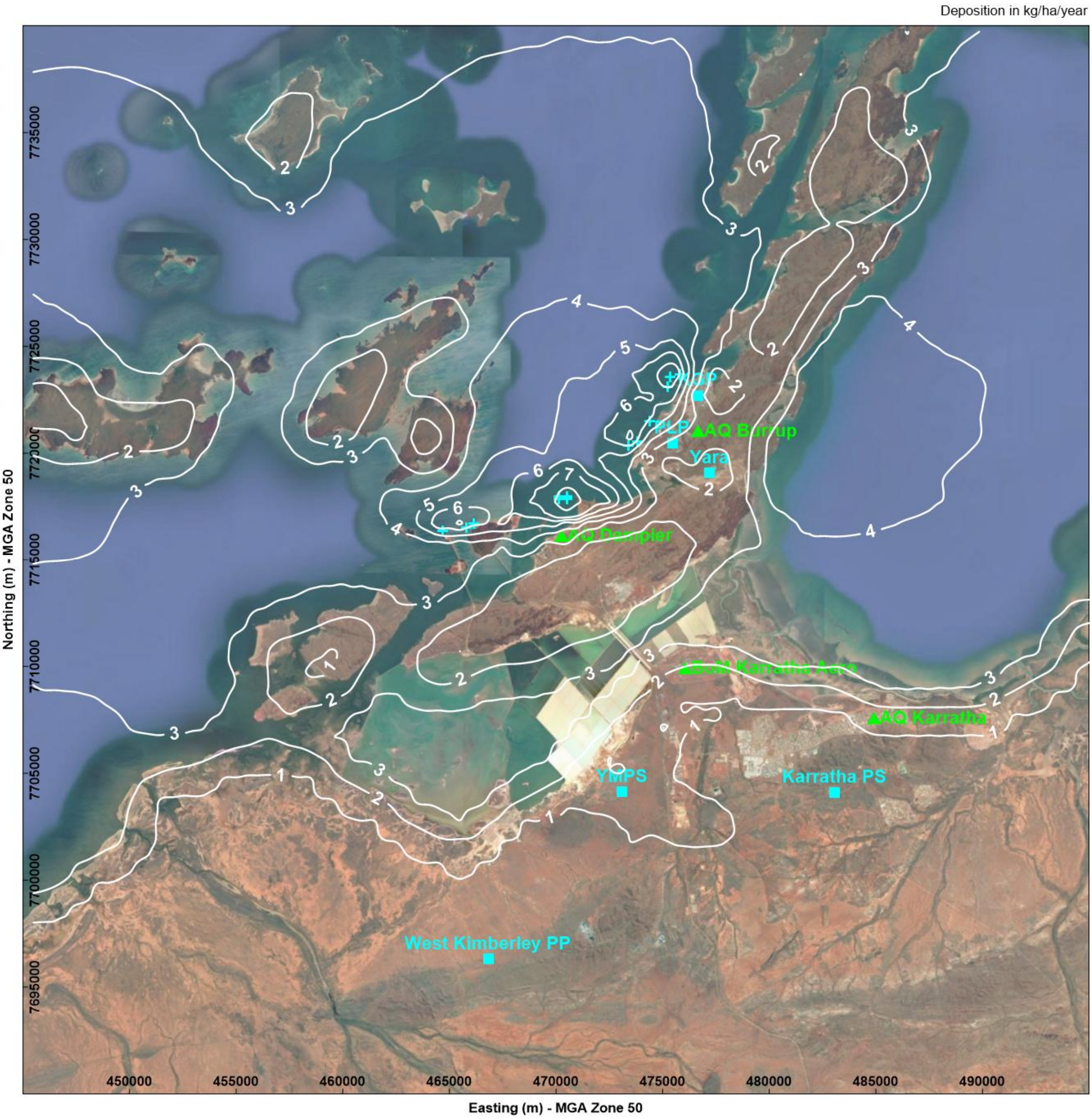



Figure 7-34: CBM – $SO_2$ deposition (kg/ha/year)

- Maximum grid receptor deposition, 13.6 kg/ha/year; higher depositions confined to shipping berths where continuously operating shipping sources were modelled.
- For assessment of effects on vegetation health; see annual average $SO_2$.

## 7.7 Summary of Results

### 7.7.1 Summary of Results – Grid Receptors

A summary of the TAPM-GRS results for the grid receptor maxima used for the assessment against the NEPM (Ambient Air Quality) standards for the protection of human health is provided in Table 7-9.

Table 7-9: Summary of TAPM-GRS Results: Grid Receptor Maxima and NEPM (Ambient Air Quality) Standards

| Assessment Parameter (units) | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A | NEPM (Ambient Air Quality) Standard |
|---|---|---|---|---|---|---|
| max 1h $NO_2$ (ppb) | 42.6 | 29.1 | 43.9 | 32.4 | 30.7 | 120 |
| annual $NO_2$ (ppb) | 5.0 | 4.9 | 5.6 | 5.7 | 5.0 | 30 |
| max 1h $O_3$ (ppb) | 61.8 | 59.2 | 63.0 | 61.0 | 60.0 | 100 |
| max 4h $O_3$ (ppb) | 58.2 | 55.3 | 59.7 | 57.4 | 56.1 | 80 |
| max 1h $SO_2$ (ppb) | 18.1 | 18.2 | 18.1 | 18.2 | 18.2 | 200 |
| max 24h $SO_2$ (ppb) | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 80 |
| annual $SO_2$ (ppb) | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 20 |

A summary of the TAPM-GRS results for the grid receptor maxima used for the assessment against the EU (2008) standards for the protection of vegetation is provided in Table 7-10.

Table 7-10: Summary of TAPM-GRS Results: Grid Receptor Maxima and EU 2008 Standards for Protection of Vegetation

| Assessment Parameter | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A | EU 2008 Standard |
|---|---|---|---|---|---|---|
| annual $NO_x$ (ppb) | 7.7 | 7.4 | 9.0 | 8.8 | 7.7 | 16 ppb at 30°C<br>(15 ppb as $NO_2$ at 0°C,<br>or 30 µg/$m^3$) |
| annual $SO_2$ (ppb) | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 8 ppb at 30°C<br>(7 ppb at 0°C,<br>or 20 µg/$m^3$) |

A summary of the TAPM-GRS results for deposition is provided in Table 7-11, which does not include the effects of future reductions in shipping fuel sulfur content. For completeness, refer to Section 8.1.1 and Figure 8-1, Figure 8-3, Figure 8-4, Figure 8-5 and Figure 8-6.

Table 7-11: TAPM-GRS Predictions for $NO_2$ and $SO_2$ Deposition: Grid Receptor Maxima (No Standards)

| Deposition Parameter | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A |
|---|---|---|---|---|---|
| annual $NO_2$ deposition (kg/ha/year) | 5.7 | 5.5 | 6.8 | 6.6 | 5.7 |
| annual $NO_2$ deposition (meq/$m^2$/year) | 12.4 | 11.9 | 14.8 | 14.3 | 12.4 |
| annual $SO_2$ deposition (kg/ha/year) | 13.6 | 13.7 | 13.7 | 13.7 | 13.7 |

### 7.7.2 Summary of Results – Discrete Receptors

A summary of the TAPM-GRS results for the discrete (sensitive) receptor locations Karratha, Burrup and Dampier, for assessment against the NEPM (Ambient Air Quality) standards, is provided in Table 7-12.

Table 7-12: Summary of TAPM-GRS Results for Discrete Receptor Locations

| Monitoring Station | CBM | KIO | FBSIA | FBSIA-KIO | FBSIA E&A | NEPM (Ambient Air Quality) Standards |
|---|---|---|---|---|---|---|
| **Maximum 1 hour average $NO_2$ (ppb)** | | | | | | |
| AQ Karratha | 24.8 | 16.1 | 28.3 | 20.9 | 17.5 | 120 |
| AQ Burrup | 33.4 | 22.4 | 34.2 | 25.4 | 22.9 | 120 |
| AQ Dampier | 24.8 | 18.2 | 25.8 | 19.5 | 19.0 | 120 |
| **Annual average $NO_2$ (ppb)** | | | | | | |
| AQ Karratha | 0.9 | 0.8 | 1.0 | 0.9 | 0.8 | 30 |
| AQ Burrup | 3.2 | 3.0 | 4.0 | 3.8 | 3.3 | 30 |
| AQ Dampier | 1.7 | 1.6 | 1.8 | 1.7 | 1.6 | 30 |
| **Maximum 1 hour average $O_3$ (ppb)** | | | | | | |
| AQ Karratha | 57.9 | 55.0 | 61.2 | 55.8 | 55.2 | 100 |
| AQ Burrup | 58.7 | 55.4 | 58.4 | 55.6 | 55.6 | 100 |
| AQ Dampier | 55.4 | 53.2 | 56.5 | 54.4 | 53.7 | 100 |
| **Maximum 4 hour average $O_3$ (ppb)** | | | | | | |
| AQ Karratha | 56.3 | 51.2 | 59.1 | 53.8 | 51.8 | 80 |
| AQ Burrup | 54.3 | 51.7 | 53.7 | 51.7 | 51.9 | 80 |
| AQ Dampier | 52.5 | 50.5 | 53.6 | 51.8 | 51.0 | 80 |
| **Maximum 1 hour average $SO_2$ (ppb)** | | | | | | |
| AQ Karratha | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 200 |
| AQ Burrup | 11.3 | 11.2 | 11.4 | 11.3 | 11.3 | 200 |
| AQ Dampier | 12.9 | 13.3 | 12.9 | 13.3 | 13.3 | 200 |
| **Maximum 24 hour average $SO_2$ (ppb)** | | | | | | |
| AQ Karratha | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 80 |
| AQ Burrup | 4.7 | 4.7 | 4.8 | 4.7 | 4.7 | 80 |
| AQ Dampier | 4.6 | 4.5 | 4.6 | 4.5 | 4.5 | 80 |
| **Annual Average $SO_2$ (ppb)** | | | | | | |
| AQ Karratha | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 20 |
| AQ Burrup | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 20 |
| AQ Dampier | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 20 |

# 8. Testing of Model Results for Deposition

### 8.1.1 Model Results for $NO_2$ Deposition

Some quality testing of the model results for $NO_2$ deposition was undertaken by comparisons with measurements obtained by Gillett (2014). Model outputs for $NO_2$ deposition were extracted for the six Gillett (2014) monitoring locations and compared with the measurements of dry deposition of $NO_2$ (meq/m$^2$/year), and total nitrogen and sulfur deposition (also expressed in units of meq/m$^2$/year); the results are listed in Table 8-1. Inspection of these results shows reasonably good, overall agreement between the modelling and monitoring and indicates two satisfactory outcomes from the modelling: (1) the $NO_x$ emissions inventory used as input to the model was sufficiently complete; and (2) the TAPM-GRS modelling of photochemistry, air pollutant dispersion, and the dry deposition of gases, was satisfactory. The results listed in Table 8-1 are also plotted in Figure 8-1.

Table 8-1: Summary of Monitoring and Model Results for $NO_2$ Deposition

| Parameter | 1[I] Gap Ridge | 2[I] Fertiliser Plant | 3[I] BMF | 4[I] KGP | 5[I] Dom | 6[B] Backgnd. |
|---|---|---|---|---|---|---|
| **Monitoring 2012/2014 (CSIRO, 2014) – all units are meq/m$^2$/year** | | | | | | |
| Total nitrogen flux | 25.5 | 23.9 | 28.8 | 17.9 | 17.1 | 9.8 |
| Dry $NO_2$ deposition | 4.4 | 4.0 | 7.7 | 4.4 | 5.8 | 1.3 |
| **Model results (this report) – all data are $NO_2$ deposition (meq/m$^2$/year)** | | | | | | |
| CBM | 1.8 | 8.5 | 5.0 | 5.7 | 6.2 | approx. 1.0 |
| KIO | 1.6 | 7.8 | 4.7 | 5.2 | 5.9 | approx. 1.0 |
| FBSIA | 2.0 | 11.6 | 5.8 | 6.8 | 8.8 | approx. 1.0 |
| FBSIA-KIO | 1.8 | 10.9 | 5.6 | 6.4 | 8.5 | approx. 1.0 |
| FBSIA E&A | 1.7 | 8.8 | 4.9 | 5.7 | 7.0 | approx. 1.0 |

- Superscript ‘B’ denotes background monitoring site; superscript ‘I’ indicates monitor in industrial area.
- Site 1: Gap Ridge accommodation camp west of Karratha; Site 2 near Yara TAN plant; Sites 4 and 5 located near Pluto LNG.
- Modelled results for background were from southern-most parts of study grid; it is expected these low, but non-zero values due to modelled biogenic $NO_x$ emissions over land (nil emissions modelled over water).

Some further analysis of the model results for $NO_2$ deposition was undertaken in an attempt to tease out differences between CBM and the other modelled scenarios, by a focus on the grid receptor results within the Dampier Archipelago National Heritage Place (DANHP) (AG, 2019). The 2601 grid receptor results were clipped using the National Heritage List Spatial Database (AG, 2019), to extract model results from within the DANHP only. The DANHP boundaries and 310 clipped points are illustrated in Figure 8-2.

Histograms of the model results for $NO_2$ deposition (meq/m$^2$/year) were created for the model grid points within the DANHP boundaries (Figure 8-2), to illustrate the differences between CBM and each of the other scenarios.

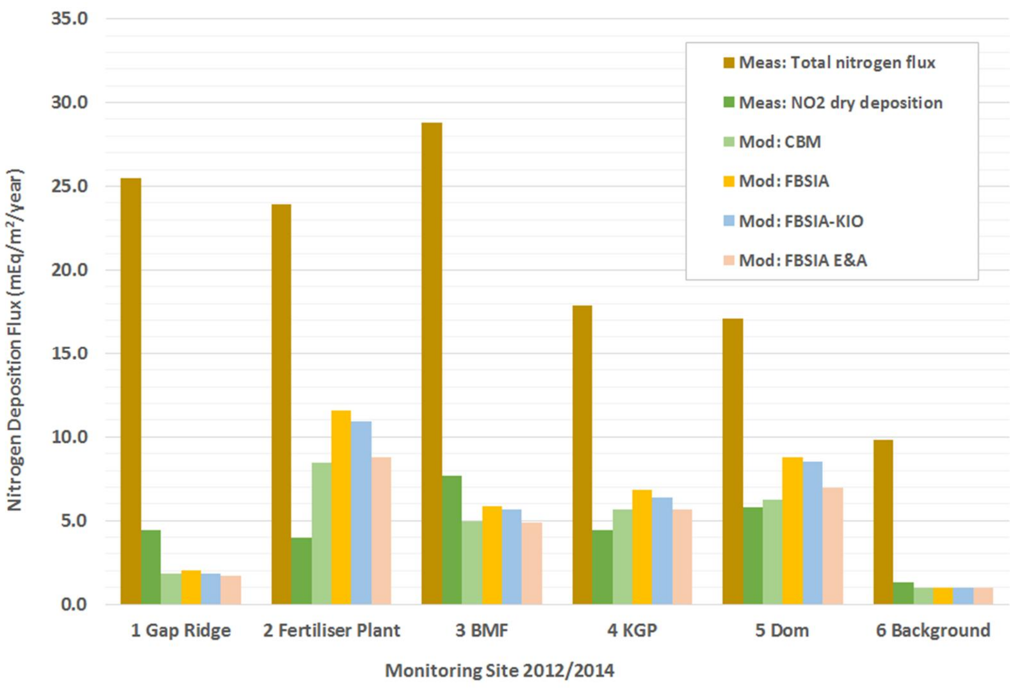



Figure 8-1: Measured and Modelled Nitrogen Fluxes (meq/m$^2$/year)

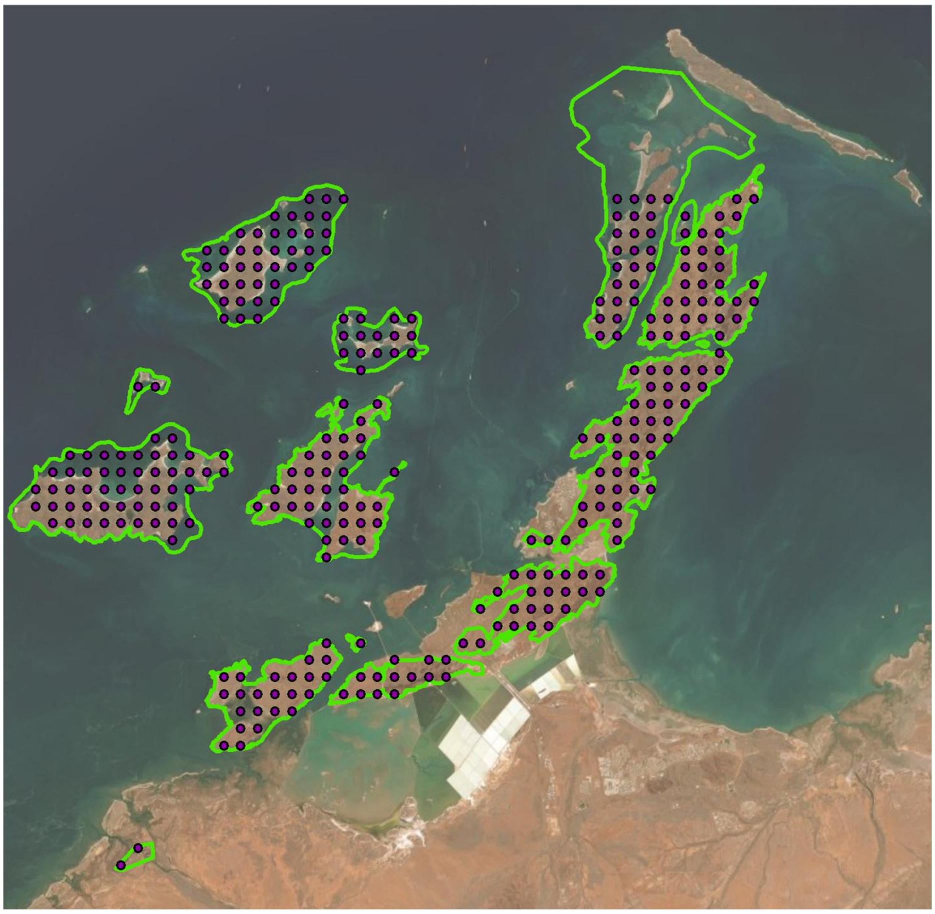


Figure 8-2: Model Grid Points Within Dampier Archipelago National Heritage Place

Model results comparing $NO_2$ deposition between CBM and each of the other modelled scenarios are provided in the following series of histograms:

- Frequency Distributions of Model Results for CBM and KIO $NO_2$ Deposition Within DANHP (Figure 8-3)
- Frequency Distributions of Model Results for CBM and FBSIA $NO_2$ Deposition Within DANHP (Figure 8-4)
- Frequency Distributions of Model Results for CBM and FBSIA-KIO $NO_2$ Deposition Within DANHP (Figure 8-5)
- Frequency Distributions of Model Results for CBM and FBSIA E&A $NO_2$ Deposition Within DANHP (Figure 8-6)

For all scenarios, the majority of the $NO_2$ deposition results for the grid receptors within the DANHP fall within the range of 1-4 meq/$m^2$/year. There are slightly fewer modelled scenario results in the lower deposition range of 1-4 meq/$m^2$/year when compared to CBM results with the exception of KIO and FBSIA E&A; whereas there are slightly fewer CBM results in the range of 5-14 meq/$m^2$/year when compared to the modelled scenario results. The highest deposition rate of 14 meq/$m^2$/year (Figure 8-4) was observed in the scenario comparing CBM and FBSIA.

To summarise – for comparative analysis of modelled $NO_2$ deposition values as a sub-component of overall nitrogen and sulfur deposition:

- KIO generally shows an observable relative reduction of deposition frequencies above 2 meq/$m^2$/year compared with CBM;
- FBSIA E&A (current and approved (Pluto Train 2) with KGP Improvement Opportunities) shows a nominally consistent and slightly lower deposition frequencies than CBM above 2 meq/$m^2$/year; and
- FBSIA and FBSIA-KIO show relative marginal increases in deposition frequencies above 3 meq/$m^2$/year.

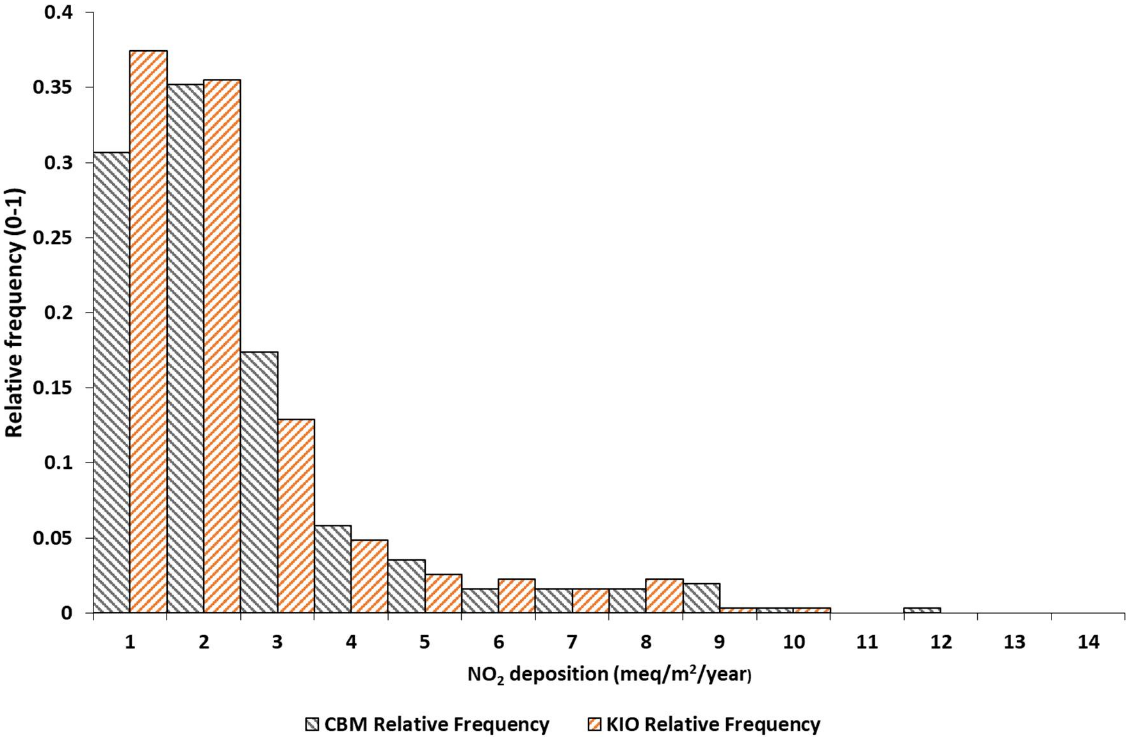



Figure 8-3: Frequency Distributions of Model Results for CBM and KIO $NO_2$ Deposition Within DANHP

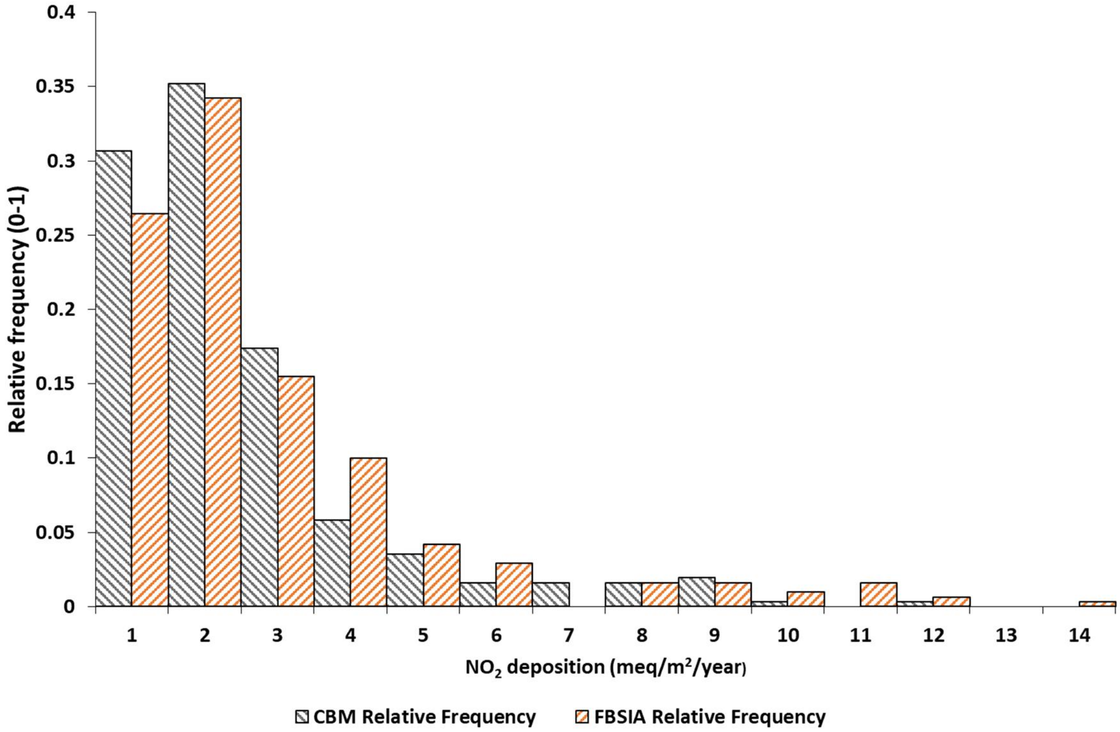



Figure 8-4: Frequency Distributions of Model Results for CBM and FBSIA $NO_2$ Deposition Within DANHP

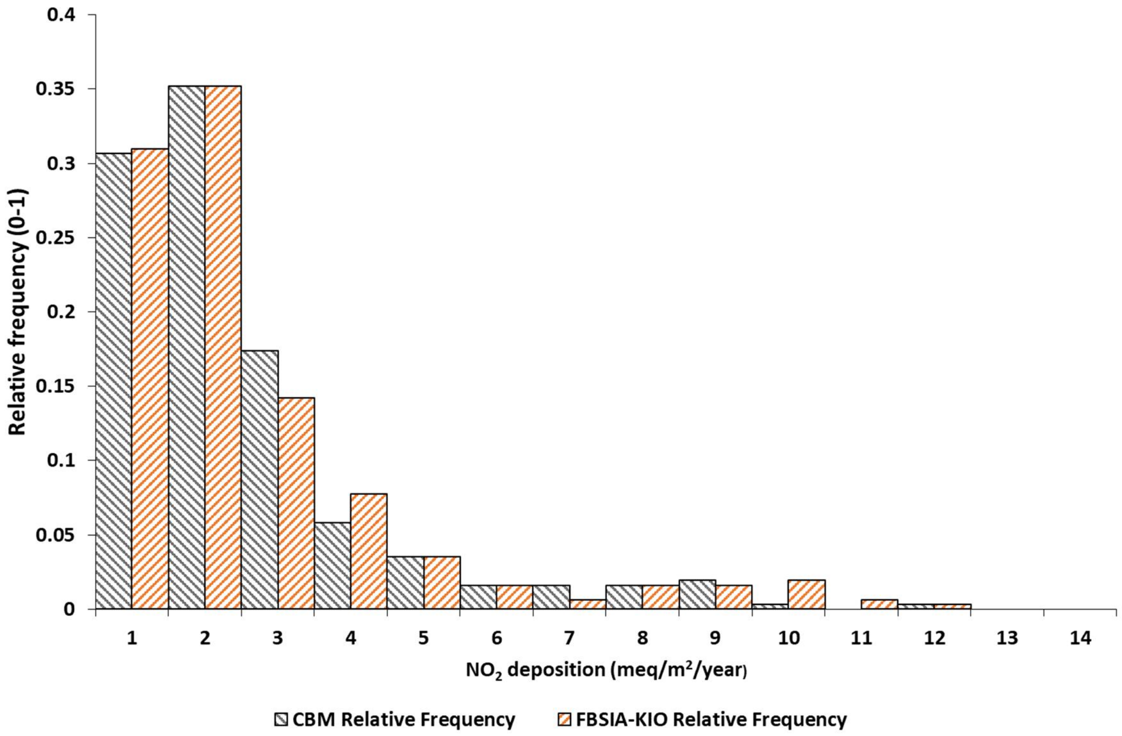



Figure 8-5: Frequency Distributions of Model Results for CBM and FBSIA-KIO $NO_2$ Deposition Within DANHP

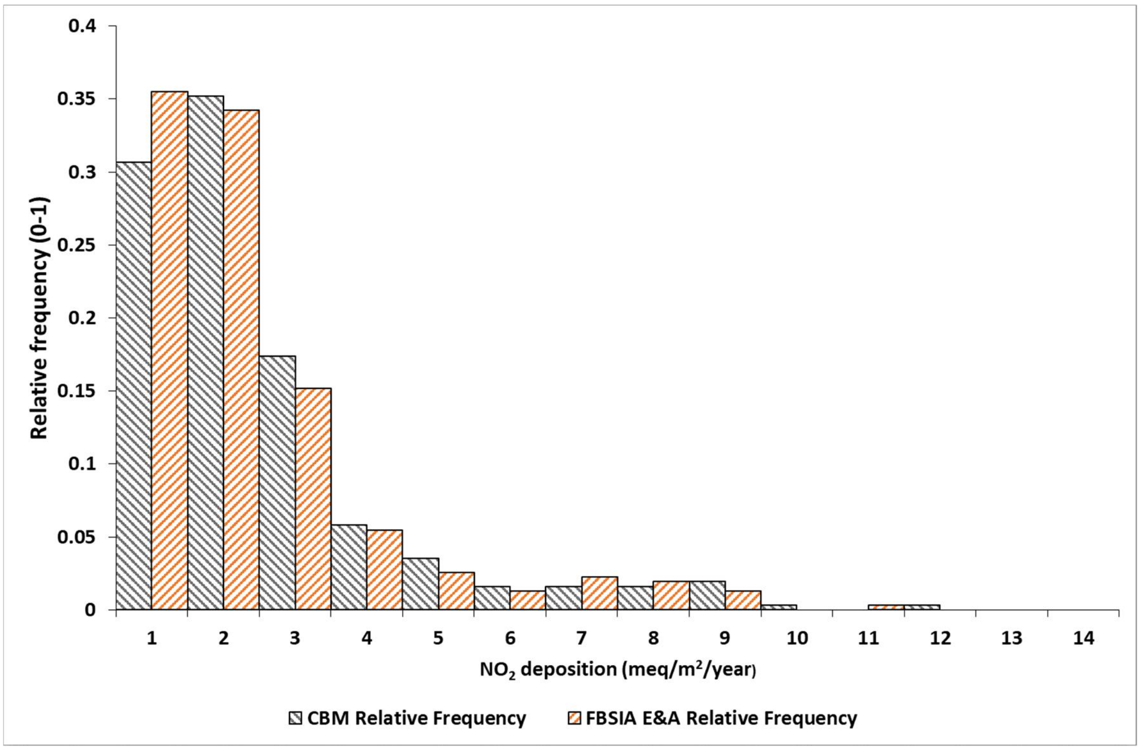



Figure 8-6: Frequency Distributions of Model Results for CBM and FBSIA E&A $NO_2$ Deposition Within DANHP

### 8.1.2 Model Results for $SO_2$ Deposition

The model results for $SO_2$ deposition (kg/ha/year), were highest around the main sources – the ship exhausts located at all berths around Burrup Peninsula; these were modelled as continuously operating. Typical values for modelled $SO_2$ deposition were 2-3 kg/ha/year around the Burrup Peninsula within approximately 1 km of the coastline. The deposition rate decreased to a minimum of approximately 1 kg/ha/year on the mainland, also within approximately 1 km of the coastline. The $SO_2$ deposition rates for all emissions scenarios were almost identical, showing only a very small effect on the baseline due to the Proposal. This is because there was only a very small difference in the $SO_2$ emissions profile between the modelled scenarios.

It is noted the modelled effects due to $SO_2$ emissions on the Burrup Peninsula are expected to have been over-estimated by the modelling undertaken for this project, which assumed $SO_2$ emissions from all the shipping berths in the study area operating continuously over the course of a year.

# 9. Conclusion

This report details the results of air quality modelling to support the Proposal. As a part of this assessment the existing air emissions scenario, Current Baseline, and potential future air emissions scenarios, were developed for the Burrup Peninsula. The results of modelling were set out to determine how the current emissions are affecting existing air quality. Potential future air emissions scenarios were modelled to increase our understanding of potential future best case, most likely, and worst-case air quality effects for the Burrup Peninsula.

The modelling methodology was set out based on a literature review that included several key CSIRO papers from the 2000s, and subsequent assessment reports completed by Woodside and specialist air quality consultants. The CSIRO meteorological, air dispersion and photochemical model, TAPM-GRS was selected for modelling for reasons of reliability and efficiency. The modelling methodology was discussed with EPA Services air quality specialists prior to the commencement of modelling (Jacobs, 2019b).

The reliability of the TAPM-GRS results was determined primarily by comparisons of model results with measurements at three monitoring stations on or adjacent the Burrup Peninsula: Burrup Road, Dampier and Karratha. The comparisons of modelling results with monitoring indicated TAPM-GRS was performing very well in terms of being able to accurately predict a variety of statistical results for $NO_2$ and $O_3$.

In summary, the $NO_2$ and $O_3$ model results of this Project, which were obtained using substantial improvements to the air emissions inventories and TAPM-GRS modelling methods as applied to the Burrup Peninsula, produced results that agreed very well with monitoring data from 2014 when KGP and PLP were operating at or near capacity.

Key results from the air quality impact assessment were:

- There were no predicted exceedances of ambient air quality standards for $NO_2$, $O_3$, and $SO_2$. All these pollutants were well below the respective NEPM (Ambient Air Quality) standards set for the protection of human health.
- There were no predicted exceedances of European Union (2008) air quality standards for $NO_x$ and $SO_2$ for the protection of vegetation.
- Results for $NO_2$ and $SO_2$ deposition were provided to assist any further assessment of impacts to land surfaces (no agreed standard for impacts).

In conclusion, based on assessments using NEPM and EU (2008) standards, there is a low risk of impact to human health and vegetation due to air emissions from the Proposal. In this context, “low risk” has been defined from predicted concentrations well below relevant air quality standards.

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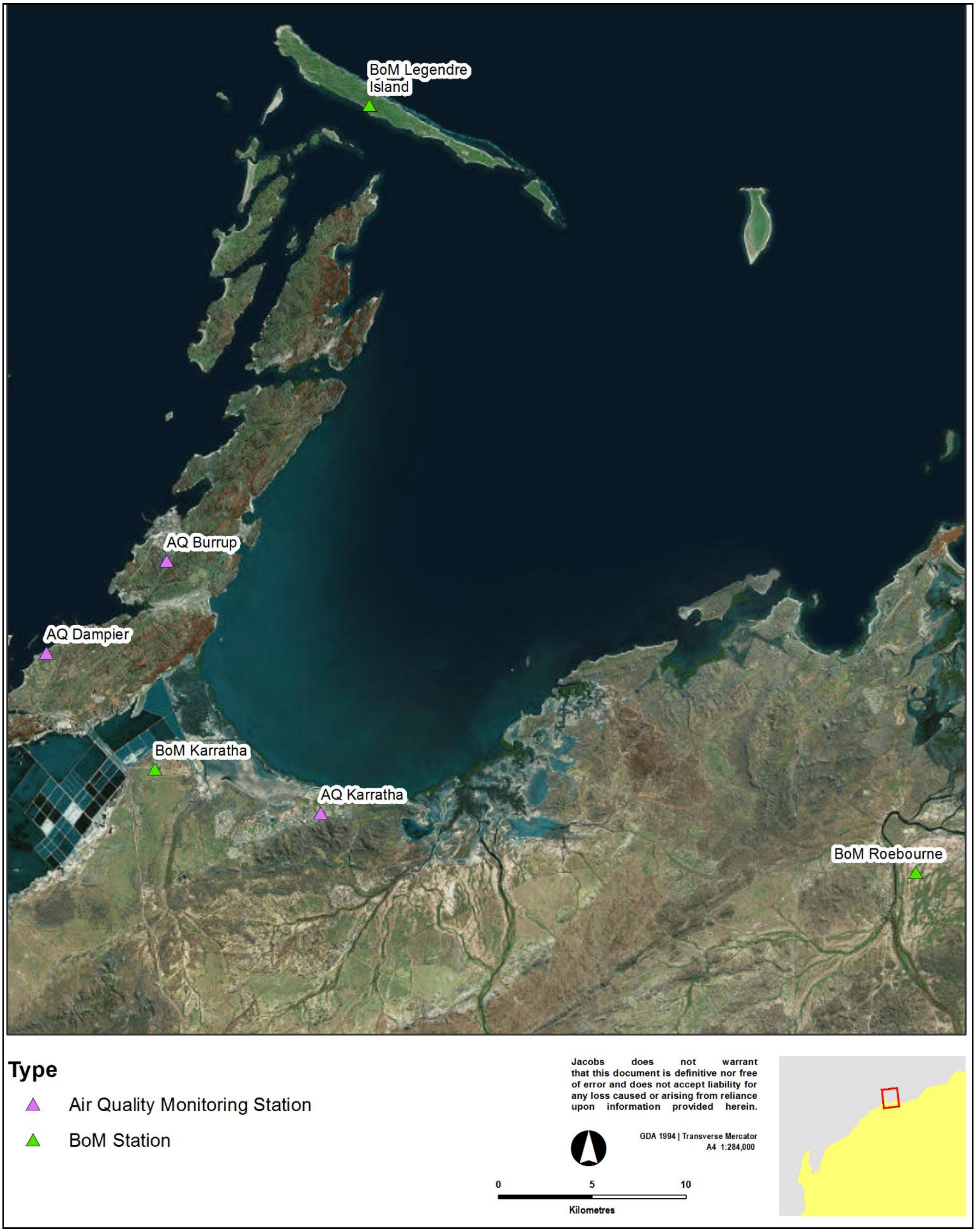
# Appendix A. Location Map and Monitoring Stations



# Appendix B. Local Meteorology

## Overview

Local meteorology is a critical input for determining the direction and rate at which emissions from a source are likely to disperse, near ground level. This section provides climatological summaries of meteorological parameters representative of the Burrup Peninsula based on Bureau of Meteorology (BoM) observations. The closest BoM weather station to the Proposal site is Karratha Aerodrome (BoM station number 004083, 20.71° S, 116.77° E, elevation 5.3m), which is located approximately 12 km south of the Proposal. The following sub-sections provide summaries of meteorological data acquired over more than two decades at Karratha Aerodrome.

## Temperature

Monthly mean maximum and minimum temperatures for BoM Karratha Aerodrome for 1993-2018 are shown in Figure B- 1. Daily maximum and minimum temperatures have ranged from 48°C in the wet season to only 7°C in the dry season, from 1993 to 2018.

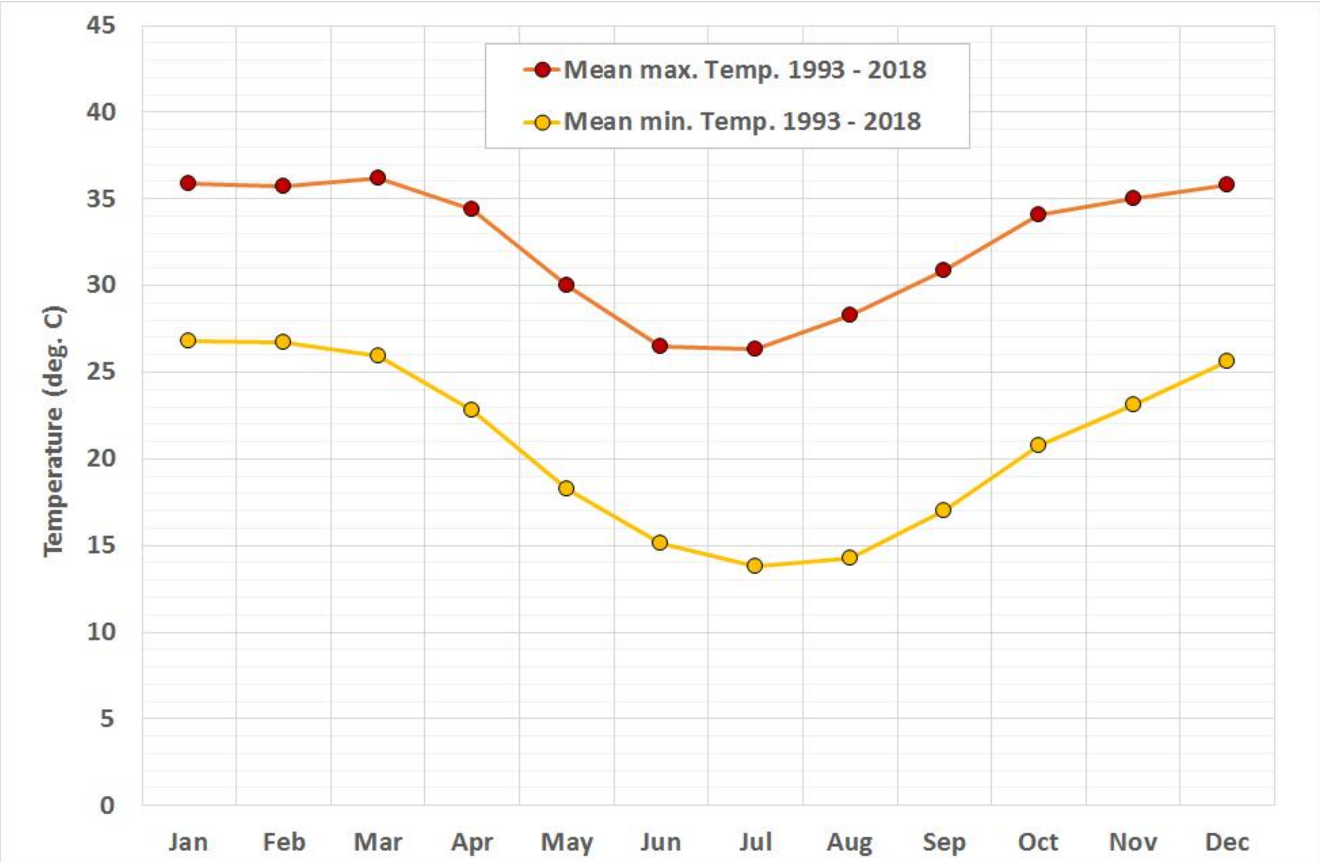



Figure B- 1: Monthly Mean-Maximum and Minimum Temperature – Karratha Aerodrome 1993-2018

## Rainfall and Relative Humidity

Monthly rainfall statistics for BoM Karratha Aerodrome are shown in Figure B- 2, and monthly mean 9am and 3pm Relative Humidity (RH) for Karratha Aerodrome for 1993-2010 are shown in Figure B- 3. The rainfall observations clearly show the Burrup Peninsula wet season running from approximately January to June, and the dry season from approximately July to December.

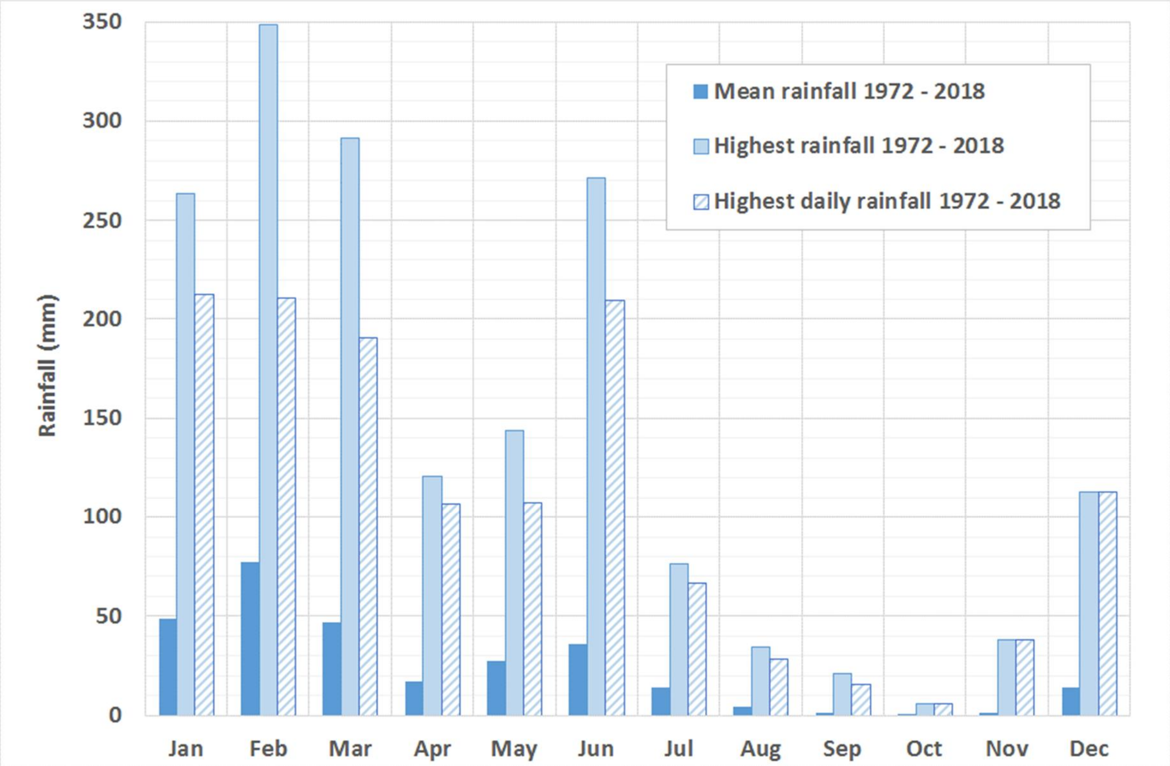



Figure B- 2: Monthly Rainfall – Karratha Aerodrome 1972-2018

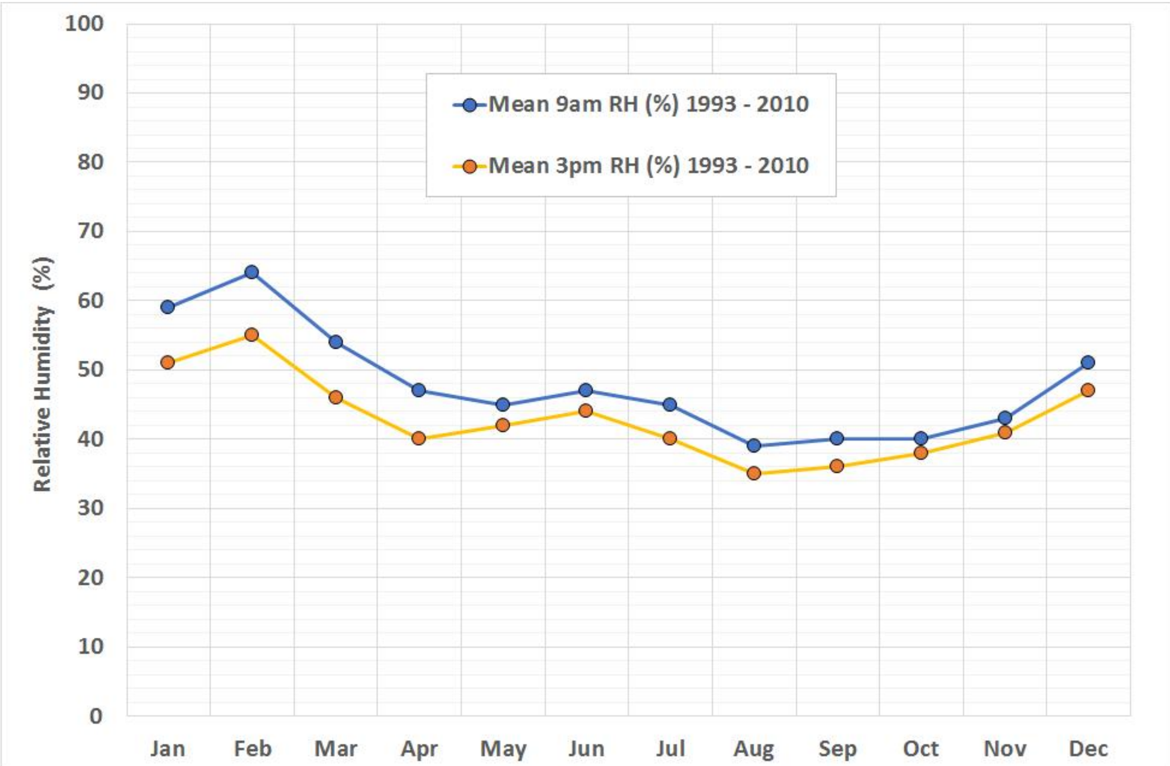



Figure B- 3: Monthly 9am and 3pm Relative Humidity – Karratha Aerodrome 1972-2018

## Wind Speed and Wind Patterns

Monthly mean daily wind speeds and maximum wind gusts for BoM Karratha Aerodrome for 2003-2018 are shown in Figure B- 4.

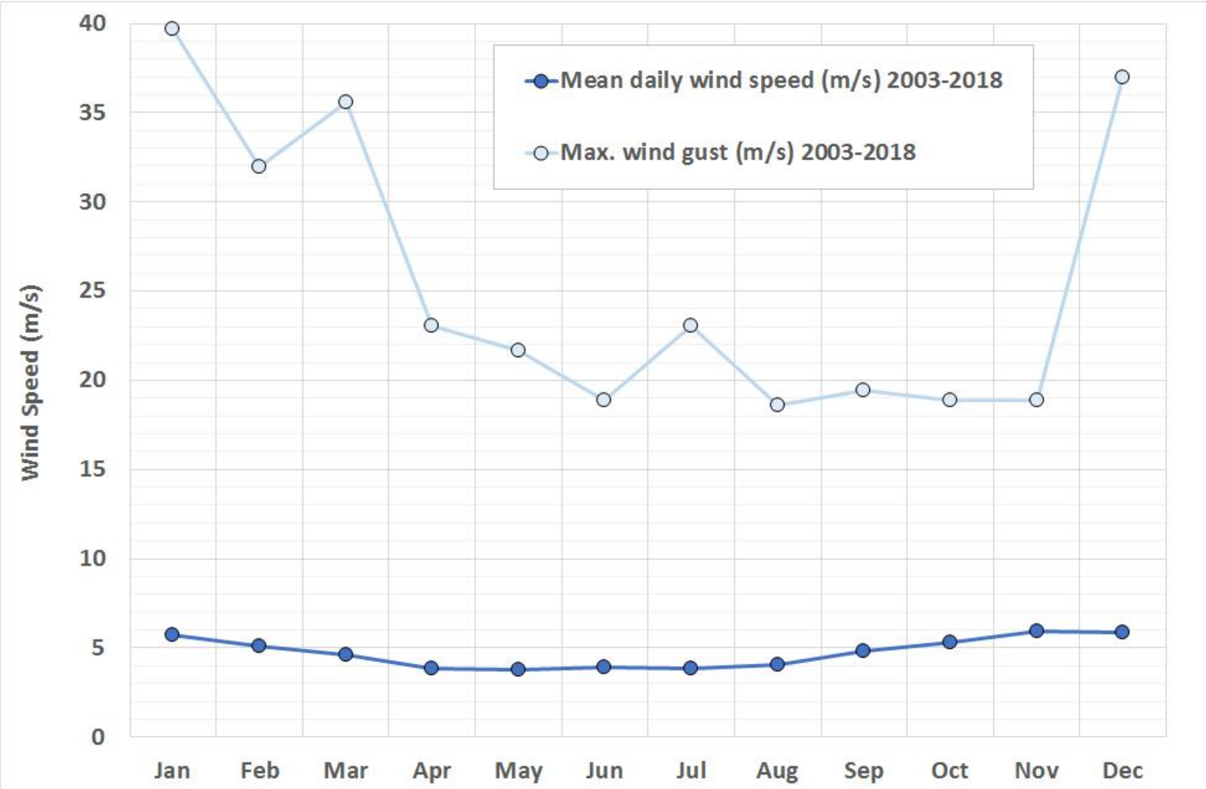



Figure B- 4: Mean Daily Wind Speed and Maximum Wind Gust – Karratha Aerodrome 1993-2018

The 2014 examples are shown in Figure B- 5. The wind roses show westerly winds were dominant during summer and spring over 2010-2018. There was significantly more annual variability in the wind patterns for autumn and winter (see Figure B- 4), but this may be an artefact of the artificial boundaries of those seasons in relation to the Pilbara's dry and wet seasons.

Hourly average wind speed statistics calculated from measurements at BoM Karratha and two other weather stations in the Burrup region in 2014, are compared in Table B- 1. The wind speeds at Karratha match those of Roebourne reasonably well. Higher wind speeds were observed at the more exposed site at Legendre Island just north of the peninsula.

Table B- 1: Wind Speed Comparisons – Burrup Peninsula 2014

| Statistic | BoM Karratha Aerodrome | BoM Roebourne | BoM Legendre Island |
|---|---|---|---|
| Data Capture % | 99.9% | 99.9% | 99.9% |
| Maximum (m/s) | 13.1 | 13.4 | 16.1 |
| 90th percentile (m/s) | 8.0 | 7.8 | 9.7 |
| 70th percentile (m/s) | 6.2 | 5.7 | 7.1 |
| Average (m/s) | 5.0 | 4.5 | 6.0 |


Figure B- 5: Annual and Seasonal Wind Roses for 2014 – BoM Karratha Aerodrome*

A full set of BoM Karratha Aerodrome wind roses for 2010-2018 is provided in the final section of this Appendix.

## Pilbara Cyclones

Cyclones have affected the coastal communities of Port Hedland, Karratha, Dampier, and Onslow, and parts of inland Pilbara. Typically, these cyclones form over warm ocean waters to the north, intensify before crossing the Pilbara coast, then track towards the south. The further south they move the more likely they will move south-easterly across inland parts of WA (BoM, 2019a). For example, the track of Tropical Cyclone Monty, 27 February to 2 March 2004, is shown in Figure B- 6 (BoM, 2019b).

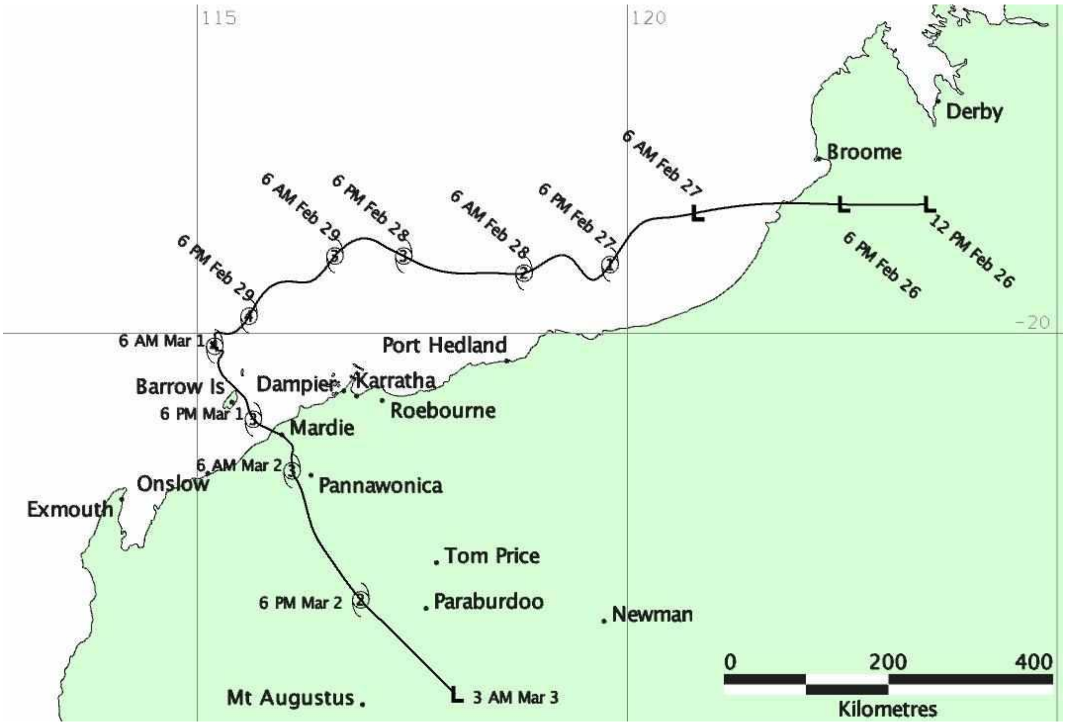



Figure B- 6: Track of Tropical Cyclone Monty 2004 (BoM, 2019b)

Heavy rainfall and flooding are the main impacts for most cyclonic events in inland Pilbara. The highest rainfall is usually found along or just east of the track for most systems. The flood potential of a cyclonic system is associated with its track, speed, areal extent and saturation of catchments from prior rainfall. Rainfall totals in excess of 100 mm are common with tropical lows that move over land (BoM, 2019a).

Cyclones have affected the Proposal's study area. The three most recent, significant cyclones affecting the Pilbara were (BoM, 2019a):

- Cyclone Bobby, 24-25 February 1995 – crossed coast just east of Onslow between midnight and 1 am on the 25th February 1995. More than 400 mm of rain fell in the Onslow area during the event. Very heavy rain associated with the cyclone caused serious flooding in the west Pilbara, Gascoyne, Goldfields and Eucla regions. Rainfall associated with this event followed heavy rains over a large part of inland WA earlier in the month.

- Cyclone Olivia, 10-11 April 1996 – crossed coast near Mardie causing wind gusts of 257 km/h before accelerating to the southeast. Pannawonica recorded gusts to 158 km/h and was extensively damaged. As Olivia passed Paraburdoo after midnight it still produced gusts to 140 km/h.

- Cyclone Monty, 1 March 2004 – passed over Mardie station west of Dampier before passing near Pannawonica where there was some damage, and the town of Pannawonica was cut-off due to flooding. Heavy rain flooded rivers. A large part of the bridge over the Maitland River on the Northwest coastal highway was washed away.

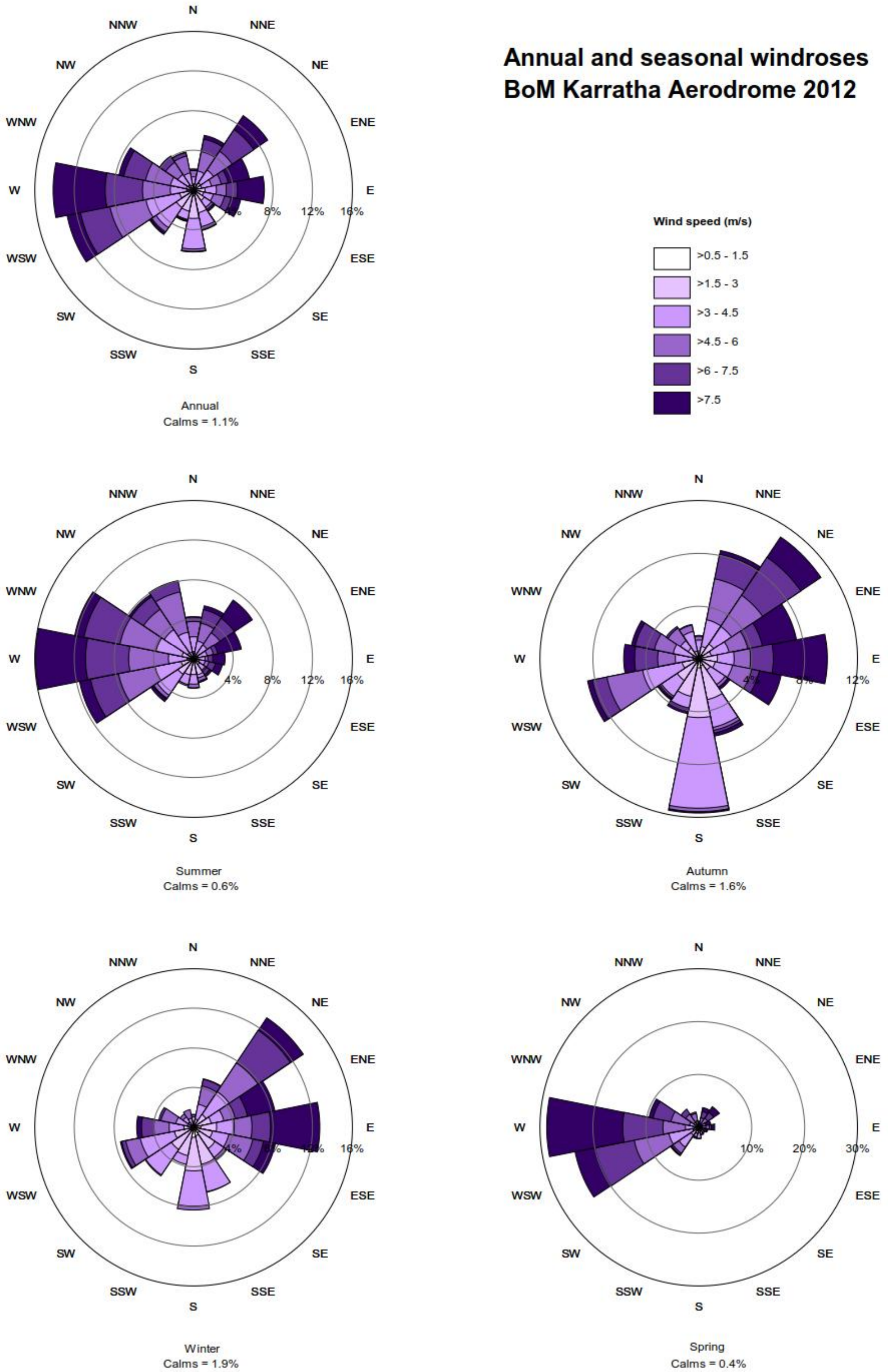
Other cyclones that probably affected Burrup Peninsula weather were (sources: BoM web site): Cyclone Dominic, 22-27 January 2009; Cyclone Laurence, 16-21 December 2009; Cyclone Heidi, 9 January 2011; Cyclone Bianca, 25 January 2011; Cyclone Carlos, 14 February 2011; Cyclone Lua, 17 March 2012; Cyclone Rusty, 22 February 2013; and Cyclone Peta, 23 January 2013.

## Wind Roses

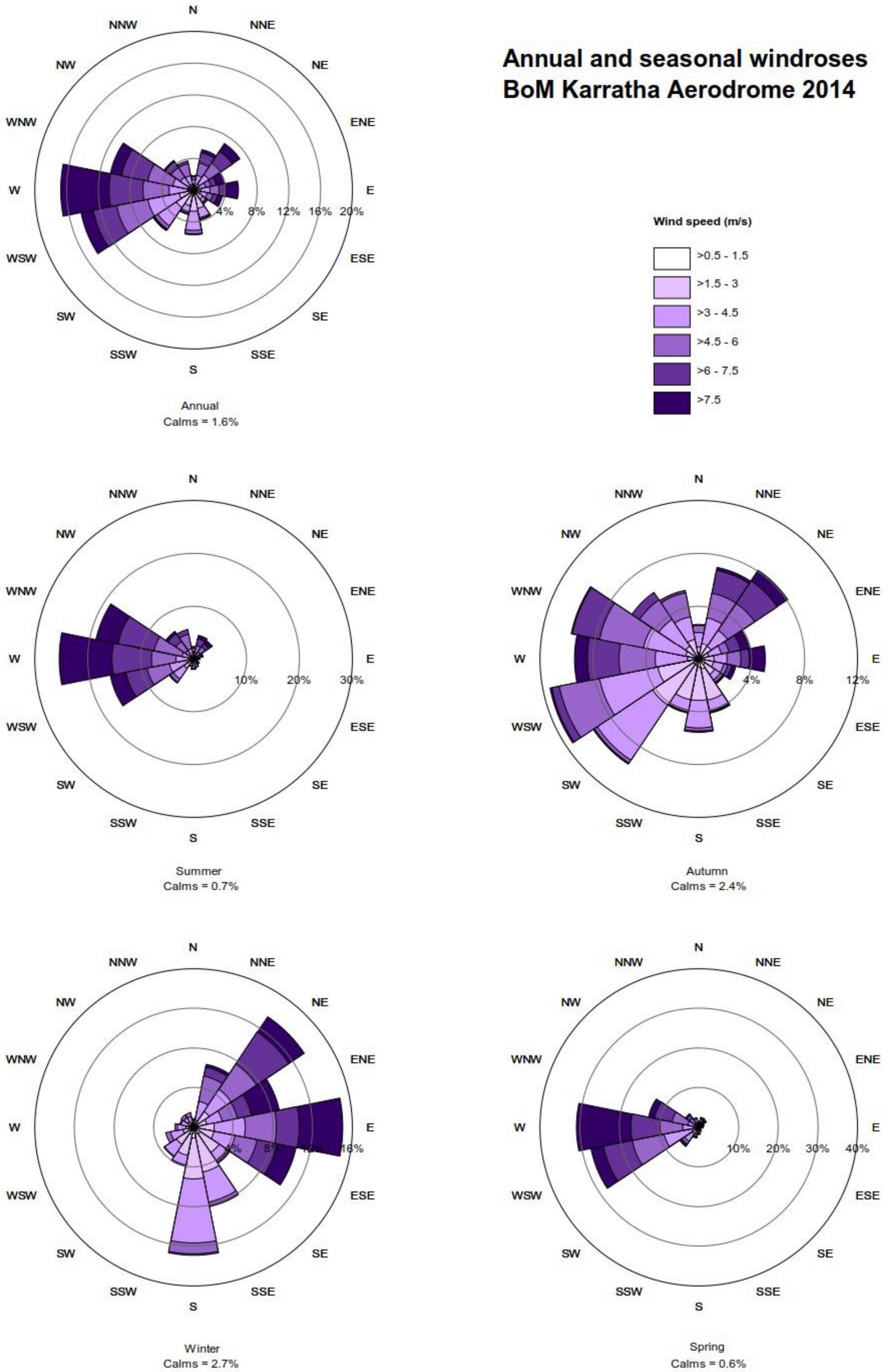
Annual and seasonal wind roses created from hourly wind speed and wind direction data for BoM Karratha Aerodrome 2010-2018 are provided overleaf.


Annual and seasonal windroses
BoM Karratha Aerodrome 2010
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Annual
Calms = 0.7%
Summer
Calms = 0.1%
Autumn
Calms = 1.0%
Winter
Calms = 1.0%
Spring
Calms = 0.6%


Annual and seasonal windroses
BoM Karratha Aerodrome 2011
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
4%
8%
12%
16%
Annual
Calms = 0.8%
5%
10%
15%
20%
25%
Summer
Calms = 0.6%
Autumn
Calms = 0.8%
Winter
Calms = 1.5%
10%
20%
30%
Spring
Calms = 0.3%


Annual and seasonal windroses
BoM Karratha Aerodrome 2012
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
8%
12%
16%
10%
20%
30%
Annual
Calms = 1.1%
Summer
Calms = 0.6%
Autumn
Calms = 1.6%
Winter
Calms = 1.9%
Spring
Calms = 0.4%


Annual and seasonal windroses
BoM Karratha Aerodrome 2013
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
4%
8%
12%
16%
10%
20%
30%
Annual
Calms = 1.0%
Summer
Calms = 0.5%
Autumn
Calms = 0.9%
Winter
Calms = 2.1%
Spring
Calms = 0.4%


Annual and seasonal windroses
BoM Karratha Aerodrome 2014
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
4%
8%
12%
16%
20%
Annual
Calms = 1.6%
10%
20%
30%
Summer
Calms = 0.7%
4%
8%
12%
Autumn
Calms = 2.4%
16%
Winter
Calms = 2.7%
10%
20%
30%
40%
Spring
Calms = 0.6%


Annual and seasonal windroses
BoM Karratha Aerodrome 2015
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Annual
Calms = 1.3%
Summer
Calms = 0.2%
Autumn
Calms = 1.1%
Winter
Calms = 3.0%
Spring
Calms = 0.9%


Annual and seasonal windroses
BoM Karratha Aerodrome 2016
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
4%
8%
12%
16%
20%
10%
30%
5%
15%
25%
Annual
Calms = 1.9%
Summer
Calms = 0.7%
Autumn
Calms = 2.4%
Winter
Calms = 3.2%
Spring
Calms = 1.2%


Annual and seasonal windroses
BoM Karratha Aerodrome 2017
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
Annual
Calms = 1.9%
Summer
Calms = 0.8%
Autumn
Calms = 2.5%
Winter
Calms = 3.4%
Spring
Calms = 0.9%


Annual and seasonal windroses
BoM Karratha Aerodrome 2018
Wind speed (m/s)
>0.5 - 1.5
>1.5 - 3
>3 - 4.5
>4.5 - 6
>6 - 7.5
>7.5
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
4%
8%
12%
16%
20%
10%
30%
40%
Annual
Calms = 0.8%
Summer
Calms = 0.2%
Autumn
Calms = 1.3%
Winter
Calms = 1.5%
Spring
Calms = 0.3%

# Appendix C. Results – Meteorological Modelling

This section provides a brief analysis of the modelling results for predicted wind speed and wind direction. The 2014 hourly datasets for the BoM weather stations at Karratha, Roebourne and Legendre Island were compared with modelled meteorological data output for the same locations, for 2014 (the simulated year used for the Proposal). The modelled predictions for wind patterns matched the observations reasonably well; annual wind roses generated from hourly data are compared in Figure C- 1.

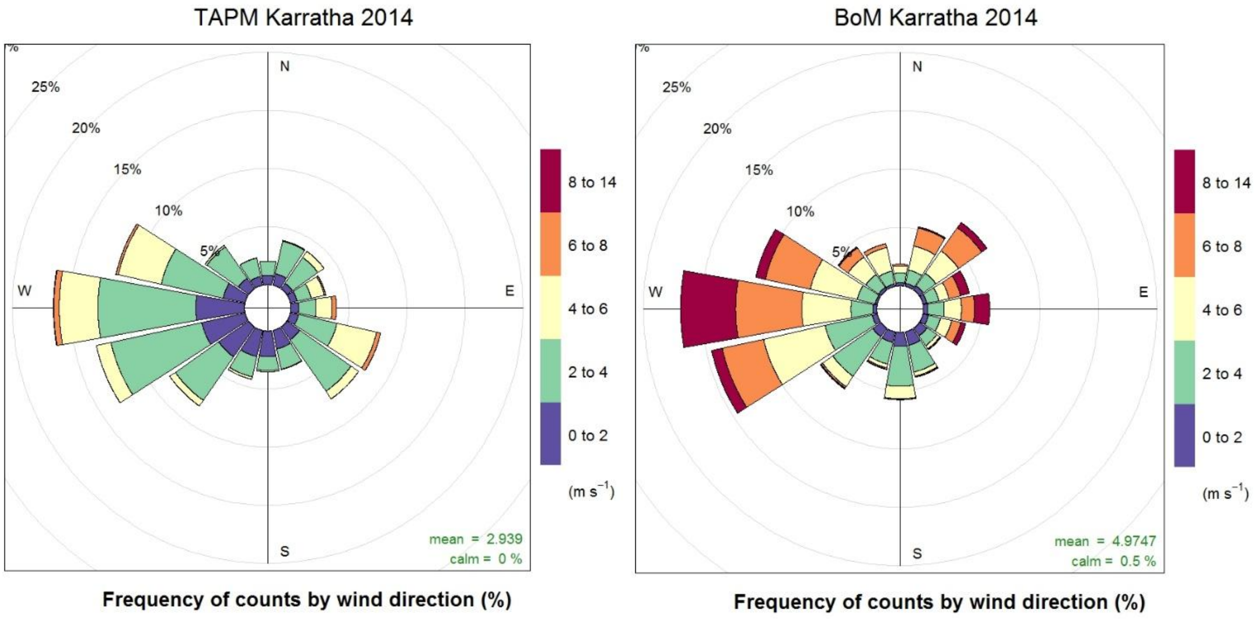



Figure C- 1: Annual Wind Roses Karratha 2014: TAPM (Left) and BoM Measurements (Right)

The wind speeds are compared in Table C- 1 and Figure C- 2. The comparisons show that TAPM consistently under-estimated wind speed for the Burrup Peninsula for 2014. Comparisons of results for other years indicated the problem is general, with TAPM underestimating wind speeds for other years also. While this is not ideal, nevertheless the TAPM estimates for air pollutant concentrations matched the air quality monitoring data reasonably well. Also, the use of these lower wind speeds in the modelling is considered to be a conservative step in the assessment, because the (modelled) dispersion is worse for lower wind speeds, therefore the predicted GLCs will be slightly higher.

Table C- 1: Comparisons of 2014 Hourly Average Wind Speeds

| Station | Karratha Aero. | | Roebourne | | Legendre Is. | |
|---|---|---|---|---|---|---|
| Source | BoM | TAPM (1 km grid) | BoM | TAPM (3 km grid) | BoM | TAPM (3 km grid) |
| No. of averages | 8755 | 8760 | 8759 | 8760 | 8756 | 8760 |
| Maximum (m/s) | 13.1 | 8.3 | 13.4 | 7 | 16.1 | 13.8 |
| 90$^{th}$ percentile (m/s) | 8 | 4.6 | 7.8 | 4.3 | 9.7 | 7.2 |
| 80$^{th}$ percentile (m/s) | 7 | 4 | 6.6 | 3.7 | 8.2 | 6.2 |
| 70$^{th}$ percentile (m/s) | 6.2 | 3.6 | 5.7 | 3.2 | 7.1 | 5.2 |
| 60$^{th}$ percentile (m/s) | 5.5 | 3.2 | 4.9 | 2.8 | 6.3 | 4.5 |

| Station | Karratha Aero. | | Roebourne | | Legendre Is. | |
|---|---|---|---|---|---|---|
| 50th percentile (m/s) | 4.8 | 2.8 | 4.2 | 2.4 | 5.6 | 3.9 |
| Average (m/s) | 4.97 | 2.94 | 4.49 | 2.63 | 5.98 | 4.08 |

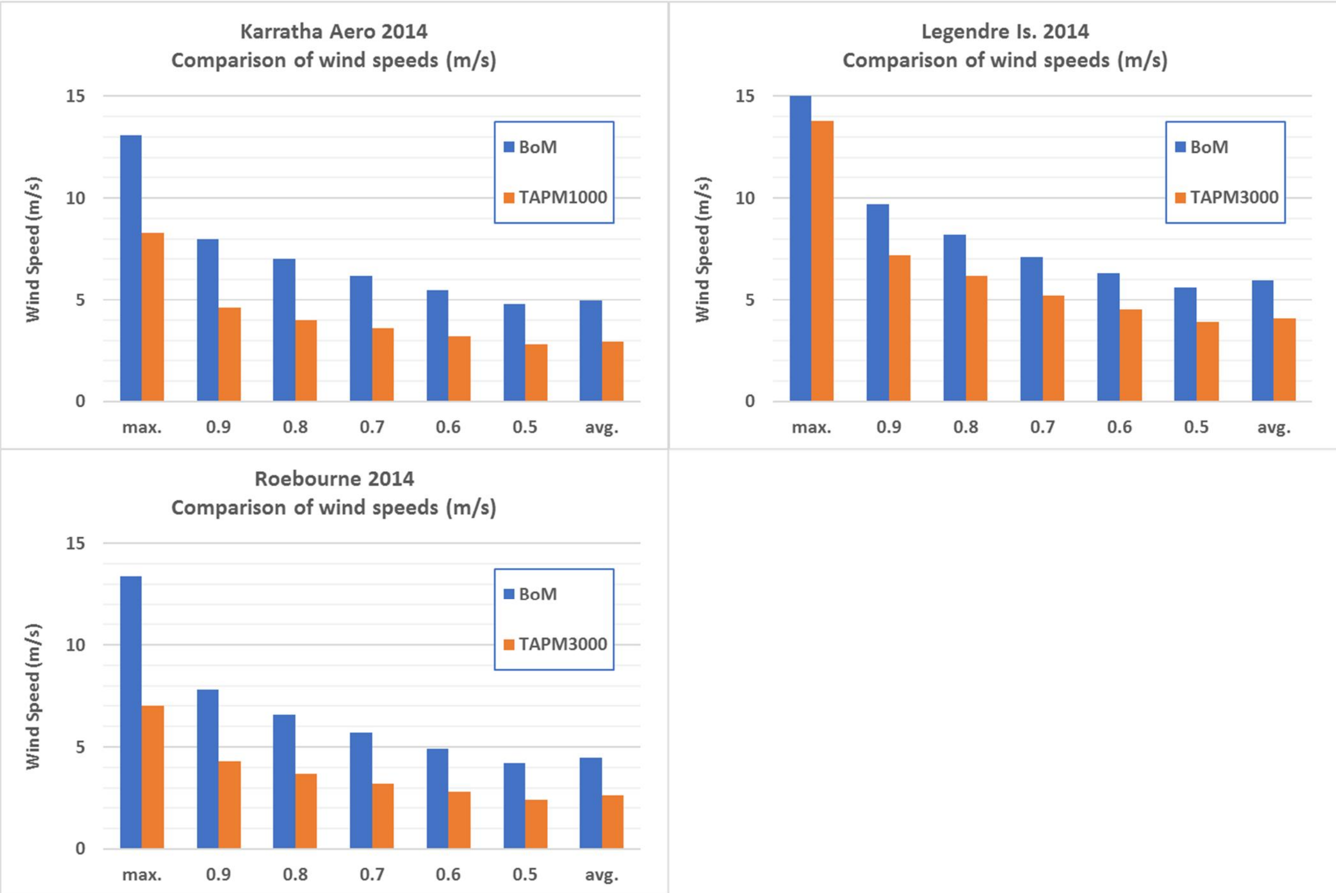



Figure C- 2: Model Results for Wind Speed Compared with 2014 Observations

In the charts shown in Figure C- 2, 'TAPM1000' means the results were obtained from the 1000-metre resolution grid; similarly 'TAPM3000' refers to the 3000-metre resolution grid (Legendre Is. and Roebourne monitoring stations were outside the TAPM study area with 1 km resolution).