Appendix L

Air quality impact assessment

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AIR ENVIRONMENT CONSULTING

Report prepared for

Santos

Narrabri Gas Project

Environmental Impact Statement

Air Quality Impact Assessment

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Glossary

Units of measurement

s	second
min	minute
h	hour
d	day
yr	year
ng	nanogram
µg	microgram
mg	milligram
g	gram
kg	kilogram
t	tonne
ng/m^3	nanogram per cubic metre
µg/m^3	microgram per cubic metre
mg/m^3	milligram per cubic metre
ppm	parts per million
ppb	parts per billion
tpa	tonnes per annum
Mtpa	million tonnes per annum
µm	micron or micrometre
mm	millimetre
m	metre
km	kilometre
m^2	square metres
m^3	cubic metres
m/s	metres per second
m^3/s	cubic metres per second
Am^3/s	actual cubic metres per second (at stack conditions)
Nm^3/s	normalised cubic metres per second (0°C, 1 Atm, dry)
Sm^3/s	standard cubic meters per second (15 °C, 1 Atm, dry)
MMSCFd	millions of standard cubic feet per day
g/s	gram per second
km/h	kilometre per hour
Atm	atmosphere (unit of air pressure) = 101.325 kPa
Pa	pascal
kPa	kilopascal
kPag	kilopascal gauge
hPa	hectopascal
°C	degrees Celsius
K	Kelvin (unit of temperature)
J	joule
kJ	Kilojoule: 1.0 x 10^3 J
MJ	megajoule: 1.0 x 10^6 J
GJ	gigajoule: 1.0 x 10^9 J
TJ	terajoule: 1.0 x 10^{12} J
PJ	petajoule: 1.0 x 10^{15} J
GJ/h	gigajoule per hour
GJ/s	gigajoule per second
MJ/s	megajoule per second
W	watts

Units of measurement

kW	kilowatts
kW_m	kilowatt of mechanical power
kW_e	kilowatt of electrical power
kWh_e	kilowatt hour electrical energy
MW	megawatts
MW_e	megawatts of electrical power
MW_{th}	megawatts of thermal power
mol	mole

Air pollutants and chemical nomenclature

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2S	hydrogen sulfide
N_2	nitrogen
NO_X	oxides of nitrogen
NO_2	nitrogen dioxide
SO_2	sulfur dioxide
O_2	oxygen
O_3	ozone
PM	particulate matter (dust)
PM_{10}	particulate matter with an aerodynamic diameter less than 10 microns
$PM_{2.5}$	particulate matter with an aerodynamic diameter less than 2.5 microns
ou	odour units – is the number of times that a sample of odour must be diluted to reduce its concentration to its detection threshold
TEG	tri-ethylene glycol
TSP	total suspended particles (airborne dust)
VOC	volatile organic compounds

Acronyms

Air Toxics NEPM	National Environment Protection (Air Toxics) Measure
AP 42	United States EPA's Compilation of Air Pollutant Emission Factors
Approved Methods	Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (DEC, 2005)
BOM	Bureau of Meteorology
CALMET	Meteorological model used in conjunction with the CALPUFF dispersion model system
CALPUFF	An advanced non-steady-state Lagrangian meteorological and dispersion modelling system
CBM	coal bed methane
Clean Air Regulation	NSW Protection of the Environment Operations (Clean Air) Regulation 2010
CSG	coal seam gas
EIA	Environment Impact Assessment
EIS	Environment Impact Statement
EMP	Environmental Management Plan
FEED	Front End Engineering Design
LGA	Local Government Area
NPI	National Pollutant Inventory
NEM	National Electricity Market
NEPM	National Environment Protection (Ambient Air Quality) Measure

Acronyms

OEH	NSW Office of Environment and Heritage (formerly Department of Environment and Conservation [DEC])
NEM	National Electricity Market
SCREEN3	Screening model (includes flaring)
TAPM	The Air Pollution Model developed the Commonwealth Scientific and Industrial Research Organisation (CSIRO)
USEPA	United States Environmental Protection Agency
VicSEPP	State Environmental Protection Policy of Victoria

Statistical terms

%ile	percentile
IOA	Index of agreement
MAE	mean absolute error
RMSE	root mean square error

Scientific terms

Boundary layer	The layer of the atmosphere from the Earth's surface to the level where the frictional influence is absent.
Mesoscale	Atmospheric phenomena having horizontal scales ranging from approximately ten to hundreds of kilometres, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones and topographically generated weather systems such as mountain waves and sea and land breezes.
Ringelmann number	The Ringelmann scale is used to measure he apparent density of smoke. The scale has five levels (Ringelmann numbers) of density inferred from a grid of black lines on a white surface which, if viewed from a distance, merge into shades of grey.
Pasquill-Gifford Scheme	Stability classification widely used in atmospheric dispersion models to define the turbulent state of the atmosphere.
Synoptic scale	General weather patterns that occur at the scale of hundreds to thousands of kilometres such as the migration of high and low pressure systems.

Executive Summary

Air Environment Consulting Pty Limited (AEC) was commissioned by GHD to lead an air quality impact assessment study of the Narrabri Gas Project. The air quality impact assessment was based on a dispersion modelling study that combines the site-specific details of the project with various assumptions and estimation techniques to simulate and assess the dispersion and impact of air pollutants in the local area. The approach defines air emission rates, source characteristics, local meteorology, land use, terrain and the location of sensitive receptors to assess the potential for future air quality to be affected in relation to the impact assessment criteria for the project.

The existing environment in the region was characterised in terms of terrain, land use and location of sensitive receptors, the mix of other local industry that release emissions to air, background air quality based on a four-month monitoring program for the project and air quality monitoring information collected by the NSW Office of Environment and Heritage (OEH).

The key air pollutant assessed for the project operations phase was nitrogen dioxide from gas and diesel fuel combustion sources associated with power generation, boilers, gas flaring and well head pumps. Other minor contaminants include fine particles and volatile organic compounds. The key air pollutant assessed for the project construction phase was dust as PM_{10}.

The assessment of construction impacts was based on the United States Western Region Air Partnership Fugitive Dust Emissions Handbook emission factors for construction related dust emissions. The operations phase emissions inventory was developed from a range of information sources including engine technical data for typical gas and diesel-fired engines, emission factors for gas and diesel-fired combustion engines from the United States Environmental Protection Agency emission factor handbooks, AP-42, Volume I, Fifth Edition, emission factors for gas and diesel-fired combustion engines from the National Pollutant Inventory emission estimation technique handbooks and information and assumptions on the project's operation and processes.

The air quality impact assessment was conducted for two project power supply options:

1. Power generation for the Leewood central gas processing facility and Bibblewindi in-field compression facility through the development and operation of a 100 MW_e gas-fired power plant at Leewood. Well pad power was provided by diesel-fired generators for the first year of operation, before being replaced or converted to gas-fired generators.
2. Grid power supplied to the Leewood central gas processing and Bibblewindi in-field compression facilities from the National Electricity Market (NEM). Well pad power would be locally supplied and based on the option 1 power supply option.

Dispersion modelling of the Leewood central gas processing and power generation facility's gas engine and boiler emission sources during routine operations, the flare during non-routine conditions, Leewood during construction and the Bibblewindi in-field compression facility during construction and operational flaring has been conducted using the following approach:

- Selection of a representative year of regional meteorology for simulation.
- Development of meteorological dataset using the CSIRO's prognostic meteorological model TAPM and Earth Tech's diagnostic meteorological model CALMET, that represents the three-dimensional wind flows and temperature profiles of the atmosphere in the region.
- Incorporation of local surface meteorological observations into the CALMET model simulation. The meteorological observations were collected by the Bureau of Meteorology (BOM) at the Narrabri Airport automatic weather station.

- The three-dimensional wind field generated by CALMET was then used with Earth Tech's air dispersion model, CALPUFF, to predict ground-level pollutant concentrations in the local area.

Dispersion modelling of well pad engine emissions and well pad, road, access track and gas, water and electricity transmission pipeline construction has been conducted using the following approach:

- Extraction and formatting of an Ausplume meteorological file at four locations across the project's CALMET model domain.
- Dispersion modelling of well pad engine emission sources using all four meteorological files to select the worst case scenario to account for well pad placement across the entire project area. A minimum separation distance was then selected for each engine type based on the worst case scenario.

The assessment determined that during construction:

- Ground-level concentrations of dust associated with the Leewood and Bibblewindi sites are predicted to be below the impact assessment criteria at all sensitive receptors.
- A separation distance between construction areas and sensitive receptors of at least 60, 30 and 140 metres for a well pad, pipeline trenching, access track and road construction area, respectively, was found to be necessary to protect receptors from ground-level PM_{10} concentrations that may exceed the assessment criteria. These buffers could be reduced through the implementation of further dust mitigation measures during construction activities.

The assessment concluded that during routine operations for power supply options 1 and 2:

- The Leewood gas processing and power generation facility is predicted to meet all relevant impact assessment criteria, including ambient air quality criteria beyond the boundary and stack emission concentration limits.

The assessment also concluded that during non-routine flaring operations above low flow conditions for power supply options 1 and 2:

- The impact assessment criteria were met at all locations beyond the boundary of both the Leewood and Bibblewindi sites.

At the well pads, the assessment determined that:

- Ground-level pollutant concentrations associated with emissions from the gas and diesel-fired generator engines during routine operation were well below the assessment criterion and therefore did not require a buffer.
- The impact assessment criteria were met at all locations beyond the well pad boundary for the operation of the pilot well flare and therefore also did not require a buffer.

All emissions associated with the project's construction and operational phases are predicted to be well below the air quality impact assessment criteria for the protection of human health and amenity at sensitive receiver areas in the region. Potential impacts associated with dust during construction or operation of the project from mobile or intermittent sources would be managed and mitigated in accordance with the project's Environmental Management Plan.

1 Introduction

Air Environment Consulting Pty Limited (AEC) was commissioned by GHD to lead an air quality impact assessment study of the Narrabri Gas Project. AEC has conducted the air quality assessment in collaboration with the GHD Air Quality Assessments Team.

Two power supply options for Leewood and Bibblewindi operations have been considered in this project during operations. Well pad power would be locally generated by diesel and gas-fired generators for both options.

1. Power generation for the Leewood central gas processing facility and Bibblewindi in-field compression facility through the development and operation of a 100 MW_e gas-fired power plant at Leewood. Well pad power provided by diesel-fired generators for the first year of operation, before being replaced or converted to gas-fired generators.

2. Grid power supplied to the Leewood central gas processing and Bibblewindi in-field compression facilities from the National Electricity Market (NEM).

A detailed air quality impact assessment of each option has been undertaken for this assessment. The assessment of construction related impact also applies to both power supply options. Additional air emissions sources during operations, that are relevant to both power supply options, include a hot oil boiler for heating requirements on the amine carbon dioxide removal circuit on each of the four gas processing trains and a flare each at Leewood and Bibblewindi. For option 1, the water treatment plant and (tri-ethylene glycol - TEG) gas dehydration regeneration boiler will be operated by electric power from the Leewood power generation plant and consequently, no additional air emissions are expected.

Air emission sources for the project are summarised in Table 1-1. Only air pollutants with health or odour based air quality impact assessment criteria have been assessed in this study. Fugitive coal seam gas (CSG) releases and fuel combustion sources also comprise greenhouse gas emissions. Greenhouse gas emissions such as methane, carbon dioxide and nitrous oxide do not have published air quality impact assessment criteria as they do not pose a direct risk to human health. Consequently, these substances have not been assessed in this air quality study These substances have been considered in the Narrabri Gas Project *Greenhouse Gas Assessment* (Santos, 2015).

Table 1-1 Air emission sources assessed for the project

Phase	Source	Air pollutants
Construction	Leewood facility Bibblewindi facility Well pads Pipeline trenching for gas, water and below ground electricity transmission lines Access tracks and roads Westport accommodation camp	Particulate matter as PM_{10}
Operation	10 x 9.7 MW_e gas-fired engines at Leewood 4 x 11.9 MW_{th} Hot Oil Boilers at Leewood Flare at Leewood Flare at Bibblewindi Diesel-fired engine at well pads Gas-fired engine at well pads Pilot flare at well pads Wilga Park 40 MW_e Power Station[1] Westport accommodation camp	Nitrogen dioxide Carbon monoxide Particulate matter as PM_{10} / $PM_{2.5}$ Volatile organic compounds Polycyclic aromatic hydrocarbons
Table note:	[1] The 40 MW_e Wilga Park Power Station has a pre-existing environmental approval and is licensed to operate under a separate license. It is not a part of the Santos Narrabri Gas Project environmental approval. The gas-fired power station is currently constructed and operating as a 16 MW_e power generation facility. The 40 MW_e power generation facility was considered as part of the cumulative air quality impact assessment.	

This report details the methods and findings of the assessment for both the project construction and operation stages.

1.1 Overview

The Proponent is proposing to develop natural gas in the Gunnedah Basin in New South Wales (NSW), southwest of Narrabri (refer Figure 1-1).

The Narrabri Gas Project (the project) seeks to develop and operate a gas production field, requiring the installation of gas wells, gas and water gathering systems, and supporting infrastructure. The natural gas produced would be treated to a commercial quality at a central gas processing facility on a local rural property (Leewood), approximately 25 kilometres south-west of Narrabri. The gas would then be piped via a high-pressure gas transmission pipeline to market. This pipeline would be part of a separate approvals process and is therefore not part of this development proposal.

The primary objective of the project is to commercialise natural gas to be made available to the NSW gas market and to support the energy security needs of NSW. Production of natural gas from coal seams under the project would deliver material economic, environmental and social benefits to the Narrabri region and the broader NSW community. The key benefits of the project can be summarised as follows:

- Development of a new source of gas supply into NSW would lead to an improvement in energy security and independence to the State. This would give NSW gas markets greater choice when entering into gas purchase arrangements. Potential would also exist for improved competition on price. Improved competition on price would have flow on benefits for NSW's economic efficiency, productivity and prosperity.
- The provision of a reduced greenhouse gas emission fuel source for power generation in NSW as compared to traditional coal-fired power generation.

- Increased local production and regional economic development through employment and provision of services and infrastructure to the project.
- The establishment of a regional community benefit fund equivalent to five per cent of the royalty payment made to the NSW Government within the future production licence area. If matched by the NSW Government, the fund could reach $120 million over the next two decades.

1.2 Description of the project

The project would involve the construction and operation of a range of exploration and production activities and infrastructure. The key components of the project are presented in Table 1-2, and are shown on Figure 1-1.

Table 1-2 Key project components

Component	Infrastructure or activity
Major facilities	
Leewood	• a central gas processing facility for the compression, dehydration and treatment of gas • a central water management facility including storage and treatment of produced water and brine • optional power generation for the project • a safety flare • treated water management infrastructure to facilitate the transfer of treated water for irrigation, dust suppression, construction and drilling activities • other supporting infrastructure including storage and utility buildings, staff amenities, equipment shelters, car parking, and diesel and chemical storage • continued use of existing facilities such as the brine and produced water ponds • operation of the facility
Bibblewindi	• in-field compression facility • safety flare • supporting infrastructure including storage and utility areas, treated water holding tank, and a communications tower • upgrades and expansion to the staff amenities and car parking • produced water, brine and construction water storage, including recommissioning of two existing ponds • continued use of existing facilities such as the 5ML water balance tank • operation of the expanded facility
Bibblewindi to Leewood infrastructure corridor	• widening of the existing corridor to allow for construction and operation of an additional buried medium pressure gas pipeline, a water pipeline, underground (up to 132 kV) power, and buried communications transmission lines
Leewood to Wilga Park underground power line	• installation and operation of an underground power line (up to a 132 kV) within the existing gas pipeline corridor
Gas field	

Gas appraisal and production infrastructure	• seismic geophysical survey
	• installation of up to 850 new wells on a maximum of 425 well pads
	  – new well types would include exploration, appraisal and production wells
	  – includes well pad infrastructure
	• installation of water and gas gathering lines and supporting infrastructure
	• construction of new access tracks where required
	• water balance tanks
	• communications towers
	• conversion of existing exploration and appraisal wells to production

Ancillary	• upgrades to intersections on the Newell Highway
	• expansion of worker accommodation at Westport
	• a treated water pipeline and diffuser from Leewood to Bohena Creek
	• treated water irrigation infrastructure including:
	  – pipeline(s) from Leewood to the irrigation area(s)
	  – treated water storage dam(s) offsite from Leewood
	• operation of the irrigation scheme

The project is expected to generate approximately 1,300 jobs during the construction phase and sustain around 200 jobs during the operational phase; the latter excluding an ongoing drilling workforce comprising approximately 100 jobs.

Subject to obtaining the required regulatory approvals, and a financial investment decision, construction of the project is expected to commence in early 2018, with first gas scheduled for 2019/2020. Progressive construction of the gas processing and water management facilities would take around three years and would be undertaken between approximately early/mid-2018 and early/mid-2021. The gas wells would be progressively drilled during the first 20 or so years of the project. For the purpose of impact assessment, a 25 year construction and operational period has been adopted.

1.3 Project location

The project would be located in north-western NSW, approximately 20 kilometres south-west of Narrabri, within the Narrabri local government area (LGA) (see Figure 1-1).

The project area covers about 950 square kilometres (95,000 hectares), and the project footprint would directly impact about one per cent of that area.

The project area contains a portion of the region known as 'the Pilliga'; which is an agglomeration of forested area covering more than 500,000 hectares in north-western NSW around Coonabarabran, Baradine and Narrabri. Nearly half of the Pilliga is allocated to conservation, managed under the NSW *National Parks and Wildlife Act 1974*. The Pilliga has spiritual meaning and cultural significance for the Aboriginal people of the region.

Other parts of the Pilliga were dedicated as State forest, and set aside for the purpose of 'forestry, recreation and mineral extraction, with a strategic aim to "provide for exploration, mining, petroleum production and extractive industry" under the *Brigalow and Nandewar Community Conservation Area Act 2005.* The parts of the project area on state land are located within this section of the Pilliga.

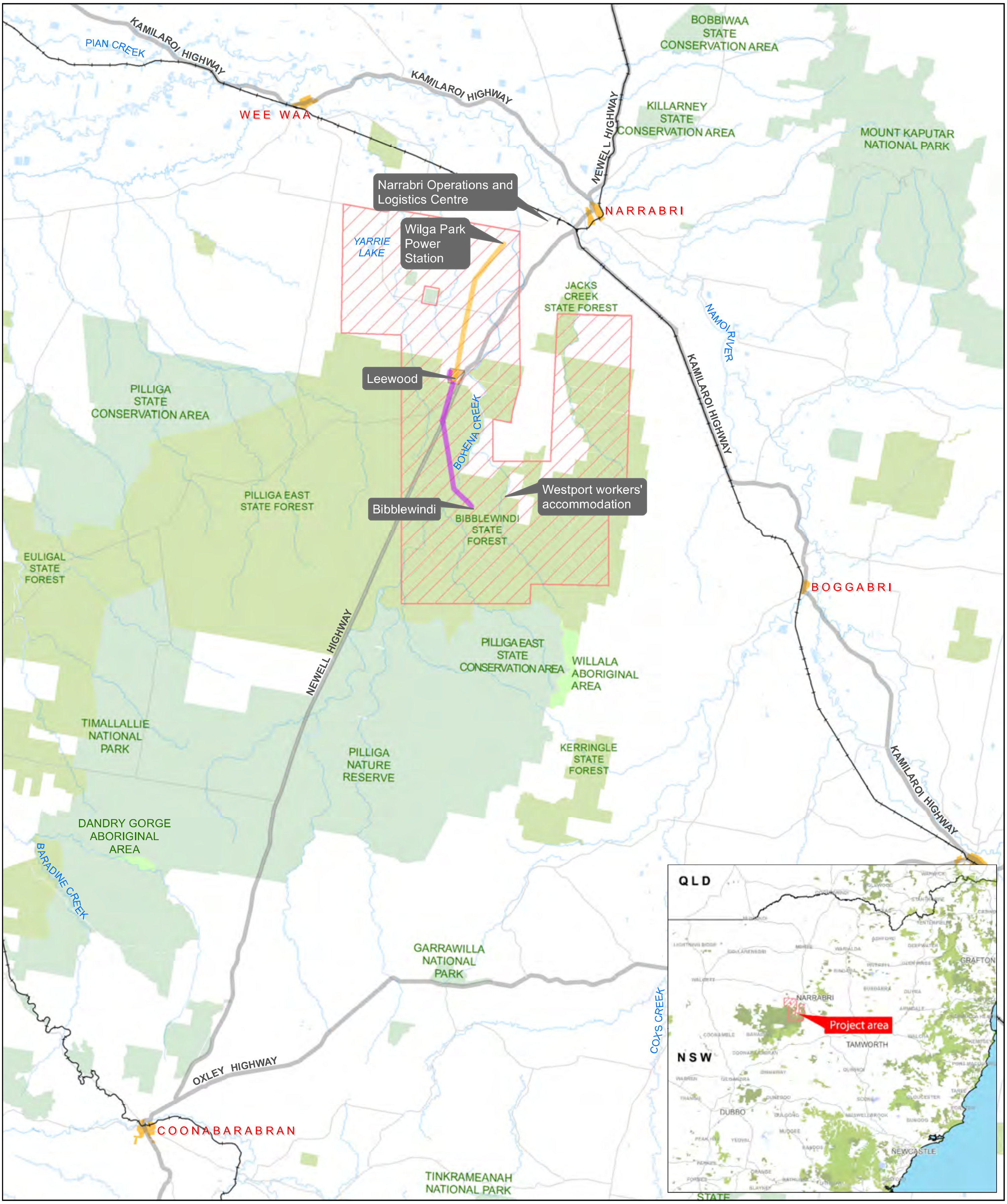
The semi-arid climate of the region and general unsuitability of the soils for agriculture have combined to protect the Pilliga from widespread clearing. Commercial timber harvesting activities in the Pilliga were preceded by unsuccessful attempts in the mid-1800s to establish a wool production industry. Resource exploration has been occurring in the area since the 1960s; initially for oil, but more recently for coal and gas.

The ecology of the Pilliga has been fragmented and otherwise impacted by commercial timber harvesting and related activities over the last century through:

- the establishment of more than 5,000 kilometres of roads, tracks and trails
- the introduction of pest species
- the occurrence of drought and wildfire.

The project area avoids the Pilliga National Park, Pilliga State Conservation Area, Pilliga Nature Reserve and Brigalow Park Nature Reserve. Brigalow State Conservation Area is within the project area but would be protected by a 50 metre surface exclusion zone.

Agriculture is a major land use within the Narrabri LGA; about half of the LGA is used for agriculture, split between cropping and grazing. Although the majority of the project area would be within State forests, much of the remaining area is situated on agricultural land that supports dry-land cropping and livestock. No agricultural land in the project area is mapped by the NSW Government to be biophysical strategic agricultural land (BSAL) and detailed soil analysis has established the absence of BSAL. This has been confirmed by the issuance of a BSAL Certificate for the project area by the NSW Government.



LEGEND

- Project area
- Leewood
- Urban
- State forest
- Parks and reserves
- Aboriginal areas
- Lakes and dams
- Watercourses
- Highways
- Major Roads
- Train line
- Leewood to Wilga Park infrastructure corridor
- Bibblewindi to Leewood infrastructure corridor

0 5 10 20
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Job Number 21-22463
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Regional context and key project infrastructure

Figure 1-1

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Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Created by: afoddy

1.4 Planning framework and structure of this report

1.4.1 Planning framework

The project is permissible with development consent under the *State Environmental Planning Policy (Mining, Petroleum and Extractive Industries) 2007*, and is identified as 'State significant development' under section 89C(2) of the *Environmental Planning and Assessment Act 1979* (EP&A Act) and the *State Environmental Planning Policy (State and Regional Development) 2011*.

The project is subject to the assessment and approval provisions of Division 4.1 of Part 4 of the EP&A Act. The Minister for Planning is the consent authority, who is able to delegate the consent authority function to the Planning Assessment Commission, the Secretary of the Department of Planning and Environment or to any other public authority.

This air quality impact assessment identifies the potential environmental issues associated with construction and operation of the project and addresses the Office of Environment and Heritage and Secretary of the Department of Planning and Environment's environmental assessment requirements for the project (DP&E 2014) including the requirements for air quality impact assessment prescribed in the *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW* (2005) and the *Protection of the Environment Operations (Clean Air Regulations)* (2010). The assessment will be used to support the EIS for the project. The requirements addressed in this report include:

- Description of the existing environment in terms of regional terrain, land use, climate and background air quality.
- Identification of sensitive receptors with the potential to be affected by air emissions generated by the project.
- Identification and description of project air emission sources, air pollutants emitted and source characteristics.
- Assessment and interpretation of the potential for impacts to air quality due to air emissions associated with project construction and operation.
- Identification of air emission mitigation and control measures.

1.4.2 Structure of report

The report is structured as follows:

- **Chapter 1 – Introduction.** This chapter introduces the project and the proponent and describes the project area.
- **Chapter 2 – Overview of assessment methodology.** This chapter defines the study area assessed in this report and describes the steps undertaken in the assessment.
- **Chapter 3 – Legislative context.** This chapter outlines the relevant Commonwealth and State legislation relating to the assessment. Any guidelines and assessment criteria (where applicable) relevant to the gasfield construction, operation and decommissioning are also identified.
- **Chapter 4 – Existing environment.** This chapter describes the existing environmental values of the study area relevant to air quality including a description of the regional terrain and land use, climate, background air quality and location of local population receptors.
- **Chapter 5 – Air emissions associated with the project.** This chapter examines the air emission sources and pollutants associated with the project's construction and operation

phases. Regulated emission targets are discussed as well as the emission source characteristics used in the dispersion modelling assessment.

- **Chapter 6 – Impact assessment methodology.** This chapter details the methods and scenarios used in the impact assessment.
- **Chapter 7 – Impact assessment findings.** This chapter examines the potential environmental impacts associated with the construction and operation of the project.
- **Chapter 8 – Conclusion.** This chapter presents a conclusion to the report and presents the next steps in the advancement of the project.

2 Overview of the Assessment Approach

The air quality impact assessment is based on a dispersion modelling study that combines the site-specific details of the project with various assumptions and estimation techniques to simulate and assess the dispersion and impact of air pollutants in the local area. The approach defines air emission rates, source characteristics, local meteorology, land use, terrain and the location of sensitive receptors to assess the potential for future air quality to be affected in relation to the impact assessment criteria promulgated in the *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (DEC, 2005)*.

The existing environment in the region has been described in terms of:

- regional terrain and land use,
- location of sensitive receptors,
- the mix of local industry,
- background air quality based on a four-month monitoring program for the project, and
- air quality monitoring information collected by the NSW Office of Environment and Heritage.

The impact assessment criteria were selected from a review of the following sources:

- *National Environment Protection Measure (Ambient Air Quality) 1998*,
- NSW Department of Environment and Conservation (NSW DEC) *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (2005)*,
- Texas Commission on Environmental Quality Toxicological section list of *Effects Screening Levels 2014*.

The key air pollutant assessed for the project operations phase was nitrogen dioxide from gas and diesel fuel combustion source exhausts associated with power generation, gas flaring and well head generators. Other minor contaminants include fine particles and volatile organic compounds. The key air pollutant assessed for the project construction phase was dust as total suspended particulate, PM_{10}, $PM_{2.5}$, and deposited dust.

The emissions inventory has been developed from:

- engine technical data for typical gas- and diesel-fired engines used in gas field projects,
- emission factors for construction related dust emissions (WRAP, 2006),
- emission factors for gas and diesel-fired combustion engines from the United States Environmental Protection Agency emission factor handbooks, AP-42, Volume I, Fifth Edition,
- emission factors for gas and diesel-fired combustion engines from the National Pollutant Inventory emission estimation technique handbooks,
- emission factors for gas-fired boilers from the United States Environmental Protection Agency emission factor handbooks, AP-42, Volume I, Fifth Edition,
- emission factors for gas-fired boilers from the National Pollutant Inventory emission estimation technique handbooks, and
- information and assumptions on the project's operation and processes.

For the air quality assessment operational phase, the assessment has been separated into routine and non-routine operations to delineate the impact of emissions that are released continuously and at a constant rate (e.g. power generation plant, boilers and well pad generators) from those released intermittently and at a variable rate (e.g. flares). Dispersion modelling of air emission sources associated with the Leewood facility during routine and non-routine operations, Leewood during construction, the Bibblewindi facility during construction and operational flaring and the Westport Accommodation Camp during construction have been conducted using the following approach:

- Selection of a representative year of regional meteorology for simulation.
- Development of meteorological dataset using the CSIRO's prognostic meteorological model TAPM and Earth Tech's diagnostic meteorological model CALMET, that represents the three-dimensional wind flows and temperature profiles of the atmosphere in the region.
- Incorporation of local surface meteorological observations into the CALMET model simulation. The meteorological observations were collected by the Bureau of Meteorology (BOM) at the Narrabri Airport automatic weather station.
- The three-dimensional wind field generated by CALMET was then used with Earth Tech's air dispersion model, CALPUFF, to predict ground-level pollutant concentrations in the local area.

Dispersion modelling of well pad generator emissions and well pad, road, access track and pipeline and below ground electricity transmission line (e.g. Leewood to Wilga Park) construction has been conducted using the following approach:

- Extraction and formatting of an Ausplume meteorological file at four locations across the project's CALMET model domain.
- Ausplume dispersion modelling of well pad engine emission sources using all four meteorological files to select the worst case scenario to account for well head placement across the entire project area. A minimum separation distance was then selected for each engine type based on the worst case scenario.

The assessment was carried out in accordance with the following NSW legislation and guidance documents:

- *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (2005)*, and
- *Generic Guidance and Optimum Model Settings for the CALPUFF modelling system for Inclusion into the Approved Methods for the Modelling and Assessment of Air Pollutants in NSW, Australia (2011)*.

Ground-level pollutant concentrations associated with operations have been predicted across a Cartesian grid covering the project area. Background levels of nitrogen dioxide and ozone have been estimated based on data collected during the project's air quality monitoring program and a review of representative monitoring data collected by OEH in other rural towns in NSW. Background levels of particulate matter, used primarily in the assessment of construction impacts, have been estimated based on representative monitoring data collected by OEH in NSW rural towns only. Emissions of nitrogen oxides from significant regional sources that have been approved but not yet built or were not operational at the time of the monitoring program have also been predicted and combined with the background monitoring data as part of the baseline condition in the cumulative impact assessment. A review of National Pollutant Inventory listed regional nitrogen oxide emission sources identified the 40 MW_e Wilga Park gas-fired power station for inclusion in the dispersion model to assess cumulative impacts. The Wilga Park power station has been assessed based on information published in the power station's environmental impact statement (Heggies, 2007). No other significant local sources of nitrogen oxide emissions were identified.

3 Legislative Requirements, Context and Air Quality Assessment Criteria

3.1 National environment protection measure

The National Environment Protection Council defines national ambient air quality standards and goals in consultation with, and with agreement from, all state governments. The air quality standards and goals were first published in 1998 in the National Environment Protection (Ambient Air Quality) Measure (Air NEPM), with revisions of particulate matter standards being conducted in 2003 and 2015. The Air NEPM is an ambient monitoring based measure that originally set out compliance standards and goals for specific large urban locations with a population greater than 25,000 people. The revised Air NEPM (2015) was amended to include the exposure of the whole population rather than large urban areas. The Air NEPM (2015) also ratified the $PM_{2.5}$ advisory standards that were introduced in the 2003 revision, and also introduced a new annual average criterion for PM_{10}.

Notwithstanding this, DEC (2005) sets out the impact assessment criteria to be used in the assessment, for which the Air NEPM standards have been adopted as assessment criteria. The Air NEPM and Approved Methods (DEC, 2005) have identified six criteria pollutants, four of which (being nitrogen dioxide, carbon monoxide, ozone and particulate matter as PM_{10}) are important to consider in this assessment for the protection of human health.

3.2 Relevant NSW statutory requirements for the protection of the air environment

In accordance with *Part 5 of the Protection of the Environment Operations (Clean Air) Regulation (2010*): *Emission of Air Impurities from Activities and Plant*, the statutory methods that are to be used for modelling and assessing emissions of air pollutants from stationary sources are outlined in the *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (2005)* (DEC, 2005). The Approved Methods provides guidance on the air quality impact assessment process including the:

- preparation of emission inventories,
- preparation of meteorological data,
- quantification and accounting for background concentrations and cumulative impact assessment,
- dispersion modelling methodology,
- presentation and interpretation of dispersion model predictions, and
- impact assessment criteria and assessment outcomes.

The Approved Methods also prescribes two levels of impact assessment:

1. Level 1 – screening-level dispersion modelling technique using worst case input data.
2. Level 2 – refined dispersion modelling technique using site-specific input data.

The assessment levels are designed so that the second level of assessment should be more accurate than the first, but that the first level is more conservative than the second. The intention of the assessment level system is not to conduct a level two assessment upon completion of a level one assessment, particularly if the level one assessment adequately demonstrates that the development is not expected to cause an impact to the air environment in relation to the impact assessment criteria.

In accordance with the guidance provided in the Approved Methods, the assessment of key plant infrastructure for the project has been conducted as a level two impact assessment through the use of site-specific input data, including:

- local terrain and land use,

- actual locations of sensitive receptors,
- TAPM prognostic model simulations over the region;
- assimilation of local surface meteorological observations into the CALMET diagnostic model,
- configuration of the CALPUFF dispersion model using site-specific emission source characteristics, dimensions and coordinate locations,
- emission rate estimates based on site-specific activity data and worst case emissions data, and
- dust emission rate estimates based on site-specific activity data and published emission factors.

Emission sources associated with infrastructure that does not yet have a fixed and defined location, and that may be re-located throughout the project, have been assessed based on a required separation distance between the source and a receiver.

3.2.1 Emission performance standards

The *Protection of the Environment Operations (Clean Air) Regulation (2010*): *Emission of Air Impurities from Activities and Plant* sets out standards of emission concentrations for new and existing scheduled premises. The standards for proposed plant and equipment to be used in the project are presented in Table 3-1.

Table 3-1 Point source emission concentration standards for scheduled premises relevant to the project

Air impurity	Activity or plant applicability	Standard of emission concentration (mg/m^3)
Nitrogen oxides, as nitrogen dioxide equivalents	Any stationary reciprocating internal combustion engine using a gaseous or liquid fuel	450 [1]
	Any boiler operating on gas	350
Carbon monoxide	Any stationary reciprocating internal combustion engine using a gaseous fuel	125[1]
	Any stationary reciprocating internal combustion engine using a liquid fuel	5,880[1]
	Any activity or plant involving combustion (except as listed above)	125[2]
Smoke	An activity or plant in connection with which liquid or gaseous fuel is burnt	Ringelmann 1 or 20% opacity[1]
	Any flare	No visible emission other than for a total period of no more than five minutes in any two hours
Volatile organic compounds[3], as n-propane	Any stationary reciprocating internal combustion engine using a gaseous fuel	40[1]
	Any stationary reciprocating internal combustion engine using a liquid fuel	1,140[1]
	Any activity or plant involving combustion (except as listed above)	40[2]
Solid particles (total)	Any crushing, grinding, separating or materials handling activity	20[2]
	Any activity or plant (except as listed above)	50[2]
Type 1 and 2 substances[4,5] (in aggregate)	Any activity or plant	1
Cadmium or mercury individually	Any activity or plant	0.2

Table note: Source: *Protection of the Environment Operations (Clean Air) Regulation (2010): Emission of Air Impurities from Activities and Plant*.

[1] Dry, 273 K, 101.3 kPa, 3% oxygen content.
[2] Dry, 273 K, 101.3 kPa.
[3] Volatile organic compound means any chemical compound that:
- is based on carbon chains or rings, and
- contains hydrogen, and
- has a vapour pressure greater than 2 mm of mercury (0.27 kPa) at 25 ^{o}C and 101.3 kPa,
- and includes any such compound containing oxygen, nitrogen or other elements, but does not include methane, carbon monoxide, carbon dioxide, carbonic acid, metallic carbides and carbonate salts.

[4] Type 1 substances include the following elements: antimony, arsenic, cadmium, lead or mercury or any compound containing one or more of those elements.
[5] Type 2 substances include the following elements: beryllium, chromium, cobalt, manganese, nickel, selenium, tin or vanadium or any compound containing one or more of those elements.

3.2.2 Ambient air quality assessment criteria

DEC (2005) sets out the ambient air quality impact assessment criteria under which air quality impacts in NSW are to be assessed. Impact assessment criteria for airborne pollutants associated with project activities are outlined in Table 3-2. Impact assessment criteria for deposited dust are presented in Criteria promulgated in the Approved Methods (DEC, 2005) have been used where available. However, the Approved Methods does not specify a criterion for all pollutants identified in the combustion source emissions associated with the project. Notwithstanding their omission from the Approved Methods, the majority of these hydrocarbon emissions identified are considered to be air contaminants and have been assessed against other suitable air quality standards and assessment criteria.

Where an air quality assessment criterion for a particular contaminant is not promulgated in the local state legislation, it is accepted practice to carry out a review of air quality standards from other jurisdictions to develop an appropriate assessment criterion. The NSW Approved Methods list of ambient air quality assessment criteria is equivalent to the list promulgated in the Victorian State Environment Protection Policy (Air Quality Management) 2001 (SEPP, 2001). The aforementioned documents represent the most exhaustive list of air quality assessment criteria of all Australian state air management policies. Consequently for this assessment, a review of international jurisdiction ambient air quality standards was carried out, with supplementary criteria being sourced from the Texas Commission on Environmental Quality *Effects Screening Levels* (2014) list in the United States. Texas has a significant oil and gas industry and consequently, has developed air pollution screening levels for a comprehensive list of hydrocarbons and other substances.

DEC (2005) classifies air pollutants into five categories according to toxicity and criteria as follows:

- Criteria air pollutants,
- Principal toxic air pollutants,
- Individual toxic air pollutants,
- Other polycyclic aromatic hydrocarbons, and
- Individual odorous air pollutants.

The criteria air pollutants are important substances monitored and assessed for the protection of human health. They are commonly found in the environment and are typically associated with urban activities such as motor vehicle use and industry. They are key pollutants emitted from fossil-fuel-burning sources, and other industries where various materials handling processes generate particulate emissions. The criteria air pollutants are monitored in densely populated urban environments under the requirements of the Air NEPM. The key pollutant substances are assessed as a cumulative impact by taking into consideration the ambient background and incorporating the predicted impact from a new activity.

The Approved Methods (DEC, 2005) states that:

> *the principal toxic air pollutants are defined on the basis that they are carcinogenic, mutagenic, teratogenic, highly toxic or highly persistent in the environment. Principal toxic air pollutants must be minimised to the maximum extent achievable through the application of best practice process design and/or emission controls. Decisions with respect to achievability will have regard to technical, logistical and financial considerations. Technical and logistical considerations include a wide range of issues that will influence the feasibility of an option: for example, whether a particular technology is compatible with an enterprise's production processes.*
>
> *Financial considerations relate to the financial viability of an option. It is not expected that reductions in emissions should be pursued 'at any cost'. Nor does it mean that the preferred option will always be the lowest cost option. However, it is important that the preferred option is cost-effective. The costs need to be affordable in the context of the relevant industry sector within which the enterprise operates. This will need to be considered on a case-by-case basis through discussions with the EPA.*

Emissions of polycyclic aromatic hydrocarbons are released from the combustion sources in trace quantities and generally rank lowly in the emissions hierarchy (with the exception of phenanthrene emissions from lean burn engines). Of the sixteen polycyclic aromatic hydrocarbons substances estimated to be in the project's emissions to air, only seven feature in the Approved Methods impact assessment criteria potency equivalency factors list for use in health risk assessment (DEC, 2005). Due to the low emissions of polycyclic aromatic hydrocarbons and the conservative approach to their assessment (i.e. an assessment of the 100th percentile concentration at the boundary or buffer distance for each source), a screening level assessment using the Texas Commission on Environmental Quality Effects Screening Levels has been used in the assessment.

Coal seam gas extraction and processing operations are not generally associated with odour emissions and impacts. Consequently for this assessment, a detailed odour impact assessment has not been conducted. As an alternative, the assessment of potential odour impacts has focused on the potential of odorous air pollutants to exceed their individual assessment criterion. The key odorous substances associated with project emissions are considered to be nitrogen dioxide, formaldehyde and acetaldehyde.

The assessment criterion of acetaldehyde is based on odour rather than the protection of human health and therefore the criterion goal is the concentration above which an odour may be detected. The odour threshold of formaldehyde is below the criteria set for the protection of human health. However, the odour threshold of nitrogen dioxide is approximately equivalent to that of the 1-hour average health criterion and consequently, odour impacts associated with nitrogen dioxide concentrations are only likely to occur at concentrations that exceed the health criterion.

Table 3-2 Ambient air quality impact assessment criteria used in the study

Air pollutant	Impact assessment criterion by averaging period (μg/m^3)					Criterion	Source
	1-hour	4-hour	8-hour	24-hour	Annual		
Criteria air pollutants							
Nitrogen dioxide	246	--	--	--	62	Health	Approved Methods
PM_{10}	--	--	--	50	30	Health	Approved Methods
$PM_{2.5}$	--	--	--	25	8	Health	Air NEPM
Total suspended particulates	--	--	--	--	90	Health	Approved Methods
Carbon monoxide	30,000		10,000	--	--	Health	Approved Methods
Ozone	214	171	--	--	--	Health	Approved Methods
Lead	--	--	--	--	0.5	Health	Approved Methods
Principal toxic air pollutants							
Acrolein	0.42	--	--	--	--	Health	Approved Methods
Arsenic and compounds	0.09	--	--	--	--	Health	Approved Methods
Benzene	29	--	--	--	--	Health	Approved Methods
Beryllium and compounds	0.004	--	--	--	--	Health	Approved Methods
1,3-Butadiene	40	--	--	--	--	Health	Approved Methods
Cadmium and compounds	0.018	--	--	--	--	Health	Approved

Air pollutant	Impact assessment criterion by averaging period (µg/m³)					Criterion	Source
	1-hour	4-hour	8-hour	24-hour	Annual		
							Methods
1,2-Dichloroethane (ethylene dichloride)	70	--	--	--	--	Health	Approved Methods
Dioxins and furans	0.000002	--	--	--	--	Health	Approved Methods
Formaldehyde	20	--	--	--	--	Health	Approved Methods
Nickel and compounds	0.18	--	--	--	--	Health	Approved Methods
Propylene	90	--	--	--	--	Health	Approved Methods
Vinyl Chloride	24	--	--	--	--	Health	Approved Methods
Individual toxic air pollutants							
Biphenyl	24	--	--	--	--	Health	Approved Methods
Chromium III compounds	9	--	--	--	--	Health	Approved Methods
Carbon Tetrachloride	12	--	--	--	--	Health	Approved Methods
Chloroethane (ethyl chloride)	48,000	--	--	--	--	Health	Approved Methods
Chloroform (trichloromethane)	900	--	--	--	--	Health	Approved Methods
Copper dusts and mists	18	--	--	--	--	Health	Approved Methods
Ethylbenzene	8,000	--	--	--	--	Health	Approved Methods
Methylene Chloride (Dichloromethane)	3,190	--	--	--	--	Health	Approved Methods
n-Hexane	3,200	--	--	--	--	Health	Approved Methods
Mercury (organic)	0.18	--	--	--	--	Health	Approved Methods
1,1,2-Trichloroethane	1,000	--	--	--	--	Health	Approved Methods
Individual odorous air pollutants							
Acetaldehyde	42	--	--	--	--	Odour	Approved Methods
Chlorobenzene	100	--	--	--	--	Odour	Approved Methods
Methanol	3,000	--	--	--	--	Odour	Approved Methods
Phenol	20	--	--	--	--	Odour	Approved Methods
Styrene	120	--	--	--	--	Odour	Approved Methods
Toluene	360	--	--	--	--	Odour	Approved Methods
Xylenes	190					Odour	Approved Methods

Air pollutant	Impact assessment criterion by averaging period (µg/m³)					Criterion	Source
	1-hour	4-hour	8-hour	24-hour	Annual		
Other hazardous and odorous air pollutants							
Butane	66,000	--	--	--	7,200	Health	TCEQ
Butyr/Isobutyraldehyde	140	--	--	--	290	Odour	TCEQ
Cyclopentane	3,400	--	--	--	340	Health	TCEQ
1,1-Dichloroethane	4,000	--	--	--	400	Health	TCEQ
1,2-Dichloropropane	460	--	--	--	46	Health	TCEQ
1,3-Dichloropropene	45	--	--	--	4.5	Health	TCEQ
Ethylene Dibromide	4	--	--	--	0.4	Health	TCEQ
Methylcyclohexane	940	--	--	--	94	Health	TCEQ
2-Methylnaphthalene	30	--	--	--	3	Health	TCEQ
n-Nonane	10,500	--	--	--	1,050	Health	TCEQ
n-Octane	3,500	--	--	--	350	Health	TCEQ
n-Pentane	4,100	--	--	--	7,100	Odour	TCEQ
1,1,2,2-Tetrachloroethane	70	--	--	--	7	Health	TCEQ
1,2,3-Trimethylbenzene	1,250	--	--	--	125	Health	TCEQ
1,2,4-Trimethylbenzene	700	--	--	--	125	Health	TCEQ
1,3,5-Trimethylbenzene	1,250	--	--	--	125	Health	TCEQ
2,2,4-Trimethylpentane	3,130	--	--	--	350	Odour	TCEQ
Polycyclic aromatic hydrocarbons							
Acenaphthene	1	--	--	--	0.1	Health	TCEQ
Acenaphthylene	200	--	--	--	50	Health	TCEQ
Anthracene	0.5	--	--	--	0.05	Health	TCEQ
Benzo(a)anthracene	0.5	--	--	--	0.05	Health	TCEQ
Benzo(a)pyrene	0.3	--	--	--	0.03	Health	TCEQ
Benzo(b)fluoranthene	0.5	--	--	--	0.05	Health	TCEQ
Benzo(e)pyrene	0.5	--	--	--	0.05	Health	TCEQ
Benzo(g,h,i)perylene[1]	0.5	--	--	--	0.05	Health	TCEQ
Benzo(k)fluoranthene	0.5	--	--	--	0.05	Health	TCEQ
Chrysene	0.5	--	--	--	0.05	Health	TCEQ
Dibenz(a,h)anthracene	0.5	--	--	--	0.05	Health	TCEQ
7,12-Dimethylbenz(a)anthracene[1]	0.5	--	--	--	0.05	--	--
Fluoranthene	0.5	--	--	--	0.05	Health	TCEQ
Fluorene	10	--	--	--	1	Health	TCEQ
Indeno(1,2,3-cd)pyrene	0.5	--	--	--	0.05	Health	TCEQ
2-Methylnaphthalene	30	--	--	--	3	Health	TCEQ
3-Methylchloranthrene[1]	0.5	--	--	--	0.05	--	--
Naphthalene	200	--	--	--	50	Health	TCEQ
Phenanthrene	0.5	--	--	--	0.05	Health	TCEQ
Pyrene	0.5	--	--	--	0.05	Health	TCEQ

Table note: [1] No air quality standard was found for 7,12-Dimethylbenz(a)anthracene and 3-Methylchloranthrene. Consequently, a concentration standard of 0.5 µg/m³ was used in line with other polycyclic aromatic hydrocarbon compounds adopted from the TCEQ screening level list.

Gas volumes are expressed at 25°C and 1 Atm (101.325 kPa).

Table 3-3 Impact assessment criteria for deposited dust

Air pollutant	Averaging period	Deposition rate $g/m^2/month$	Note	Source
Deposited dust	Annual	2	Maximum increase in deposited dust level	Approved Methods
Deposited dust	Annual	4	Maximum total deposited dust level	Approved Methods

Table note: Dust is assessed as insoluble solids as defined by AS3580.10.1-1991.

3.3 Approach to air quality impact assessment

This air quality impact assessment has been undertaken primarily as a level two impact assessment (as defined in the Approved Methods, DEC 2005) with the inclusion of site-specific information and modelling processes. Notwithstanding this approach, some additionally conservative level one assessment measures have also been incorporated to account for uncertainties in the methodology and future changes in the project conditions or local environment beyond the proponent's control. At this stage of the environmental impact assessment, decisions on engine models and specifications have not been finalised and therefore assumptions have been made on typical engine technical data for gas field development projects.

For this air quality impact the following assessment approach has been taken, in accordance with the requirements of the Approved Methods (DEC, 2005):

- Criteria air pollutants have been assessed as the 100^{th} percentile of predicted impact plus background at locations beyond the Leewood and Bibblewindi locations. This is considered highly conservative as the assessment criteria specifies assessments to be made at existing and future off-site sensitive receptors.
- Principal toxic, individual toxic and odorous air pollutants have been assessed as the 99.9^{th} percentile of predicted incremental impact at locations beyond the boundaries of the Leewood and Bibblewindi locations. This is considered highly conservative as the assessment criteria specifies assessments to be made at existing and future off-site sensitive receptors.
- Polycyclic aromatic hydrocarbons have been assessed as the 100^{th} percentile of predicted incremental impact at locations beyond the boundaries of the Leewood and Bibblewindi locations. This is also considered highly conservative as the assessment criteria specifies assessments to be made at existing and future off-site sensitive receptors.
- Impacts associated with infrastructure with locations that are not yet defined, such as well pads, roads and pipeline and transmission line trenches have been assessed to determine the buffer limiting pollutant. This infrastructure will, in the future, be located to account for the separation distance prescribed in this assessment.

4 Existing Environment

4.1 Terrain and land use

The terrain and land use in the project area is a mix of rolling rural cultivated and cleared agricultural land, state forest used by the timber industry (hereafter referred to as forest) and scrubby forest. As part of the western slopes in northern NSW, the terrain tends to slope down to the west, with the project area modelled in this assessment having an elevated peak in the south-east and sloping downhill to the north-west corner of the model domain. Figure 7-1 in section 7.2.2 of this report, which describes the meteorological modelling methodology, illustrates the topography identified and applied in the air quality modelling.

Figure 7-2 (in section 7.2.2) illustrates the land use identified within the model domain, and indicates that approximately 70 percent of the project area is forested land and 30 percent is agricultural. The urban area of Narrabri occupies only a small portion in the north-east of the domain. Note that the meteorological model domain is significantly broader than the project area in order to incorporate the important geophysical features of the region and to downsize synoptic-scale meteorological features to the local-scale important in this assessment.

4.2 Assessment of the regional climate

The assessment of regional climate in the project area is based on climate statistics collected by the BOM at the Narrabri Airport automatic weather station between 2001 and 2013. This hourly averaged dataset has also been used to inform the air quality modelling for the assessment of air quality impacts.

The BOM's climate classification for the region, as depicted in Figure 4-1, is for a temperate climate with warm to hot summers and cool winters (BOM, 2014a). The summer months (December, January and February) and the month of June tend to be the wettest on average with between 50 and 100 mm per month, while the remaining months tend to experience well below 50 mm of rainfall.

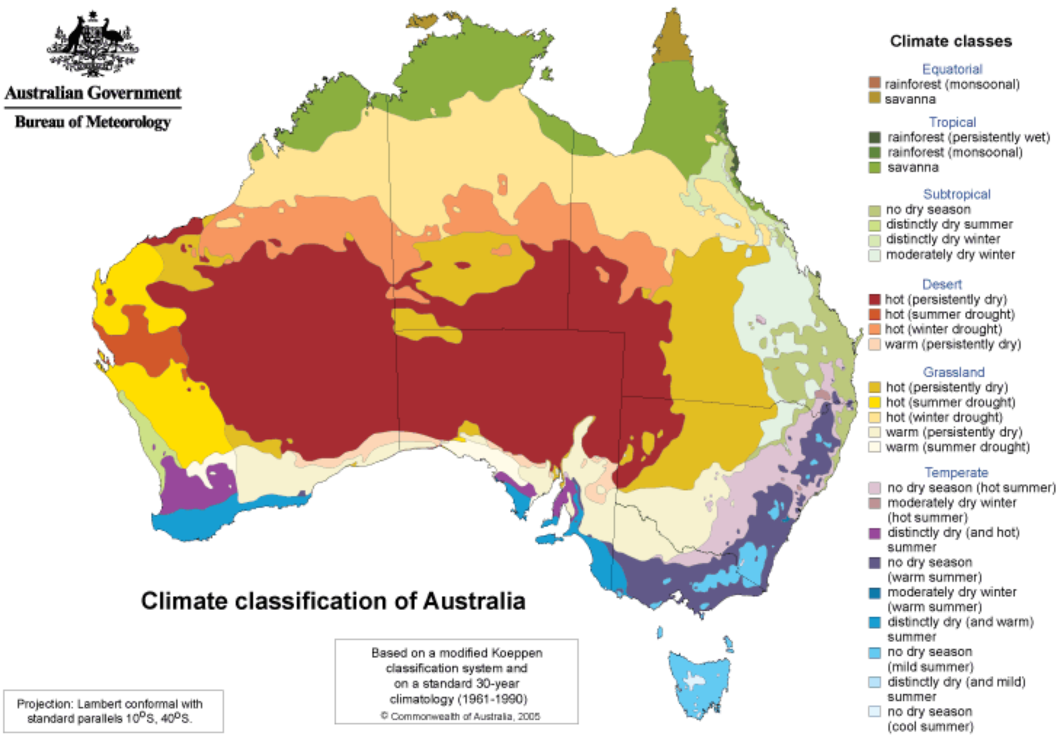


Figure 4-1 Climate classification of Australia

The monthly temperature distribution at Narrabri is presented in Figure 4-2, which illustrates the monthly highest, mean maximum and minimum, and 10th and 90th percentiles. Figure 4-3 provides a further examination of the warm spring and summer temperatures presenting the average number of days above 30, 35 and 40°C. Average monthly solar exposure is presented in Figure 4-4.

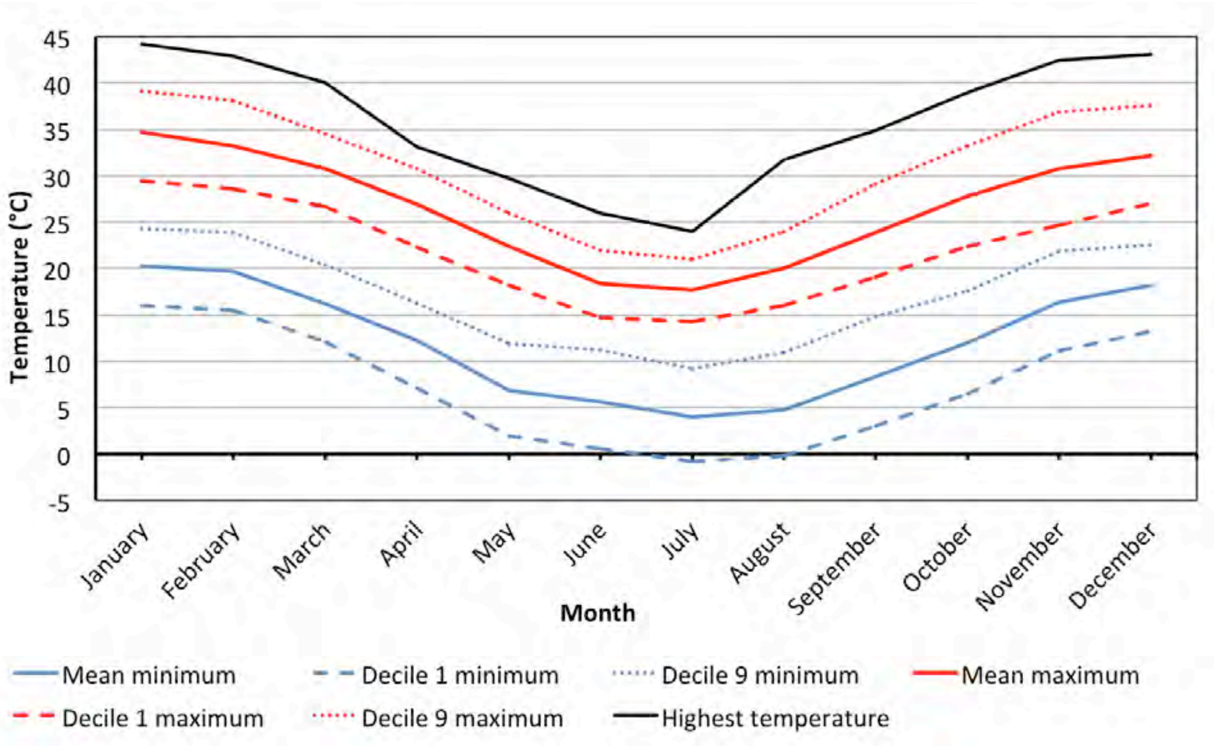


Figure 4-2 Monthly temperature statistics

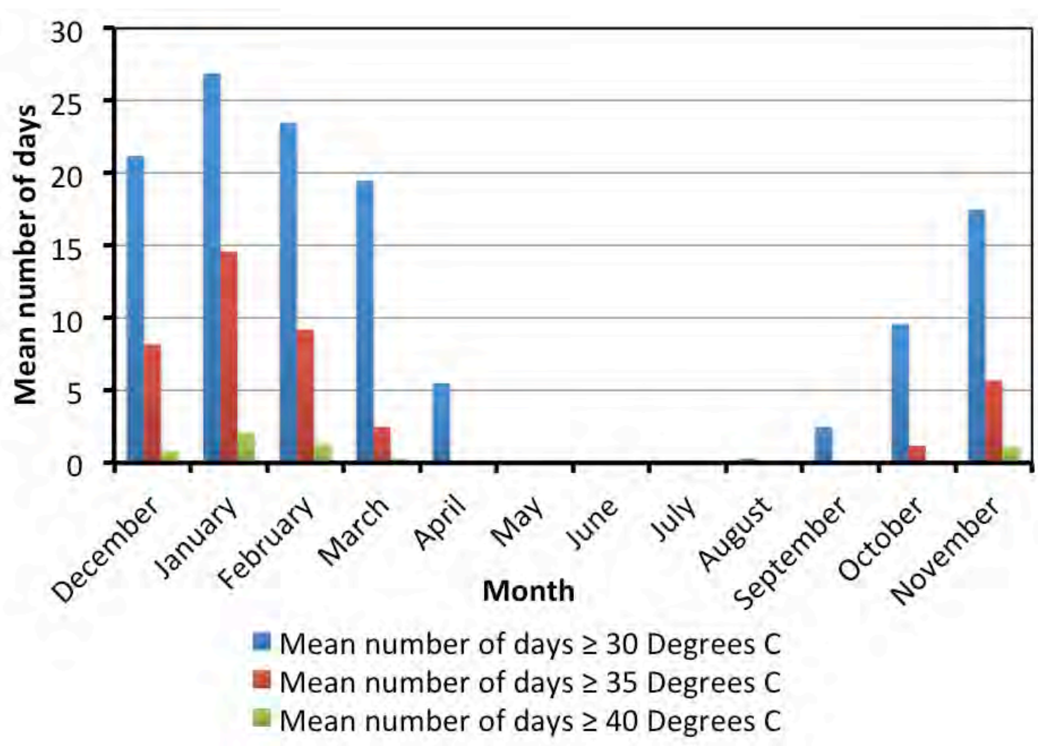


Figure 4-3 Average number of warm days by month

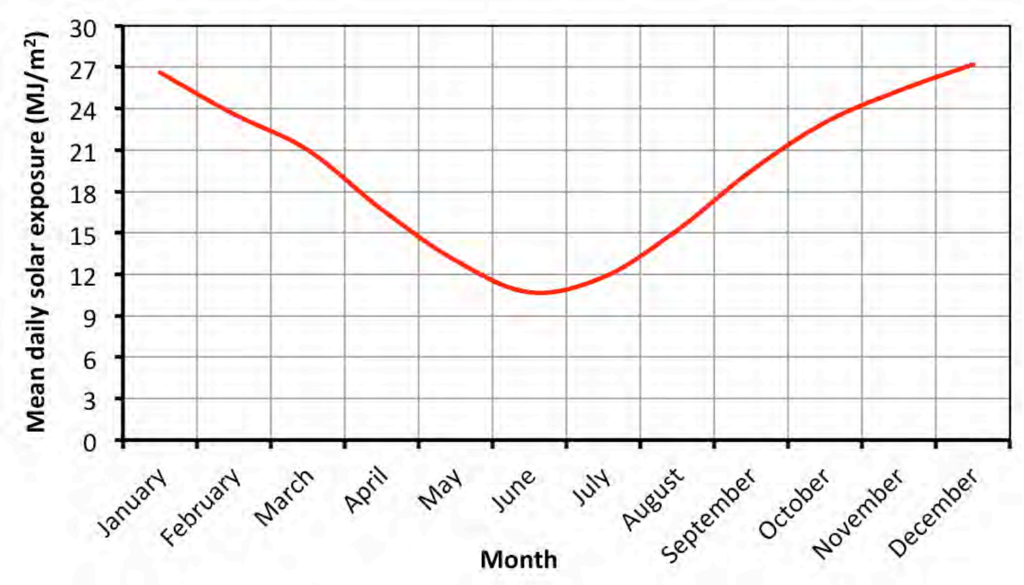


Figure 4-4 Average monthly solar exposure

Annual mean rainfall at Narrabri Airport was 569 mm for the period 2001 – 2013, with a highest annual recorded rainfall total for the period of 891 mm in 2004. This short-term annual rainfall average at the airport illustrates a change in average annual rainfall patterns for the region. By comparison, the Narrabri Post Office dataset between 1891-2013 had an annual average rainfall of 660 mm, an annual mean decrease in short term rainfall totals of 91 mm or 14 percent. Rainfall in the region is also described by the monthly highest, mean maximum and minimum and 10^{th} and 90^{th} percentiles and number of rain days statistics, as presented in Figure 4-5 and Figure 4-6.

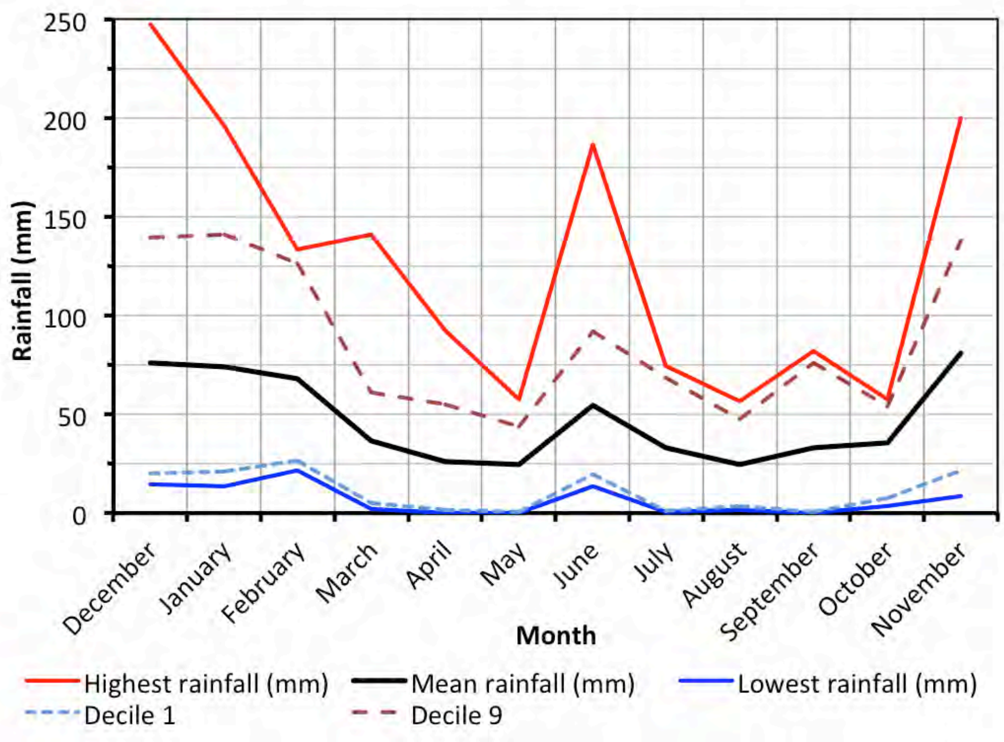


Figure 4-5 Average and extreme rainfall totals by month

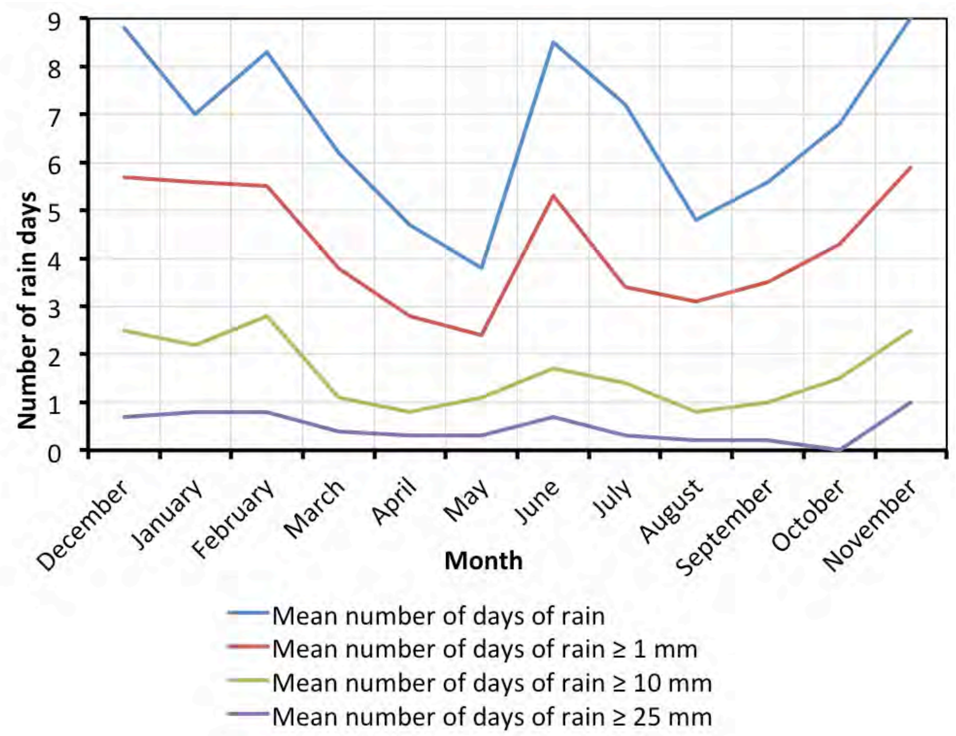


Figure 4-6 Daily rainfall intensity statistics by month

Thunder days and lightning ground flash density was also investigated for the climate assessment. Figures 4-7 to 4-9 inclusive denote the annual variation in thunderstorm and lightning activity across eastern Australia. The annual average thunder-day map is based on observed thunderstorm activity at approximately 300 weather stations over a 10-year period (1990-1999). The lightning maps (refer to Figures 4-7 to 4-9) are based on eight years of satellite-derived data (1995-2002) (BOM, 2014c, d, e).

The annual thunder-day map shows thunderstorms are most frequent over the northern half of the country, and generally decrease southward, with lowest frequencies in southeast Tasmania. A secondary maximum is also apparent in southeast Queensland and over central and eastern New South Wales, extending into the north-eastern Victorian highlands (BOM, 2014c). The average number of thunder days annually in the project area is approximately 25-30 days (refer to Figure 4-7).

The average annual lightning ground flash density map depicts the geographical distribution of cloud-to-ground flashes (BOM, 2014d). The average annual lightning ground flash density in the project area is between one to two flashes per kilometre per year (refer to Figure 4-8).

The average annual total lightning flash density map illustrates the geographical distribution of both cloud-to-ground and cloud-to-cloud flashes (BOM, 2014e). The average annual total lightning flash density in the project area is five flashes per kilometre per year (refer to Figure 4-9).

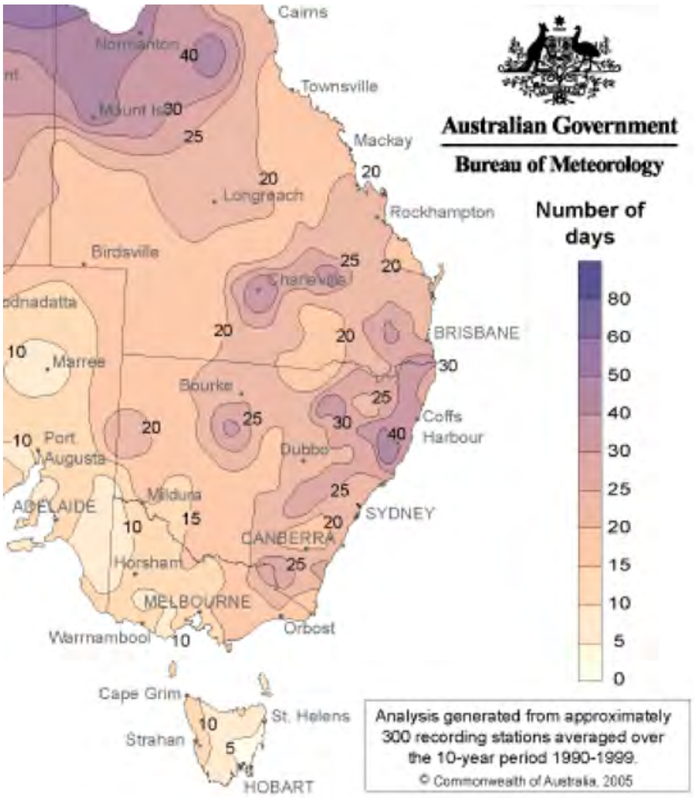


Figure 4-7 Average annual thunder days

Source: BOM, 2014c.

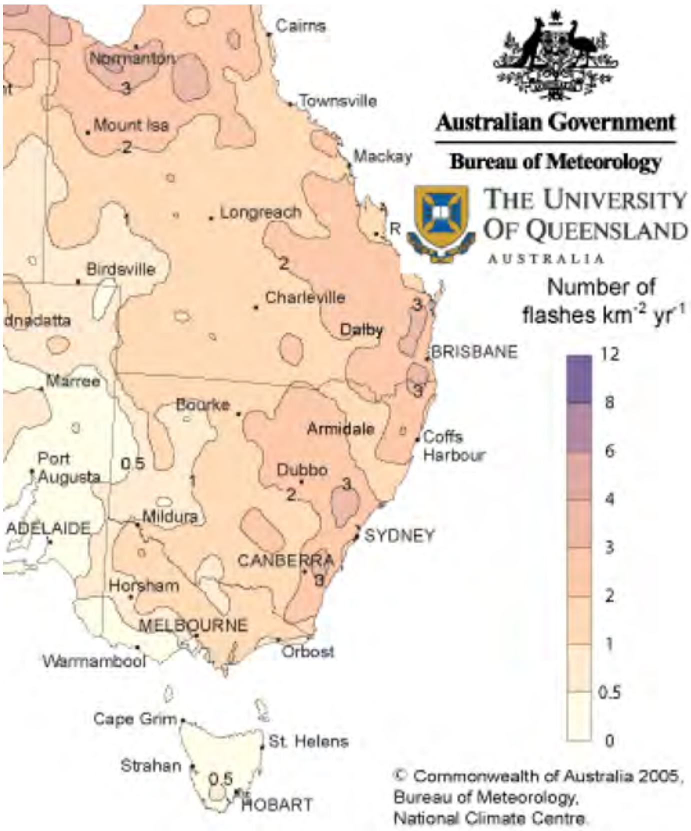


Figure 4-8 Average annual lightning ground flash density

Source: BOM, 2014d.

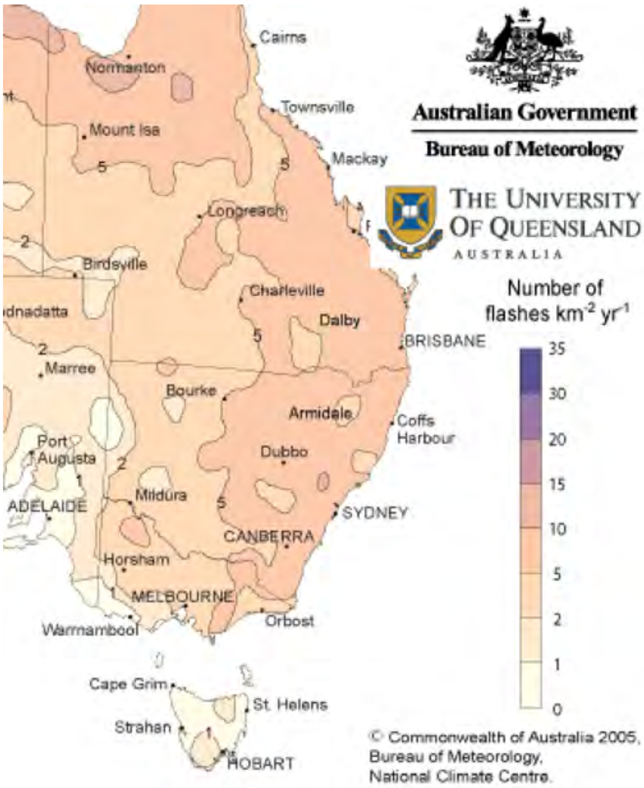


Figure 4-9 Average annual total lightning flash density

Source: BOM, 2014e.

The Narrabri region tends to be dominated by winds from the south-east quadrant and to a lesser extent winds from the north. The annual distribution of wind at Narrabri is presented as a wind rose diagram in Figure 4-10, while the breakdown of seasonal and daily winds are presented in Figure 4-11 and Figure 4-12, respectively.

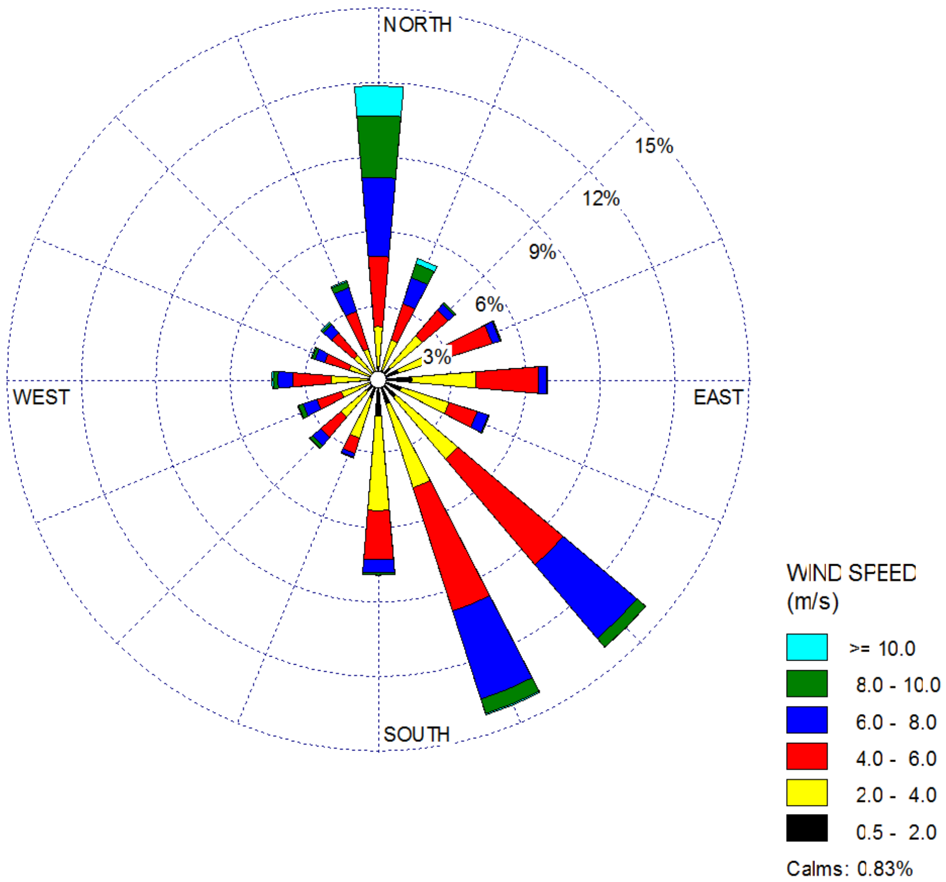


Figure 4-10 Annual distributions of wind speed and direction at Narrabri

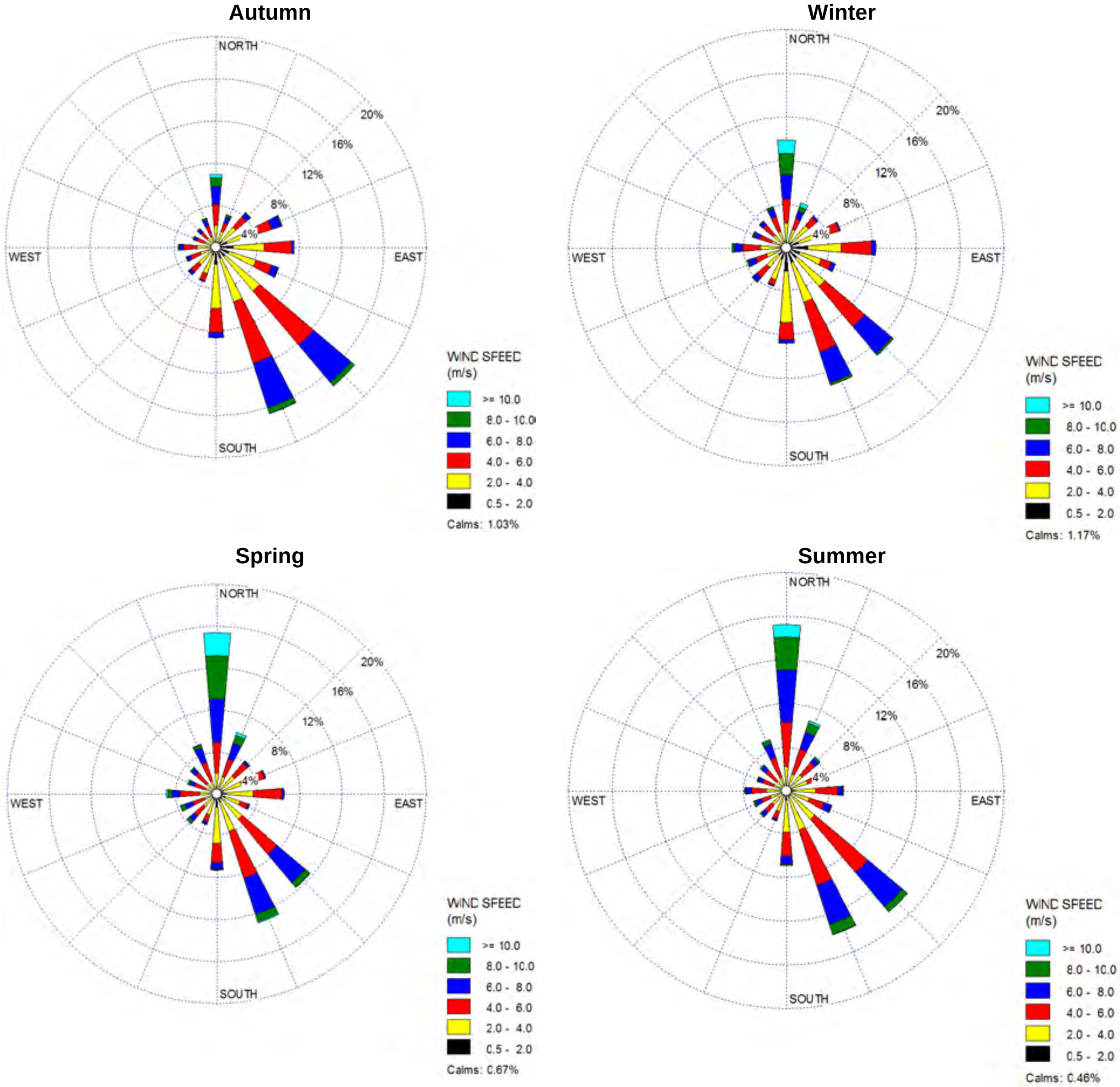


Figure 4-11 Seasonal distributions of wind speed and direction at Narrabri

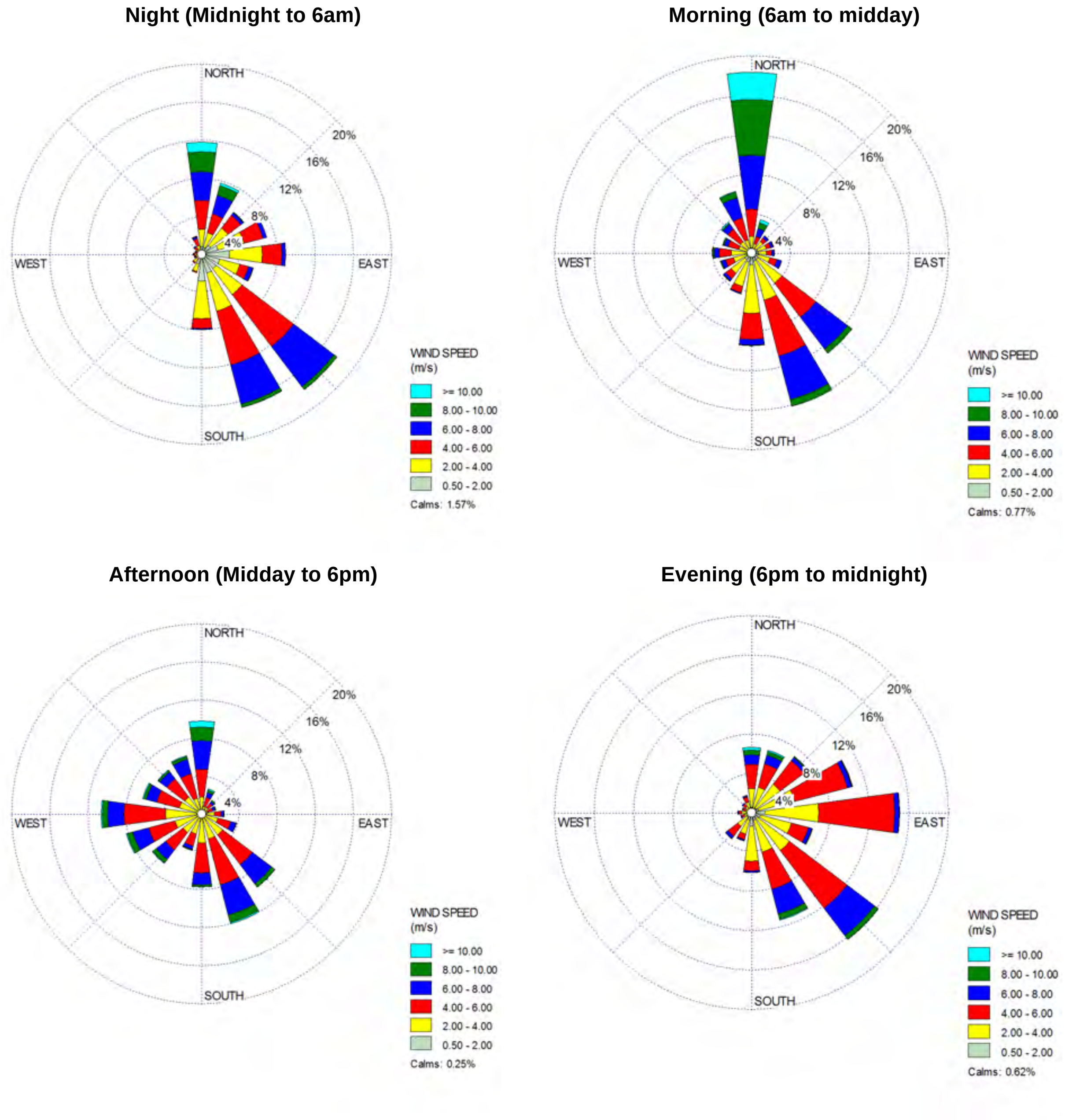


Figure 4-12 Daily distributions of wind speed and direction at Narrabri

The wind rose diagrams indicate that the distributions of wind from season to season do not change significantly. Overall, the patterns remain relatively consistent. Southeasterly winds are a dominant flow throughout each day however; the westerly component tends to develop during the afternoon, while the northerly component tends to ease during the evening.

4.3 Background air quality

4.3.1 Emissions associated with existing local industries

Regional air quality within the project area is mainly influenced by mining, coal seam gas (CSG) exploration activities, and agriculture. The National Pollutant Inventory (NPI) lists 16 sources of emissions within the Narrabri and Gunnedah Local Government Areas (LGA). Of the 16 emission sources, seven are associated with extractive industries for which the primary emissions are likely to be dust, with minor emissions of nitrogen oxides and volatile organic compounds.

Three industries are associated with fuel storage and distribution, where volatile organic compounds will likely be released. Odour is likely to be the primary emission for four industries associated with intensive animal husbandry or processing. Finally, the former Narrabri CSG Project (appraisal wells that provide gas to the Wilga Park Power Station) and the Wilga Park Power Station itself are only partially operating. All of the industries are relatively well separated from the project by distance so that cumulative impacts are likely to be negligible.

Sources of air emissions listed on the NPI in the Narrabri LGA include:

- Boggabri Coal Mine,
- Boral Narrabri Quarry,
- Cargill Processing Narrabri,
- Lowes Petroleum Narrabri Depot,
- Boland Petroleum Narrabri Depot,
- Narrabri Coal Mine – Baan Baa,
- Narrabri CSG Project,
- Wilga Park gas-fired power station, and
- Tarrawonga Coal Mine.

Sources of air emissions listed on the NPI in the Gunnedah LGA include:

- Baiada Kilimani Poultry Facility,
- Baiada Woodleigh 3 Poultry Facility,
- Gunnedah Depot,
- Gunnedah Leather Processors,
- Sunnyside Open Cut Coal Mine,
- Rocglen Coal Mine, and
- Whitehaven Rail Siding.

4.3.2 Ambient air quality in regional NSW

There is no publicly available air quality monitoring data for the Narrabri region. The nearest air quality monitoring stations that provide publicly available data are operated by the Office of Environment and Heritage (OEH) in NSW. These monitors are located in Tamworth, Beresfield, Bathurst and the Hunter Valley Air Quality Monitoring Network in Muswellbrook and Singleton. Table 4-1 outlines the nearest monitoring stations and the pollutants assessed to determine the background air quality in the region.

Table 4-1 NSW OEH monitoring stations and pollutants considered in the background assessment

Monitoring station	Approximate distance and direction from project	Air pollutants measured
Tamworth	140 km to the east-south-east	Particulate matter as PM_{10}
Muswellbrook	230 km to the south-east	Nitrogen dioxide
Singleton	270 km to the south-east	Nitrogen dioxide
Beresfield	320 km to the south-east	Nitrogen dioxide Ozone

Due to the significant effect of coal mines on dust loads in the Hunter Valley region, the Muswellbrook and Singleton PM_{10} measurements were not considered to be representative of the PM_{10} background concentrations in the Narrabri region. Consequently, they were not reviewed for the assessment of background PM_{10} for the project. Tamworth was therefore considered to be more appropriate than most sites for the assessment of PM_{10} concentrations, although concentrations there were found to be quite high.

The Muswellbrook and Singleton monitoring stations are also situated proximate to the dominant nitrogen oxides source in the region, being the Macquarie Generation Bayswater and Liddell coal-fired power stations. Nitrogen dioxide concentrations from the Muswellbrook and Singleton monitors were reviewed for reference as they were considered to be more representative of a rural town or industrial area, rather than the nitrogen oxide monitoring stations in the Sydney Greater Metropolitan Region, which are dominated by traffic, shipping and industrial sources. Descriptive statistics of background air quality monitoring of nitrogen dioxide, ozone and PM_{10} concentrations are summarised in Table 4-2, Table 4-3 and Table 4-4, respectively.

Table 4-2 Summary of nitrogen dioxide concentration statistics

Site	Year	Highest 1-hr average ($\mu g/m^3$ at $0^{\circ}C$)	Annual mean ($\mu g/m^3$ at $0^{\circ}C$)	Events above criteria
Muswellbrook	2011	94.3	14.6	0
	2012	90.2	19.5	0
	2013	86.1	19.0	0
Singleton	2011	27.1	10.4	0
	2012	37.3	17.6	0
	2013	36.3	16.4	0
Beresfield	2000	65.6	15.9	0
	2001	94.3	20.9	0
	2002	102.5	20.8	0
	2003	82.0	18.4	0
	2004	90.2	19.5	0
	2005	77.9	19.0	0
	2006	73.8	20.0	0
	2007	67.7	18.7	0
	2008	63.6	16.7	0
	2009	73.8	12.7	0
	2010	65.6	14.7	0

Site	Year	Highest 1-hr average (µg/m^3 at 0°C)	Annual mean (µg/m^3 at 0°C)	Events above criteria
	2011	86.1	18.7	0
	2012	90.2	19.5	0
	2013	84.1	18.2	0
NSW criteria	--	246	62	N/A

Table 4-3 Summary of ozone concentration statistics at Beresfield

Year	Highest 1-hr average (µg/m^3 at 0°C)	Number of exceedances of the 1-hr average criterion	Annual mean (µg/m^3 at 0°C)
2000	141.2	0	41.0
2001	173.3	0	34.0
2002	207.6	0	36.1
2003	162.6	0	33.6
2004	224.7	1	35.4
2005	192.6	0	34.9
2006	188.3	0	33.9
2007	171.2	0	35.0
2008	137.0	0	32.6
2009	154.1	0	35.2
2010	188.3	0	32.4
2011	151.9	0	32.0
2012	149.8	0	31.1
2013	164.8	0	31.5
NSW criteria	214	N/A	N/A

Table 4-4 Summary of PM_{10} concentration statistics at Tamworth

Year	Highest 1-hr average	Highest 24-hr average	6th highest 24-hr average	70th %ile 24-hr average	Annual mean	Number of criteria exceedance days
2001	93.1	32.6	25.6	15.8	13.5	0
2002	1105	197.1	62.5	22.0	20.6	7
2003	967.1	241.6	54.5	18.9	17.9	7
2004	185.4	56.2	40.5	24.1	20.7	2
2005	673.2	88.7	27.7	18.9	16.5	0
2006	315.1	47.8	37.4	20.2	16.7	0
2007	182.3	48.8	34.2	18.6	15.8	0
2008	315.9	100.4	40.9	17.4	15.8	3
2009	6804.6	1791.4	159.0	21.0	27.2	17
2010	118.6	29.1	25.3	14.0	12.0	0
2011	130.6	50.9	28.4	15.3	13.1	1
2012	172.9	55.1	40.2	18.3	15.9	1
2013	182.5	47.5	38.5	19.2	16.7	0
NSW criteria	N/A	N/A	50	N/A	30	5 allowable exceedances

Table note: Units in µg/m^3 at 0°C

The year 2009 experienced very high dust concentrations due to several days of dust storms in May and September. The year 2009 is therefore considered to be an extreme year for use in assessing background concentrations. Dust storms and bushfires also occurred in other very hot and dry years (e.g. 2002 and 2003) causing very high maximum daily concentrations. Notwithstanding this, the Tamworth PM_{10} data indicates high concentrations that are synonymous with an urbanised environment in a warm temperate climate that has a mix of rural and commercial industry. The Tamworth PM_{10} data is considered to be relatively high given the difference in the land uses in the project area, which predominantly comprises forest, scrubland and agricultural use.

The 70^{th} percentile concentration of PM_{10} at Tamworth has been presented for consideration in the cumulative impact assessment, in accordance with the guidance provided in EPAV (2007). The Victorian government guidance document prescribes the use of the 70^{th} percentile concentration of PM_{10} to be assessed in aggregate with the predicted maximum concentration from the proposal, as an alternative to the NSW Approved Methods approach where a contemporaneous hourly background concentration is added to predictions based on representative local measurements. This is considered to be an appropriate method of assessing the cumulative impact of PM_{10} for two key reasons:

1. In consideration of the relatively high background dust loads observed at Tamworth that are not considered to be well aligned with conditions near Narrabri and the Pilliga Forest. It is not considered to be appropriate to assess the PM_{10} cumulative impact in the non-urban Pilliga Forest environment with background data from a populated urbanised regional centre more than 130 kilometres away. This is due to the expectation that the source and composition of particulate matter will be different and comprise of significantly more fine particles from industry and motor vehicle traffic emissions.

2. The primary source of particulate emissions for the project will be during construction. During operation, gas-fired engines with emit negligible quantities of particulate matter by comparison with ambient background sources. Further, construction-based dust emissions will be time and space variant and highly variable in emission load. This non-continuous emission rate profile cannot be meaningfully assessed concurrently with a contemporaneous background. It is therefore difficult to assess with meaning or certainty, the cumulative dust impact at any given point in time.

Consequently, the predicted maximum impact anywhere beyond the boundary, of the average dust emissions, has been combined with the highest 70^{th} percentile dust concentration at Tamworth for the cumulative assessment.

4.3.3 Air quality monitoring in the project area

To supplement the NSW OEH monitoring data a four-month air quality monitoring program was conducted from 10 April to 5 August 2014 to measure nitrogen oxides, nitric oxide, nitrogen dioxide, ozone and meteorology in the project area. A detailed assessment of the monitoring program is presented in Appendix A, with a brief summary of the findings presented in Table 4-5 and Table 4-6.

Table 4-5 Descriptive statistics of 1-hour average concentrations of nitrogen dioxide

Statistic	Concentration (µg/m^3)	Percentage of criterion (%)
Mean	2.6	1.1
Maximum	18.5	7.5
99th percentile	10.7	4.3
95th percentile	6.2	2.5
90th percentile	4.8	1.9
75th percentile	3.6	1.5
Impact assessment criterion	246	N/A

Table 4-6 Descriptive statistics of 1-hour and 4-hour average concentrations of ozone

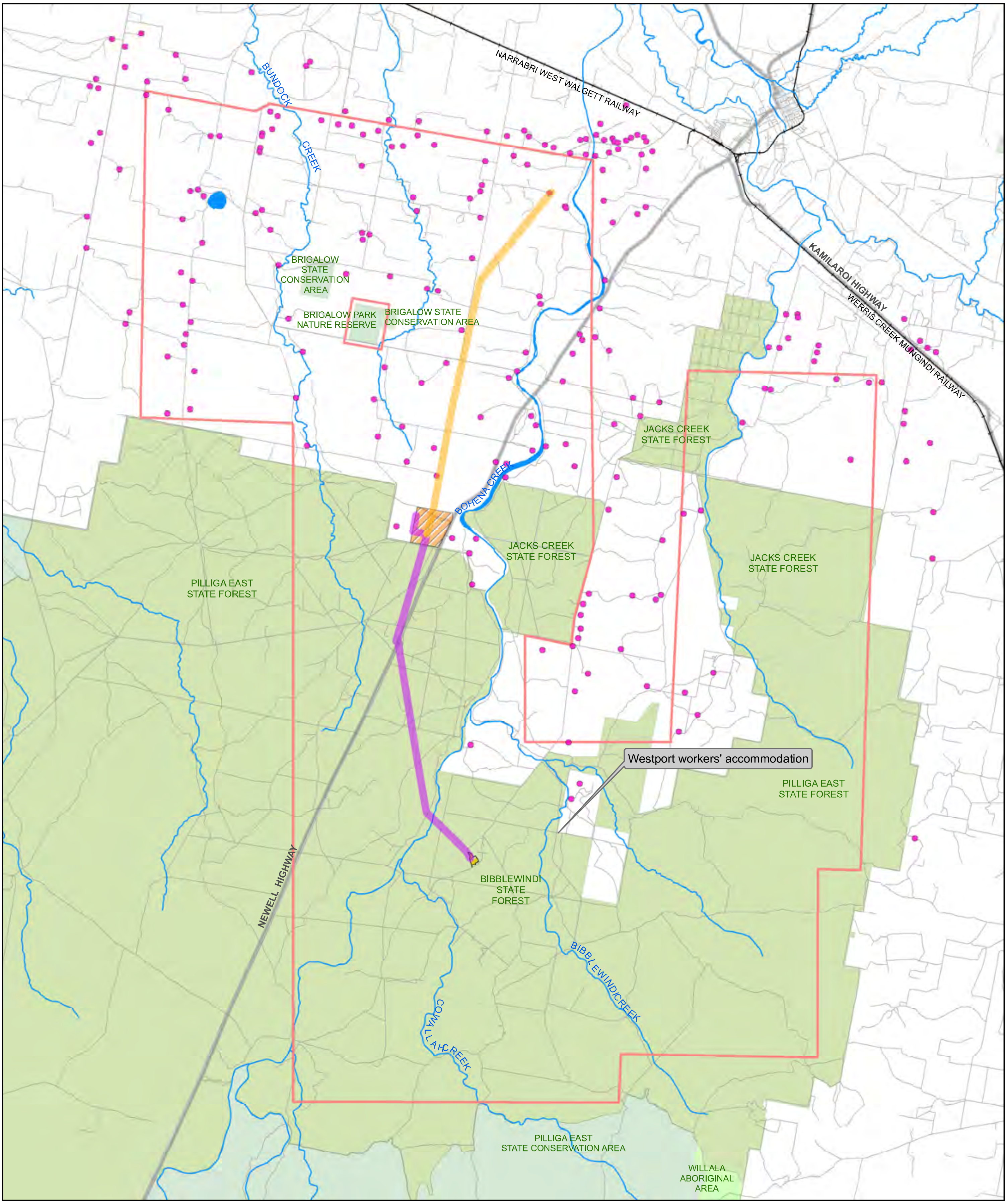
Statistic	1-hour		4-hour	
	Concentration (µg/m^3)	Percentage of criterion (%)	Concentration (µg/m^3)	Percentage of criterion (%)
Mean	33.1	15.5	32.5	19.0
Maximum	74.2	34.7	72.0	42.1
99th percentile	68.7	32.1	67.2	39.3
95th percentile	61.2	28.6	59.6	34.8
90th percentile	58.7	27.4	57.3	33.5
75th percentile	52.3	24.4	49.9	29.2
Impact assessment criterion	214	N/A	171	N/A

The monitoring in the project area determined that:

- Ambient concentrations of nitrogen dioxide are considered to be very low and well below the NSW impact assessment criterion.
- Ambient concentrations of ozone are considered to be low and well below the NSW impact assessment criterion.
- While regional nitrogen dioxide and ozone concentrations are influenced by photochemical activity, and therefore likely to increase during the summer period due to strong solar insolation, the lack of significant urban and industrial background emission sources of primary pollutants in the region suggest that the low concentrations observed during the monitoring period are highly unlikely to increase to levels near to, or in exceedance of, the impact assessment criteria.
- Due to the consistently low concentrations of nitrogen dioxide and ozone measured, the monitoring program was discontinued after four months.

4.4 Location of sensitive receptors

The location of sensitive receptors identified for the dispersion modelling assessment within ten kilometres of Leewood and Bibblewindi are presented in Figure 4-13.



LEGEND

- Project area
- Leewood
- Bibblewindi
- Parks and reserves
- State forest
- Aboriginal areas
- Lakes and dams
- Watercourses
- Roads
- Train line
- Sensitive receivers
- Leewood to Wilga Park infrastructure corridor
- Bibblewindi to Leewood infrastructure corridor

0 1.75 3.5 7
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Job Number 21-22463
Revision A
Date Feb 2015

Sensitive receivers in the project area

Figure 4-13

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Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Created by: jrichardson

5 Air Emissions associated with the Project

5.1 Construction phase

The primary emission of concern during the construction phase was found to be dust as PM_{10}. Fine particle emissions associated with exhausts from mobile plant and stationary engines used during construction activities are accounted for in the dust emission factors for earthmoving and handling that have been used in the study. Emissions of nitrogen oxides and other fuel combustion gases during construction are considered to be similar to those emitted from the gas engines during operation and less significant than the dust emitted during construction. Notwithstanding this, engine emission sources during construction are expected to be discontinuous, transient and mobile. In contrast, engines during operation will be continuous, steady and stationary. As a result, PM_{10} was considered to be the buffer-limiting pollutant for construction activities.

Dust emissions for each construction area have been calculated using generic emission factors (WRAP, 2006) based on a range of typical construction activities and the cleared working area of each facility, including the:

- Leewood central gas processing, water treatment and power generation facility,
- Bibblewindi in-field compressor station,
- A well pad area,
- A gas or water pipeline or below ground electricity transmission line construction or trenching area, and
- The construction of a road or access track.

Construction surface area dimensions, emission factors and dust emission rates for the various particle size fractions, (i.e. total suspended particulate (TSP), PM_{10} and $PM_{2.5,}$ are presented in Table 5-1, Table 5-2 and Table 5-3, respectively). Emission factors account for standard dust emission management and mitigation strategies during construction such as the spraying of water on unpaved roads, access tracks, exposed areas and stockpiles.

Table 5-1 Construction area dimensions for the dust impact assessment

Construction area emission source	Length (m)	Width (m)	Area (m^2)	Area (ha)
Leewood central gas processing, water storage and treatment and power generation facility[1]	500	500	250,000	25
Bibblewindi in-field compressor station	400	400	160,000	16
Well pad area	100	100	10,000	1
Leewood to Bibblewindi pipeline construction Trenching area Access tracks Below ground electricity transmission line between Leewood and Wilga Park[2]	100	40	4,000	0.4
Road construction with cut and fill excavation[2]	100	40	4,000	0.4

Table note: [1] Construction of the Leewood site over two to three years has been assessed as a maximum footprint area of 25 ha at any one time. This 25 ha area will move around the site as various components are constructed such as the power plant, gas compression facilities, water treatment plant, flare pad, access roads and site offices. This takes into to consideration the total available footprint (excluding a northern Brigalow no-go zone) of 206 ha.

[2] Linear infrastructure corridor construction areas such as roads and pipelines have been assessed as sections that will be reproduced in sequence.

Table 5-2 Dust emission factors for construction based on the WRAP emission factors

Particle size	Emission factor	Units	Notes
General construction with minor earth excavation			
TSP	1.90E-05	$g/m^2/s$	TSP/PM_{10} ratio assumed to be a factor of 2
PM_{10}	0.11 9.51E-06	tons PM_{10}/acre/month $g/m^2/s$	WRAP handbook - General construction using Best Available Control Measures (BACM) with minimal earth movement, i.e. cut and fill.
$PM_{2.5}$	9.51E-07	$g/m^2/s$	$PM_{2.5}$/PM_{10} ratio assumed to be 0.1
Road construction with excavation			
TSP	7.26E-05	$g/m^2/s$	TSP/PM_{10} ratio assumed to be a factor of 2
PM_{10}	0.42 3.63E-05	tons PM10/acre/month $g/m^2/s$	WRAP handbook - Road construction using Best Available Control Measures (BACM) with significant earth movement, i.e. cut and fill, typical of road construction.
$PM_{2.5}$	3.63E-06	$g/m^2/s$	$PM_{2.5}$/PM_{10} ratio assumed to be 0.1

Table 5-3 Dust emission rates for construction areas based on the WRAP emission factors

Location of source	Total source emissions (g/s)		
	TSP	PM_{10}	$PM_{2.5}$
Leewood central gas processing facility	4.76	2.38	0.24
Bibblewindi in-field compressor station	3.04	1.52	0.15
Well pad area	0.19	0.095	0.0095
Leewood to Bibblewindi pipeline construction Trenching area Access tracks Below ground electricity transmission line between Leewood and Wilga Park	0.076	0.038	0.0038
Road construction with cut and fill excavation	0.291	0.145	0.0145

5.2 Operations phase

5.2.1 Coal seam gas composition and processing

CSG differs from conventional (or traditional) oil and gas in that it is almost entirely comprised of methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2) and water vapour ($H_2O_{(g)}$). There are also very small traces of ethane (C_2H_6). Coal seam gas does not contain reduced sulfide species (such as hydrogen sulfide and mercaptans) or liquid hydrocarbons that have to be removed during processing.

The fate of each chemical constituent of the coal seam gas as it is processed can be summarised as follows:

- Methane is the principal product gas stream. A portion of methane is also consumed within the process as fuel gas in boilers and gas engine generators used for site power generation.
- Carbon dioxide is a product contaminant and is removed during gas processing, either through membrane treatment or amine treatment. The reject stream from the membrane treatment also has some methane in it, and consequently may be used as fuel gas or disposed of via a flare. The carbon dioxide removed during amine treatment is discharged to atmosphere directly from the stripping column.

- Nitrogen is not removed during processing. Notwithstanding this, a small portion of nitrogen will pass through to the reject stream from the carbon dioxide membrane treatment plant and ultimately be discharged to atmosphere, via either combustion as a fuel gas in the boilers and generators or the disposal flare system. The majority of nitrogen present in the feed gas will pass through into the product gas stream. Nitrogen (as N_2) is not a pollutant as it is the major component of the atmosphere.
- Ethane, in tiny traces, is present in the feed gas. The small ethane component will not be removed by processing and hence become part of the product gas stream.
- Water, in the liquid phase, is removed in the slug catcher at the start of the process. Between each stage of compression, water (in the vapour phase) is condensed (into the liquid phase) and removed from the gas stream by filter coalescers prior to each subsequent compression stage. The liquid water may contain some trace hydrocarbon contaminants such as lubricating oils used in the compression plant. After the final stage of compression most of the residual water vapour is removed by the tri-ethylene glycol (TEG) dehydration system. The water removed is emitted to atmosphere from the stripping section of the TEG dehydration system where methane is used as stripping gas.

Emissions to air from the CSG production process may be categorised as one of three classifications:

1. **Air pollutants** that affect environmental values associated with air quality including the protection of human health, the aesthetic environment and the biodiversity of ecosystems. The primary pollutant of concern is nitrogen dioxide generated by the combustion of fuel gas in boilers, generators and flares. Minor and trace pollutants include carbon monoxide, fine particles and hydrocarbons.
2. **Greenhouse gases** that have a direct impact on the climate system and subsequent ecological processes. Gases such as carbon dioxide, methane, nitrous oxide and other trace greenhouse gases are emitted directly from gas processing and the combustion of fuel gas in boilers, generators and flares.
3. **Non-harmful gases** such as nitrogen and water vapour that are abundant in the atmosphere.

The impact of air pollutants associated with the project are the focus of this report. Greenhouse gases have been assessed in the *Greenhouse Gas Assessment Report* (Santos, 2015).

5.2.2 Power option considerations

Two options for providing electrical power to the project were considered in the assessment of air quality impacts:

1. Power generation for the Leewood central gas processing facility and Bibblewindi in-field compression facility through the development and operation of a 100 MW_e gas-fired power plant at Leewood. Well pad power is provided by diesel-fired generators for the first year of operation, before being replaced or converted to gas-fired generators.
2. Power supplied to the Leewood central gas processing and Bibblewindi in-field compression facilities from the National Electricity Market. Well pad power provided by diesel-fired generators for the first year of operation, before being replaced or converted to gas-fired generators.

The project air emission sources assessed for each option are listed in Table 5-4.

Table 5-4 Air emission sources by power supply option

Option 1 – Leewood power generation	Option 2 – Power from the national grid
Diesel-fired well pad engines	Diesel-fired well pad engines
Gas-fired well pad engines	Gas-fired well pad engines
Pilot well flare	Pilot well flare
Bibblewindi in-field compression facility flare	Bibblewindi in-field compression facility flare
Leewood central gas processing facility hot oil boilers	Leewood central gas processing facility hot oil boilers
Leewood central gas processing facility flare	Leewood central gas processing facility flare
Leewood 100 MW_e power generation plant	

5.2.3 Air pollutants assessed

The most important air pollutant generated by the project, based on the ratio of its emission rate to impact assessment criterion, is nitrogen dioxide released as oxides of nitrogen. Oxides of nitrogen released from fuel combustion sources primarily comprise a range of oxidised nitrogen based compounds including nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O). Of these substances, nitrogen dioxide is considered to be a key criterion pollutant with the potential to affect human health, while nitric oxide and nitrous oxide are not considered harmful to human health. Nitrous oxide, however, is a significant greenhouse gas.

Air pollutants emitted from engines have been ranked according to this ratio and presented in Appendix B. The 1-hour average criterion for each pollutant has been used where applicable. The 24-hour average criterion of PM_{10} has been used in the absence of a 1-hour average value. The ranking is based on the emission rate and it is assumed that the 100th percentile ground level concentration is assessed. In reality for the assessment in accordance with the Approved Methods (DEC, 2005), the 99.9th percentile is assessed in isolation for non-criteria air pollutants. Consequently, those pollutants rank slightly lower in importance by comparison to criteria pollutants such as nitrogen dioxide with background.

Once the ranking was conducted, the key pollutants were determined and nitrogen oxides plus the next five most important pollutants were assessed. This approach eliminates the need to assess all pollutants in detail. This is because each pollutant with a lower ranking will have less of an impact than the pollutants ranked above it. Pollutants associated with each engine source have been presented in tables of ranked order in this section.

5.2.4 Project processes and related air emissions

The air emission sources associated with each component of project operations and the operating conditions are outlined in Table 5-5.

Table 5-5 Project components, operating conditions and related air emission sources considered in the assessment

Component	Location	Project operating condition	Activity/ source	Operational condition	Emission condition	Number of emission sources	Operational basis
Gas and water extraction and collection	Well pads across gas field	Routine	Diesel-fired engine	Continuous	Continuous	Variable[1]	First year of well operation
Gas and water extraction and collection	Well pads across gas field	Routine	Gas-fired engine	Continuous	Continuous	Variable[1]	Replaces diesel engine when local gas source comes on line
Gas and water extraction and collection	Well pads across gas field	Non-routine	Pilot well flare	Discontinuous	Discontinuous	Variable	Gas pressure management prior to well gas production phase
In-field compression facility	Bibblewindi	Routine	Electric-drive gas compressors	Continuous	No emissions	0	Gas processing - compressors will be electric-drive with no air emissions
In-field compression facility	Bibblewindi	Non-routine	Gas flare	Discontinuous	Discontinuous	1	Gas pressure management during emergency or maintenance conditions
Central gas processing facility	Leewood	Routine	Electric-drive gas compressors, 4 train configuration	Continuous	No emissions	0	Gas processing - compressors will be electric-drive with no air emissions
Central gas processing facility	Leewood	Routine	Hot oil boilers, 1 per train	Continuous	Continuous	4	Gas processing
Central gas processing facility	Leewood	Non-routine	Gas flare	Discontinuous	Discontinuous	1	Gas pressure management during emergency or maintenance conditions
Power generation plant	Leewood	Routine	10 x 9.7 MW_e gas-fired generators, 2 train configuration	Continuous	Continuous	10	100 MW_e power supply for Leewood and Bibblewindi facilities
Water treatment facility	Leewood	Routine	Pumps, water treatment process equipment	Continuous	No emissions	0	Water treatment plant will be electric-driven

Table note: [1] The total quantity of operating well pads will be up to 425 over the project lifetime. Only a subset of the total project well pads will have diesel or gas engines operating on them at any given time. The number of operating engines at any given time is not known at this stage and will likely vary throughout the project lifetime.

Other important sources of nitrogen oxides in the region, that are not associated with the project, were also considered in the cumulative impact assessment. Wilga Park Power Station has an environmental approval for 40 MW_e of gas-fired power generation but only 16 MW_e of generating capacity has currently been installed. At the time of the background air quality monitoring program, between 10 April and 5 August 2014, Wilga Park power station was not operating. Consequently, the monitoring program did not account for ambient concentrations of nitrogen dioxide and ozone associated with emissions from Wilga Park. In order to address this baseline deficiency, nitrogen oxide emissions associated with Wilga Park's fully approved generating capacity were modelled and combined with the project's ambient monitoring data for inclusion in the cumulative impact assessment. This approach provided the spatial and temporal distributions of dispersed emissions across the project area for the major existing source in the region. The monitoring data provided temporal variations in pollutant concentrations at a single location. Wilga Park emissions data and source characteristics were based on information published in the power station's environmental impact statement (Heggies, 2007).

5.2.5 Emissions from routine operations

Power generation plant

If power supply option 1 is selected a 100 MW_e gas-fired power generation plant would be developed at Leewood to supply the power requirements for gas processing, compression and other site infrastructure at both the Leewood and Bibblewindi facilities. Consequently, there are no air emissions associated with the gas compressors and water treatment plant as they would be electric drive. If power option 2 is selected, this power plant would not be required and power will be sourced from the national grid.

The configuration of the 100 MW_e gas-fired power plant, including engine units, is yet to be determined (i.e. will be subject to detailed Front-end Engineering Design [FEED]). Notwithstanding this, for the purpose of assessing typical impacts in this study, it has been assumed that the plant will comprise a total of twelve 9.7 MW_e gas-fired generation units in two 5+1 train configurations, that is five generator units will supply the continuous power with a sixth engine installed in each train to provide for system redundancy. A maximum of five generators in each train would operate at one time (i.e. total of 10 engines operational at once).

The gas-fired engines identified for, and assessed in, this study were lean-burn low NO_X type engines that meet the NSW *Protection of the Environment Operations (Clean Air) Regulation (2010*) Group 6 standards of emission concentration for nitrogen oxides and other pollutants. The dispersion modelling assessed ground-level concentrations of engine exhaust emissions released to atmosphere from 30 metre tall stacks. The preliminary power plant configuration assessed was for the stacks to be co-located together at the end of each train. The location and configuration of the six stack exhaust plumes from each train were found to have the potential to merge in the atmosphere after their release. Consequently, the engine emissions from the six stacks associated with each train were effectively modelled as a single combined stack to simulate the enhanced buoyancy characteristics of plume merging in the modelling assessment.

The gas-fired engine exhaust characteristics are detailed in Table 5-6, while the emissions of nitrogen oxides and particulate matter based on typical engine technical specifications are presented in Table 5-7. Table 5-8 presents the engine emission rates of nitrogen oxides and carbon monoxide based on the NSW emission concentration standards. Emissions of all pollutants including volatile organic compounds and polycyclic aromatic hydrocarbons based on the United States EPA AP-42 emission factors are presented in ranked order of their importance in the assessment in Table 5-9. The assessment of nitrogen dioxide emissions has been based on both the engine emission data and the emissions at the NSW emission concentrations standard limit.

Emissions for nitrogen oxides based on AP-42 emission factors have not been assessed as they are considered to be an over-estimation of the actual emissions based on new technology and nominal engine vendor technical data used in the assessment.

Table 5-6 Nominal gas-fired power generation engine exhaust characteristics

Exhaust characteristics	Units	Single engine stack	'Effective stack' 5 stacks combined
Engine output power	kW_e	9,730	--
Fuel consumption (energy rate)	MJ/s	23.8	--
Fuel consumption (by volume)	Sm^3/s	0.92	--
Stack height	m	30	30
Stack exit (inside) diameter	m	1.2	2.68
Stack cross sectional area	m^2	1.13	5.65
Stack exhaust velocity	m/s	26.3	26.3
Stack exhaust temperature	$^{\circ}C$	360	360
Exhaust gas moisture content	%	9.8	9.8
Exhaust gas oxygen content	%	11.2	11.2
Actual stack exhaust volume flow	Am^3/s	29.8	149
Normal stack exhaust volume flow ($0^{\circ}C$, 1 Atm, wet)	Nm^3/s, wet	12.9	64.3
Normal stack exhaust volume flow ($0^{\circ}C$, 1 Atm, dry)	Nm^3/s, dry	11.1	55.5
Buoyancy flux parameter[1]	m^4/s^3	49	245
Buoyancy enhancement factor [N_E] for co-located plumes[2]	--		4.97

Table note: [1] Based on Briggs (1965) plume rise equation
[2] Based on Manins *et* al, 1992.

Table 5-7 Emissions data for nitrogen oxides and particulate matter based on nominal engine specifications

Parameter	Units	Nitrogen oxides	Particulate matter
Concentration	mg/Nm^3 ($0^{\circ}C$, 1 Atm, dry, 5% O_2)	400	10
Emission rate per engine	(g/s)	2.7	0.2
Modelled emission rate per 'merged' stack (five engines combined)	(g/s)	13.5	0.9
Annual emissions per engine	kg/yr	85,000	5,800
Annual emissions for 10 engines[1]	kg/yr	855,000	58,000

Table note: [1] Based on 100 per cent engine availability at 100 per cent load.

Table 5-8 Emissions data for nitrogen oxides and carbon monoxide based on NSW emission concentration standards

Parameter	Units	Nitrogen oxides	Carbon monoxide
Concentration	mg/Nm^3 (0°C, 1 Atm, dry, 5% O_2)	450[1]	125[1]
Emission rate per engine stack	(g/s)	5.0	1.4
Modelled emission rate per 'merged' stack (five engines combined)	(g/s)	25.0	6.9
Annual emissions per engine[2]	kg/yr	158,000	43,800
Annual emissions for 10 engines[2]	kg/yr	1,575,000	438,000

Table note: [1] NSW *Protection of the Environment Operations (Clean Air) Regulation (2010)* standards of emission concentration
[2] Based on 100 per cent engine availability at 100 per cent load.

Table 5-9 Ranked emissions for lean-burn gas-fired engines at the Leewood power generation plant based on US EPA AP-42 emission factors

Pollutant	AP42 emission factor (g/MJ)	Emission rate per engine (g/s)	Emission rate per stack (five engines combined) (g/s)
Acrolein	0.00221	0.053	0.26
Nitrogen oxides	0.95	22.7	113.3
Formaldehyde	0.0227	0.54	2.71
Acetaldehyde	0.00359	0.086	0.43
PM_{10}	0.0041	0.10	0.49
Carbon monoxide	1.60	38.1	190.7
Phenanthrene	4.47E-06	1.07E-04	5.33E-04
Benzene	1.89E-04	4.51E-03	2.26E-02
Ethylene Dibromide	1.90E-05	4.54E-04	2.27E-03
Biphenyl	9.12E-05	2.17E-03	1.09E-02
1,3-Butadiene	1.15E-04	2.74E-03	1.37E-02
Acenaphthene	5.38E-07	1.28E-05	6.41E-05
Carbon Tetrachloride	1.58E-05	3.76E-04	1.88E-03
Pyrene	5.85E-07	1.39E-05	6.97E-05
Fluoranthene	4.77E-07	1.14E-05	5.69E-05
Chrysene	2.98E-07	7.11E-06	3.55E-05
Methylcyclohexane	5.29E-04	1.26E-02	6.31E-02
Phenol	1.03E-05	2.46E-04	1.23E-03
Toluene	1.75E-04	4.18E-03	2.09E-02
2-Methylnaphthalene	1.43E-05	3.40E-04	1.70E-03
Xylene	7.91E-05	1.89E-03	9.43E-03
Methanol	1.08E-03	2.56E-02	1.28E-01
Benzo(e)pyrene	1.78E-07	4.26E-06	2.13E-05
Butyr/Isobutyraldehyde	4.34E-05	1.04E-03	5.18E-03
n-Pentane	1.12E-03	2.67E-02	1.33E-01
Vinyl Chloride	6.41E-06	1.53E-04	7.64E-04
1,3-Dichloropropene	1.14E-05	2.71E-04	1.35E-03
1,1,2,2-Tetrachloroethane	1.72E-05	4.10E-04	2.05E-03
Fluorene	2.44E-06	5.81E-05	2.91E-04
Naphthalene	3.20E-05	7.63E-04	3.81E-03

Pollutant	AP42 emission factor (g/MJ)	Emission rate per engine (g/s)	Emission rate per stack (five engines combined) (g/s)
n-Hexane	4.77E-04	1.14E-02	5.69E-02
1,2-Dichloroethane	1.01E-05	2.42E-04	1.21E-03
Benzo(b)fluoranthene	7.14E-08	1.70E-06	8.51E-06
Chlorobenzene	1.31E-05	3.12E-04	1.56E-03
Styrene	1.01E-05	2.42E-04	1.21E-03
n-Octane	1.51E-04	3.60E-03	1.80E-02
2,2,4-Trimethylpentane	1.08E-04	2.56E-03	1.28E-02
Cyclopentane	9.76E-05	2.33E-03	1.16E-02
1,2-Dichloropropane	1.16E-05	2.76E-04	1.38E-03
Tetrachloroethane	1.07E-06	2.54E-05	1.27E-04
1,1,2-Trichloroethane	1.37E-05	3.26E-04	1.63E-03
Chloroform	1.23E-05	2.92E-04	1.46E-03
Acenaphthylene	2.38E-06	5.67E-05	2.84E-04
1,3,5-Trimethylbenzene	1.45E-05	3.47E-04	1.73E-03
1,2,4-Trimethylbenzene	6.15E-06	1.47E-04	7.33E-04
1,2,3-Trimethylbenzene	9.89E-06	2.36E-04	1.18E-03
n-Nonane	4.73E-05	1.13E-03	5.64E-03
Butane	2.33E-04	5.55E-03	2.77E-02
Methylene Chloride (Dichloromethane)	8.60E-06	2.05E-04	1.03E-03
1,1-Dichloroethane	1.01E-05	2.42E-04	1.21E-03
Ethylbenzene	1.71E-05	4.07E-04	2.04E-03
Chloroethane	8.04E-07	1.92E-05	9.59E-05

Gas processing - hot oil boilers

During gas processing at Leewood, carbon dioxide will be removed from the feed gas in order to meet the required product gas specifications. To achieve this, carbon dioxide is selectively absorbed using an amine solution. The absorbed carbon dioxide is subsequently “stripped” from the amine solution in a stripping column and released to atmosphere. Emissions of carbon dioxide from this process are accounted for in the *Greenhouse Gas Emissions report (Santos, 2015)* in this Environmental Impact Statement.

To facilitate removal of carbon dioxide from the amine solution in the stripping column, heat is added to the amine solution through a reboiler installed at the base of the stripping column. A closed loop hot oil heating circuit heated by a gas-fired hot oil boiler provides the heating requirements for the amine reboilers. One hot oil boiler and amine absorption unit will be used on each of the four gas processing and compression trains. Consequently, four hot oil boilers would be used. Each boiler’s estimated heating requirement is equivalent to a gas fuel consumption of 11.9 MJ/s.

The hot oil boiler exhaust gas characteristics are presented in Table 5-10. Emission rates of criteria pollutants based on National Pollutant Inventory emission factors and the NSW emission concentration standards are presented in Table 5-11 and Table 5-12, respectively. Emissions of all other pollutants including volatile organic compounds, polycyclic aromatic hydrocarbons and dioxins and furans based on the United States EPA AP-42 and Australian National Pollutant Inventory emission factors are presented in ranked order of their importance in the assessment in Table 5-13.

Table 5-10 Nominal gas-fired hot oil boiler exhaust characteristics

Exhaust characteristics	Units	Value
Fuel consumption (heat rate)	MJ/s	11.9
Fuel consumption (by volume)	Sm^3/s	0.46
Stack height	m	10
Stack exit (inside) diameter	m	0.8
Stack cross sectional area	m^2	0.505
Stack exhaust velocity	m/s	10
Stack exhaust temperature	°C	120
Exhaust gas moisture content	%	11.0
Exhaust gas oxygen content	%	1.6
Actual stack exhaust volume flow	Am^3/s	5.1
Normal stack exhaust volume flow (0°C, 1 Atm, wet)	Nm^3/s, wet	3.5
Normal stack exhaust volume flow (0°C, 1 Atm, dry)	Nm^3/s, dry	3.1
Buoyancy flux parameter[1]	m^4/s^3	3.8

Table note: [1] Based on Briggs (1965) plume rise equation.

Table 5-11 Gas boiler emissions data for nitrogen oxides, carbon monoxide and particulate matter based on NPI emission factors

Parameter	Units	Nitrogen oxides	Carbon monoxide	Particulate matter
Concentration	mg/Nm^3 (0°C, 1 Atm, dry, 3% O_2)	185	156	13.7
Emission rate per engine	(g/s)	0.58	0.49	0.04
Annual emissions per boiler	kg/yr	18,200	15,400	1,350
Annual emissions for 4 boilers [1]	kg/yr	73,000	61,500	5,400

Table note: [1] Based on 100 per cent engine availability at 100 per cent load.
Particulate matter is ranked the second most important pollutant based on NPI data.
Carbon monoxide is ranked the sixth most important pollutant based on NPI data.
Emission factors are based on ≤30 MW_e wall-fired boilers (NPI, 2011, p.37, Table 21).

Table 5-12 Boiler emissions data for nitrogen oxides and carbon monoxide based on NSW emission concentration standards

Parameter	Units	Nitrogen oxides	Carbon monoxide
Concentration	mg/Nm^3 (0°C, 1 Atm, dry, 3% O_2)	350[1]	125[1]
Emission rate per boiler stack	(g/s)	1.1	0.4
Annual emissions per boiler[2]	kg/yr	34,500	12,300
Annual emissions for 4 boilers[2]	kg/yr	138,000	49,200

Table note: [1] NSW *Protection of the Environment Operations (Clean Air) Regulation (2010)* standards of emission concentration
[2] Based on 100 per cent engine availability at 100 per cent load.

Table 5-13 Ranked emissions for gas-fired boilers based on AP-42 emission factors

Pollutant	AP42 emission factor (g/MJ)	Emission rate per boiler (g/s)
Cadmium[1]	5.36E-07	6.38E-06
Nickel[2]	1.02E-06	1.21E-05
Formaldehyde	3.16E-05	3.76E-04
Dioxins and furans[3]	2.41E-12	2.87E-11
Arsenic	9.74E-08	1.16E-06
Mercury	1.26E-07	1.50E-06
Lead	2.43E-07	2.89E-06
Pentane	1.10E-03	1.30E-02
Hexane	7.59E-04	9.03E-03
Chromium III	6.82E-07	8.12E-06
Beryllium	5.85E-10	6.96E-09
Dichlorobenzene	5.06E-07	6.02E-06
Benzene	8.85E-07	1.05E-05
Copper	4.14E-07	4.93E-06
Phenanathrene	7.17E-09	8.53E-08
7,12-Dimethylbenz(a)anthracene	6.74E-09	8.03E-08
Butane	8.85E-04	1.05E-02
Pyrene	2.11E-09	2.51E-08
Toluene	1.43E-06	1.71E-05
Fluoranthene	1.26E-09	1.50E-08
Anthracene	1.01E-09	1.20E-08
Benzo(a)pyrene	5.06E-10	6.02E-09
Indeno(1,2,3-cd)pyrene	7.59E-10	9.03E-09
Chrysene	7.59E-10	9.03E-09
Benzo(k)fluoranthene	7.59E-10	9.03E-09
Benzo(b)fluoranthene	7.59E-10	9.03E-09
Benz(a)anthracene	7.59E-10	9.03E-09
3-Methylchloranthrene	7.59E-10	9.03E-09
Naphthalene	2.57E-07	3.06E-06
Dibenzo(a,h)anthracene	5.06E-10	6.02E-09
Benzo(g,h,i)perylene	5.06E-10	6.02E-09
Acenaphthene	7.59E-10	9.03E-09
2-Methylnaphthalene	1.01E-08	1.20E-07
Fluorene	1.18E-09	1.40E-08
Acenaphthylene	7.59E-10	9.03E-09

Table note: [1] The emission concentration of cadmium, based on emission factors, is estimated to be 0.002 mg/Nm^3. This concentration is 1 per cent of the NSW emission concentration standard.

[2] The aggregate emission concentration of Type 1 and 2 substances, based on emission factors, is estimated to be 0.01 mg/Nm^3. This concentration is 1 per cent of the NSW emission concentration standard for Type 1 and 2 substances.

[3] Emission rate for dioxins and furans based on the NPI emission factor. This emission rate is an estimate only and is dependent on the presence of pre-cursor substances and boiler combustion conditions.

[2] The aggregate emission concentration of volatile organic compounds, based on emission factors, is estimated to be 16.6 mg/Nm^3. This concentration is approximately 42 per cent of the NSW emission concentration standard.

Well pad generators

Generators will operate at the well pads to provide site power for pumps and other infrastructure through the life of the project. Initially engines will be diesel-fired but switch to gas-fired once gas flow from the wells comes on line. It is assumed that on average this would take twelve months.

Based on preliminary project engineering design, the power capacity and emission characteristics of typical gas field generator engines have been determined using nominal engine technical data and emission factors. The well pad gas-fired generators exhaust characteristics are detailed in Table 5-14, while the emissions of nitrogen oxides and particulate matter based on engine technical specifications and the NSW emission concentration standards are presented in Table 5-15 and Table 5-16, respectively. Emissions of all pollutants including volatile organic compounds and polycyclic aromatic hydrocarbons based on the United States EPA AP-42 emissions factors are presented in ranked order of their importance in the assessment in Table 5-17.

Table 5-14 Nominal gas-fired well pad engine exhaust characteristics

Exhaust characteristics	Units	Value
Engine output power	kVA	114
Fuel consumption (heat rate)	MJ/s	0.31
Fuel consumption (by volume)	Sm^3/s	0.012
Stack height	m	2.2
Stack exit diameter	m	0.1
Stack cross sectional area	m^2	0.008
Stack exhaust velocity	m/s	53.0
Stack exhaust temperature	°C	581
Stack exhaust volume flow	L/s	416
Actual stack exhaust volume flow	Am^3/s	0.42
Normal stack exhaust volume flow (0°C, 1 Atm, wet)	Nm^3/s, wet	0.13
Buoyancy flux parameter[1]	m^4/s^3	0.8

Table note: [1] Based on Briggs (1965) plume rise equation.

Table 5-15 Gas-fired engine emissions data for nitrogen oxides and carbon monoxide based on nominal engine specifications

Parameter	Units	Nitrogen oxides	Carbon monoxide
Emission factor	g/kWh_e	0.67	2.68
Concentration	mg/Nm^3 (0°C, 1 Atm)	141	565
Emission rate per engine	(g/s)	0.02	0.08
Annual emissions per engine[1]	kg/yr	593	2,370

Table note: [1] Based on 100 per cent engine availability at 100 per cent load.

Table 5-16 Gas-fired engine emissions data for nitrogen oxides and carbon monoxide based NSW emission concentration standards

Parameter	Units	Nitrogen oxides	Carbon monoxide
Concentration	mg/Nm^3 (0°C, 1 Atm, dry, 3% O_2)	450[1]	125[1]
Emission rate per engine[2]	(g/s)	0.06	0.02
Annual emissions per engine[3]	kg/yr	1,890	524

Table note: [1] NSW *Protection of the Environment Operations (Clean Air) Regulation (2010)* standards of emission concentration.
[2] Based on normal stack exhaust volume flow (0°C, 1 Atm, wet).
[3] Based on 100 per cent engine availability at 100 per cent load.

Table 5-17 Ranked emissions for lean burn gas-fired well pad engines based on AP-42 emission factors

Substance	AP42 emission factor (g/MJ)	Emission rate (g/s)
Acrolein	0.0022	0.00068
Formaldehyde	0.023	0.0070
Acetaldehyde	0.0036	0.0011
Particulate matter	0.0041	0.0013
Carbon monoxide	1.6	0.49
Phenanthrene	4.47E-06	1.38E-06
Benzene	1.89E-04	5.84E-05
Ethylene Dibromide	1.90E-05	5.88E-06
Biphenyl	9.12E-05	2.81E-05
1,3-Butadiene	1.15E-04	3.54E-05
Acenaphthene	5.38E-07	1.66E-07
Carbon Tetrachloride	1.58E-05	4.87E-06
Pyrene	5.85E-07	1.80E-07
Fluoranthene	4.77E-07	1.47E-07
Chrysene	2.98E-07	9.20E-08
Methylcyclohexane	5.29E-04	1.63E-04
Phenol	1.03E-05	3.18E-06
Toluene	1.75E-04	5.41E-05
2-Methylnaphthalene	1.43E-05	4.41E-06
Xylene	7.91E-05	2.44E-05
Methanol	1.08E-03	3.32E-04
Benzo(e)pyrene	1.78E-07	5.51E-08
Butyr/Isobutyraldehyde	4.34E-05	1.34E-05
n-Pentane	1.12E-03	3.45E-04
Vinyl Chloride	6.41E-06	1.98E-06
1,3-Dichloropropene	1.14E-05	3.50E-06
1,1,2,2-Tetrachloroethane	1.72E-05	5.31E-06
Fluorene	2.44E-06	7.52E-07
Naphthalene	3.20E-05	9.87E-06
n-Hexane	4.77E-04	1.47E-04
1,2-Dichloroethane	1.01E-05	3.13E-06
Benzo(b)fluoranthene	7.14E-08	2.20E-08

Substance	AP42 emission factor (g/MJ)	Emission rate (g/s)
Chlorobenzene	1.31E-05	4.03E-06
Styrene	1.01E-05	3.13E-06
n-Octane	1.51E-04	4.66E-05
2,2,4-Trimethylpentane	1.08E-04	3.32E-05
Cyclopentane	9.76E-05	3.01E-05
1,2-Dichloropropane	1.16E-05	3.57E-06
Tetrachloroethane	1.07E-06	3.29E-07
1,1,2-Trichloroethane	1.37E-05	4.22E-06
Chloroform	1.23E-05	3.78E-06
Acenaphthylene	2.38E-06	7.34E-07
1,3,5-Trimethylbenzene	1.45E-05	4.49E-06
1,2,4-Trimethylbenzene	6.15E-06	1.90E-06
1,2,3-Trimethylbenzene	9.89E-06	3.05E-06
n-Nonane	4.73E-05	1.46E-05
Butane	2.33E-04	7.18E-05
Methylene Chloride (Dichloromethane)	8.60E-06	2.65E-06
1,1-Dichloroethane	1.01E-05	3.13E-06
Ethylbenzene	1.71E-05	5.27E-06
Chloroethane	8.04E-07	2.48E-07

The well pad diesel-fired generator engine exhaust characteristics are detailed in Table 5-18, while the emissions of nitrogen oxides and particulate matter based on the NSW emission concentration standards are presented in Table 5-19. No engine specific emission rates were available for the diesel engines and consequently, the Australian National Pollutant Inventory and United States EPA AP-42 emission factors have been used. Emissions of all pollutants including volatile organic compounds and polycyclic aromatic hydrocarbons based on the AP-42 emissions factors are presented in ranked order of their importance in the assessment in Table 5-20. The NPI emission factors used in the assessment did not meet the NSW emission concentration Group 6 standards. Generator engines that meet the NSW emission standards will be selected during the project's FEED process.

Table 5-18 Nominal diesel-fired well pad engine exhaust characteristics

Exhaust characteristics	Units	Value
Engine output power	kVA	114
Diesel fuel consumption	g/kWh_e	210
Fuel consumption (heat rate)	MJ/s	0.096
Stack height	m	2.5
Stack exit diameter	m	0.1
Stack cross sectional area	m^2	0.008
Stack exhaust velocity	m/s	49.1
Stack exhaust temperature	$^{\circ}C$	530
Actual stack exhaust volume flow	Am^3/s	0.39
Normal stack exhaust volume flow ($0^{\circ}C$, 1 Atm, wet)	Nm^3/s, wet	0.13
Buoyancy flux parameter[1]	m^4/s^3	0.8

Table note: [1] Based on Briggs (1965) plume rise equation.

Table 5-19 Diesel-fired engine emissions data for nitrogen oxides and carbon monoxide based NSW emission concentration standards

Parameter	Units	Nitrogen oxides	Carbon monoxide
Concentration	mg/Nm^3 ($0^{\circ}C$, 1 Atm)	450[1]	5,880[1]
Emission rate per engine	(g/s)	0.06	0.77
Annual emissions per engine[2]	kg/yr	1,860	24,300

Table note: [1] NSW *Protection of the Environment Operations (Clean Air) Regulation (2010*) standards of emission concentration
[2] Based on 100 per cent engine availability at 100 per cent load.

Table 5-20 Ranked emissions for diesel-fired well pad engines based on NPI and AP-42 emission factors

Pollutant	Emission factor	Emission rate (g/s)
Oxides of nitrogen	1.90E-02 kg/kWh_e [1]	0.51[3]
Particulate matter	1.30E-03 kg/kWh_e [1]	0.03
Acrolein	3.98E-02 ng/J [2]	3.82E-06
Formaldehyde	5.07E-01 ng/J [2]	4.87E-05
Phenanthrene	1.26E-02 ng/J [2]	1.21E-06
Benzene	4.01E-01 ng/J [2]	3.85E-05
Carbon monoxide	4.10E-03 kg/kWh_e[1]	0.11[4]
Propylene	1.11E+00 ng/J [2]	1.07E-04
Acetaldehyde	3.30E-01 ng/J [2]	3.17E-05
Fluoranthene	3.27E-03 ng/J [2]	3.14E-07
Pyrene	2.06E-03 ng/J [2]	1.97E-07
Acenaphthylene	2.18E-03 ng/J [2]	2.09E-07
Anthracene	8.04E-04 ng/J [2]	7.72E-08
Acenaphthene	6.11E-04 ng/J [2]	5.86E-08
Benzo(a)anthracene	7.22E-04 ng/J [2]	6.94E-08
Fluorene	1.26E-02 ng/J [2]	1.21E-06
Xylenes	1.23E-01 ng/J [2]	1.18E-05
Dibenz(a,h)anthracene	2.10E-04 ng/J [2]	2.02E-08
Toluene	1.76E-01 ng/J [2]	1.69E-05
Benzo(g,h,l)perylene	7.22E-02 ng/J [2]	6.94E-06
1,3-Butadiene	1.68E-02 ng/J [2]	1.61E-06
Indeno(1,2,3-cd)pyrene	2.51E-04 ng/J [2]	2.41E-08
Chrysene	1.52E-04 ng/J [2]	[2]1.46E-08
Benzo(a)pyrene	8.08E-05 ng/J [2]	7.76E-09
Naphthalene	3.65E-02 ng/J [2]	3.50E-06
Benzo(k)fluoranthene	6.67E-05 ng/J [2]	6.40E-09
Benzo(b)fluoranthene	4.26E-05 ng/J [2]	4.09E-09

Table note: [1] Australian National Pollutant Inventory emission factor
[2] United States EPA AP42 emission factor
[3] Diesel engine emissions of oxides of nitrogen are based on NPI emission factors and have an emission concentration of 3,861 mg/Nm^3 ($0^{\circ}C$, 1 Atm, wet). This concentration exceeds the NSW Class 6 limit.
[4] Diesel engine emissions of carbon monoxide are based on NPI emission factors and have an emission concentration of 1,104 mg/Nm^3 ($0^{\circ}C$, 1 Atm, wet). This concentration meets the NSW Class 6 limit.

5.2.6 Emissions from non-routine operations - flares

Gas flaring will be undertaken at Leewood and Bibblewindi for flow and pressure management during maintenance and other non-routine operations. Flares may also be used to manage gas flow at the pilot wells that are not connected to the gas pipeline infrastructure during gas field development.

A key consideration in flare emission modelling and impact assessment is the thermal buoyancy created by the heat of the combustion zone and the mechanical velocity created by the flow rate and turbulence. In order to model the flare emission dispersion adequately, the United States EPA approved SCREEN3 method was used in conjunction with information supplied by the proponent. This method adjusts the nominal stack height and diameter to account for the combustion zone dimensions and effects and replaces these parameters with an 'effective' stack height and diameter.

The SCREEN3 method adjusts the flare plume rise with a buoyancy flux parameter based on the assumption that 55 percent of the total heat is lost due to radiation, with the remaining 45 percent released as sensible heat that contributes to the buoyancy of the plume. Plume dispersion is calculated by the model from above the combustion zone (i.e. height of the effective stack). The height of the combustion zone is equivalent to the difference between the effective and nominal stack heights. The effective diameter accounts for the assumption that the flame may be bent over to a 45 degree angle from the vertical due to the wind. This provides for a potential worst case plume extent at its release point.

The operational and emission release characteristics of each of the flares at the pilot wells, Bibblewindi and Leewood gas processing facilities are described in Table 5-21 and Table 5-22 respectively. Flare emissions are presented in Table 5-23 and Table 5-24. All flare emissions have been presented for completeness. The pilot well flares represent a very small proportion of flare emissions and potential impact.

Table 5-21 Flare operational characteristics

Parameter	Units	Well pad pilot	Bibblewindi	Leewood
Peak energy release rate	GJ/hr	154	7,494	7,494
	GJ/s	0.043	2.08	2.08
Flare mass rate	kg/s	1.45	70. 8	70.8
Flare flow rate	MMSCFd	5	244	244
(@ standard conditions - 15 ^{o}C, 1 Atm)	Sm^3/s	1.6	80.0	80.0

Table 5-22 Flare emission release characteristics

Pollutant	Units	Pilot well	Bibblewindi	Leewood
Temperature[1]	K	1,273	1,273	1,273
Exit velocity[1]	m/s	20.0	20.0	20.0
Nominal stack height	m	5.0	46.0	46.0
Effective stack height[1]	H_{sl}	12.0	90.7	90.7
Effective diameter[1]	m	2.09	14.8	14.8
Heat Rate (QH) [1]	kcal/s	4,590	223,987	223,987
Flare combustion zone height above flare stack tip	m	7.0	44.7	44.7

Table note: [1] Based on SCREEN3 method and calculations.

Table 5-23 Flare emission based on AP-42 emission factors

Pollutant	Emission factor (g/GJ)	Pilot well (g/s)	Bibblewindi (g/s)	Leewood (g/s)
Nitrogen dioxide	29.2	1.2	60.9	60.9
Carbon monoxide	159.1	6.8	331.1	331.1
Total Hydrocarbons	60.2	2.6	125.3	125.3

Table 5-24 Breakdown of hydrocarbon emissions from flares based on AP-42 emission factors

Pollutant	Average emission contribution (%)	Pilot well (g/s)	Bibblewindi (g/s)	Leewood (g/s)
Methane	55	1.41	68.91	68.91
Ethane/Ethylene	8	0.21	10.02	10.02
Acetylene	5	0.13	6.26	6.26
Propane	7	0.18	8.77	8.77
Propylene	25	0.64	31.32	31.32

6 Other major emission sources considered in the region - Wilga Park Power Station

The potential cumulative impact of the Wilga Park gas-fired power station has also been considered in the assessment. The Wilga Park power station was not operating at the time of the air monitoring program. Consequently, the nitrogen dioxide data collected was not representative of the background near Leewood when it is operating. To complete the assessment of potential future baseline conditions and understand the spatial variability of ground-level concentrations of the most important air pollutant, nitrogen dioxide, when operating, the Wilga Park facility has been assessed in the dispersion modelling study based on information published in the power station's environmental impact statement.

It should be noted that the power station was designed for and granted the required environmental approvals for 40 MW_e of power generating capacity. Whilst approval has been granted for 40 MW_e of generating capacity, only 16 MW_e of generating capacity has been installed. Since the installation was completed, the power station has only been operated intermittently and rarely at full generating capacity. It is not known whether the additional approved capacity will be constructed in the future. Whilst there are no imminent plans for the proponent to increase the installed generating capacity of the Wilga Park power station, as 40 MW_e of generation capacity has been approved, the full 40 MW_e of capacity has been assessed in the air quality impact assessment, as this represents the worst case scenario.

A summary of the 40 MW_e Wilga Park Power Station exhaust characteristics and emission rates are provided in Table 6-1 and Table 7-2, respectively. The calculation of plume buoyancy and merging factors indicates that the plumes are not likely to merge or gain significant dispersion benefit from merging. Consequently, an enhanced plume buoyancy effect was not modelled.

Table 6-1 Wilga Park Power Station emission exhaust characteristics

Parameter	Units	1 MW_e gas reciprocating engines	3 MW_e gas reciprocating engines
Number of units	--	10	10
Number of stacks per unit	--	1	1
Stack height	m	3.8	12.5
Stack exit diameter	m	0.33	0.6
Stack cross sectional area	m^2	0.086	0.28
Stack exhaust velocity	m/s	12.0	12.0
Stack exhaust temperature	^oC	375	375
Actual stack exhaust volume flow	Am^3/s	1.03	3.39
Normal stack exhaust volume flow (0^oC, 1 Atm, wet)	Nm^3/s, wet	0.43	1.43
Buoyancy flux parameter[1]	m^4/s^3	1.73	5.72
Buoyancy enhancement factor [N_E] for co-located plumes[2]	--	1	1.01

Table note: [1] Based on Briggs (1965) plume rise equation
[2] Based on Manins *et al*, 1992.

Table 6-2 Wilga Park Power Station emission rates of oxides of nitrogen

Parameter	Units	1 MW_e gas reciprocating engines	3 MW_e gas reciprocating engines
Concentration	mg/Nm^3 ($0^{\circ}C$, 1 Atm, wet, actual O_2)	104	804
Emission rate	g/s	0.045	1.15
Total annual emissions	kg/yr	1,419	36,266

7 Assessment Methodology

7.1 Selection of a representative year of meteorology

In order to select a representative year for the meteorological model simulation, a detailed analysis was conducted of observed inter-annual meteorological variability at the Narrabri Airport automatic weather station over the five-year period between March 2008 and February 2013. This detailed analysis is provided in Appendix C.

The March to February annual sequence was used in order that the consecutive months in a season were not separated. When using a calendar year (i.e. January to December), the summer month of December at the end of the year is not in sequential order with the January and February summer months. This can lead to anomalies in weather patterns caused by yearly and multi-year fluctuations such as El Niño Southern Oscillation (ENSO). If a La Niña classified summer is followed by a neutral or El Niño classified summer the sequence of summer weather conditions is broken by modelling a calendar year. In addition to this, the ENSO pattern, an important variable to be considered in the representative year selection, tends to begin around June and builds through the spring and summer months, before easing into a shoulder period in the autumn months of April and May. It is therefore appropriate to analyse annual meteorological variability in Eastern Australia on the basis of a March to February annual period.

The assessment comprised an analysis of the distributions of wind speed, wind direction, the U and V vector components of the wind, temperature and relative humidity on a year on year basis as well as each year against the mean of the five-year period. In addition to this, the monthly and annual variability of rainfall was investigated and the annual ENSO classification.

Based on the outcome of the analysis of observed inter-annual meteorological variability at Narrabri Airport, the one-year period between 1 March 2008 and 28 February 2009 was selected for the modelling.

7.2 Meteorological modelling

As described in Section 5.2, the primary source of air emissions from the project during normal operations will be associated with power generation activities at the central gas processing facility at Leewood. Relatively small quantities of emissions are also expected to be released continuously from well head engines across the gas field. Intermittent, short duration emissions are also likely at Bibblewindi due to non-routine operations such as gas flaring. While the Leewood gas processing facility and Bibblewindi in-field compression facility locations are known and fixed, in contrast the location of well heads are not known at this stage of the assessment process but will come and go over the life of the project and vary due to gas exploration discoveries and well gas production rates. Consequently, a flexible and modular approach to the meteorological and dispersion modelling was developed to account for the varying availability of project information as the project develops through the approvals, construction and operational phases.

The meteorological file used in the air dispersion model was developed using the TAPM-CALMET two-stage modelling suite. TAPM was run to develop a three-dimensional simulation of the atmosphere in the region for direct input to the CALMET model. CALMET was then used to downscale the regional meteorological profile developed using TAPM to incorporate and refine the local geography. Meteorological observations from the BOM AWS at Narrabri Airport were also incorporated into CALMET to improve the model's performance. The CALMET output file is formatted for use in the CALPUFF dispersion model.

TAPM and CALMET were configured to appropriately characterise the wind field in the project and surrounding areas. The inputs used in the TAPM and CALMET models are outlined in the following section, while a detailed evaluation of the meteorological model's performance in simulating local meteorology at Narrabri Airport is presented in Appendix D.

The TAPM and CALMET model domains were configured to be able to assess air quality impacts in the broader region from sources situated across the entire project area. This approach provides for spatial flexibility as the project develops. Notwithstanding this, the approach also provides for the modelling of fine-scale localities or sub-grids with CALPUFF, or the extraction of site-specific meteorological files for assessment using the Ausplume dispersion model.

The approach to modelling the well pad generators, which may be located in yet to be determined locations across the project area, was to extract four Ausplume formatted meteorological files from the CALMET model grid in locations where gas wells are located in close proximity to the project's infrastructure centres or areas near residential development. The four sites selected were Leewood, Bibblewindi, Wilga Park and Narrabri township. All source-receptor buffer assessments have been determined using the four meteorological files, in order to assess the worst case buffer based on varying meteorology across the project area. The predicted impacts were then used to develop separation distances for each project emission source.

7.2.1 TAPM prognostic meteorological model

The Air Pollution Model (TAPM) was developed by the CSIRO for use in simulating regional meteorological and air pollution events. TAPM is a coupled synoptic-scale prognostic meteorological and air dispersion modelling system designed to operate on a standard desktop computer.

The model requires synoptic meteorological information input for the region of interest that are generated by a global model similar to the large-scale models used to forecast the weather. TAPM incorporates re-analysed and validated synoptic weather forecast data at a resolution of approximately 75 km and at elevations of between 100 m and 5,000 m above the surface with regionally-specific terrain, land use, soil moisture content and soil type, to simulate the meteorology of a region as well as at a specific location. TAPM then solves the equations of atmospheric fluid dynamics to predict the hourly state of the atmosphere over a given time period.

TAPM (v.4.0.3) was configured as follows:

- Mother domain grid size of 30 km with 3 nested daughter grids of 10 km, 3 km and 1.5 km.
- 50 x 50 grid points for all modelling domains.
- 25 vertical levels from the surface up to 8,000 m above the ground.
- Domain centre coordinate: UTM: 55H 756.010 m (east); 6626.165 m (north); Latitude = 30° 28', Longitude = 149° 40'.
- TAPM defaults for terrain and sea surface temperatures.
- Augmented land use based on correlation with aerial imagery.
- Default options selected for advanced meteorological inputs.
- Year modelled: 1 March 2008 and 28 February 2009.
- Meteorological observations were not assimilated.

TAPM was initiated with the default topographical information supplied with the model. This dataset is based on the Geoscience Australia 9-second terrain height database and has a grid spacing of approximately 300 metres. This dataset is commonly used in Australia for air dispersion modelling and is considered to be appropriate for use in this assessment.

The vegetation classification scheme used in TAPM is based on United States Geological Survey (USGS) Earth Resources Observation Systems (EROS) global land cover data at 30-second grid resolution (approximately one kilometre). This database is considered to be less accurate than the topographical information used. Consequently, a review and update of the land surface classification data was undertaken prior to running TAPM. The primary default vegetation cover classification was Shrubland (low sparse), which was considered to be too uniform for the region. Aerial imagery of the project area indicated significant areas of forest (i.e. the Pilliga Forest) interspersed with low, sparse shrubland. Consequently, the land use vegetation classification was updated to reflect the aerial photography.

7.2.2 CALMET diagnostic meteorological pre-processor

CALMET is an advanced non-steady-state diagnostic three-dimensional meteorological pre-processor for the CALPUFF dispersion model. The model is capable of operating in three key modes by:

1. Assimilating surface and upper air meteorological observations from multiple sites within the modelling domain.
2. Initialisation from three-dimensional gridded meteorological information supplied by a prognostic model such as TAPM.
3. A hybrid mode whereby surface wind flows from the TAPM three-dimensional gridded data is effectively 'nudged' through the assimilation of local surface observations.

For this assessment, the United States EPA approved version of CALMET (Version 5.8) was configured in hybrid mode with hourly data from the BOM's Narrabri Airport AWS incorporated into the TAPM 3-D prognostic simulation for the same time period. The application of CALMET for this purpose is specifically designated in New South Wales (Approved Methods, DEC, 2005) with model guidance documentation also provided (OEH, 2011).

CALMET was set up as the fifth nest in the meteorological simulation at a grid resolution of 500 m. The TAPM prognostic grid data is used by the CALMET diagnostic model as an 'initial guess' before making adjustments to the local wind fields for the kinematic effects of terrain, slope flows, blocking effects and three-dimensional divergence minimisation. The coupled approach improves the mesoscale prognostic simulation generated by TAPM with the refined local-scale land use and terrain capabilities of CALMET. The CALMET output provides a complete set of three-dimensional wind fields, temperature profiles and other important meteorological variables throughout the atmosphere for application in the simulation of plume dispersion.

CALMET was configured in Hybrid Mode with the Narrabri Airport AWS data incorporated to improve the model's performance in simulating the local wind flows. This option was selected due to the relatively poor performance of TAPM to simulate the distribution of wind speed. TAPM was found to significantly over-predict the frequency of light winds less than 3.5 m/s, and under-predict the frequency of moderate wind speeds in the 3.5 – 5.5 m/s range. To address and adjust this, the local wind observations were assimilated into the CALMET model run.

CALMET was configured as follows:

- Model domain area of 55 km x 55 km was based on 110 grid points at a resolution of 0.5 km.
- CALMET model southwest corner location, or origin, was located at UTM Zone 55 coordinates 727.700 km east and 6594.308 km north. The CALMET domain extended 55 km to the east and north to coordinates 782.200 km east and 6648.808 km north.
- 11 vertical levels at 0 m, 20 m, 40 m, 60 m, 90 m, 120 m, 180 m, 250 m, 500 m, 1000 m, 2000 m, 3000 m.

- Year modelled: 1 March 2008 and 28 February 2009.
- TAPM generated prognostic meteorological inputs as a CALTAPM.M3D file used as an 'initial guess' field only.
- Wind field options for Hybrid Mode were guided by the recommendations outlined in the *Generic Guidance and Optimum Model Settings for the CALPUFF modelling system for Inclusion into the Approved Methods for the Modelling and Assessment of Air Pollutants in NSW, Australia* (OEH, 2011), with the exception of the settings for Kinematic Effects and the O'Brien Vertical Velocity Adjustment. The following inputs were selected:
    - TERRAD = 18 km
    - ICLOUD = 3
    - IEXTRP = 4
    - RMAX1 = 14
    - RMAX2 = 14
    - RMAX3 = 14
    - R1 = 15
    - R2 = 15
    - LVARY = T
    - Kinematic effects were computed (IKINE = 1)
    - O'Brien adjustment for vertical velocity smoothing (IOBR = 1)

The undulating nature of the terrain means that hills and valleys create flow divergence and convergence as the wind moves around the natural obstacles. A better representation of the vertical velocity was required (by setting IKINE=1) to maintain mass consistency and to more accurately represent the situations of plume diversion around elevated terrain. The TERRAD variable was set to a value of 18.0 km based on an inspection of the terrain elevations in the immediate vicinity of the site and based on OEH (2011) guidance. The parameter LVARY was used to switch on the varying radius of influence. This results in the radius of influence being expanded when no stations are within the fixed radius of influence value.

The geophysical data file for CALMET was manually constructed using terrain height information supplied by TAPM and aerial imagery to determine appropriate land use and vegetation cover. The default CALMET land use parameters of surface roughness, albedo, soil type and moisture levels and leaf area index were applied. An illustration of the model terrain height information on the CALMET grid is presented in Figure 7-1, while the vegetation cover is presented in Figure 7-2.

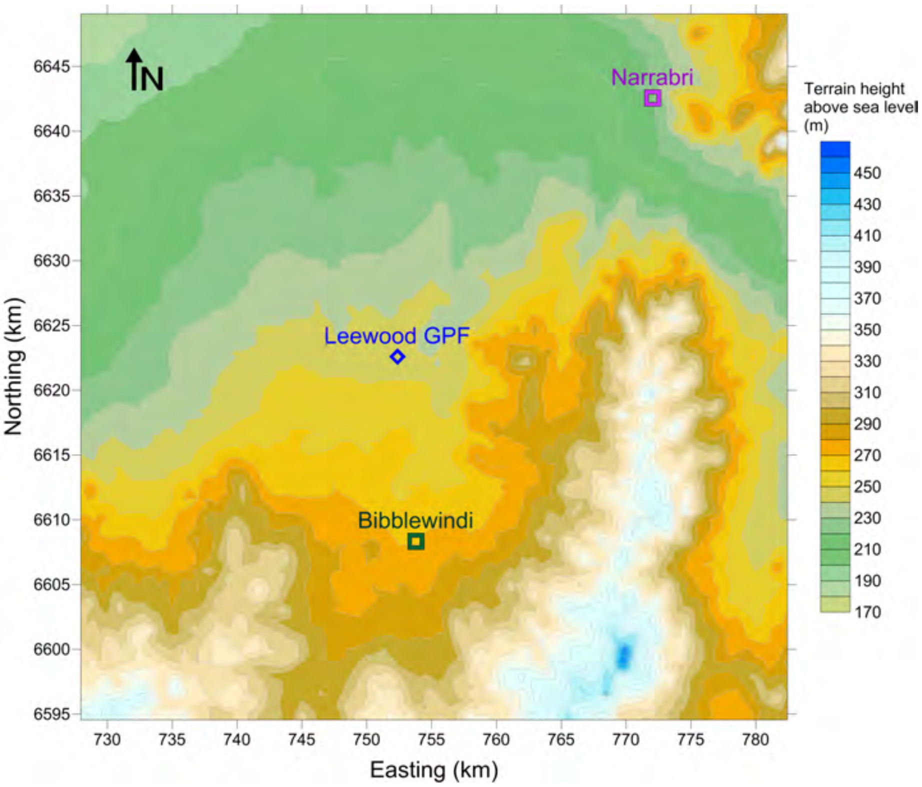


Figure 7-1 Topographic map of terrain height data used in CALMET

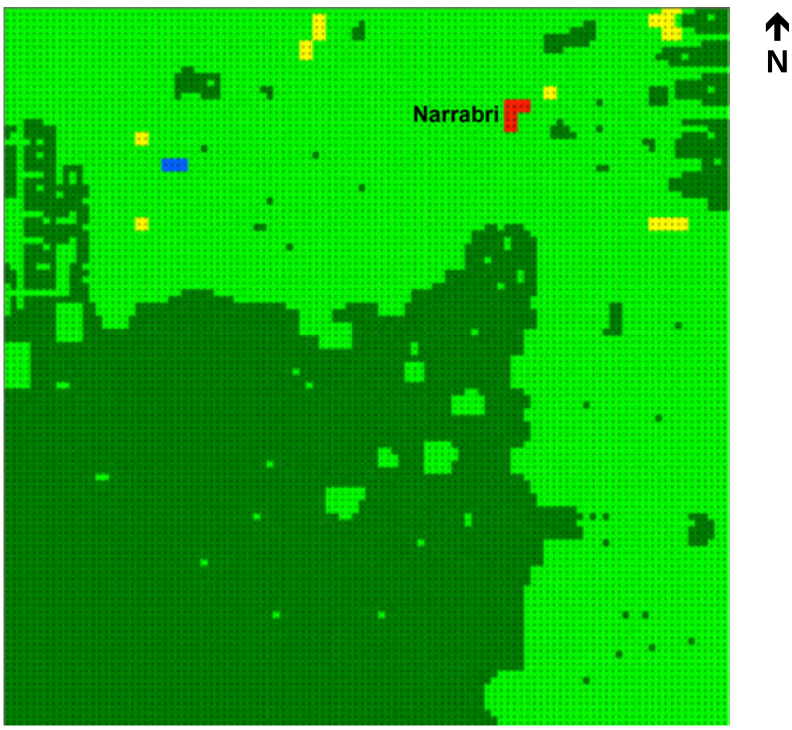


Figure note:	Red =	Class 10: Urban or Built-up land.
	Light Green =	Class 20: Agricultural Land – Non-irrigated.
	Yellow =	Class 30: Rangeland.
	Dark Green =	Class 40: Forest Land.
	Blue =	Class 50: Water.

Figure 7-2 Vegetation cover at each grid node used in CALMET

7.2.3 Meteorological model performance evaluation

An evaluation of the TAPM and CALMET meteorological model's performance in simulating the local meteorology was conducted. The assessment, showing detailed statistical and graphical analysis, is presented in full in Appendix D.

The evaluation determined that TAPM demonstrated reasonable performance in predicting the distribution of key meteorological variables such as wind direction and temperature. However, it did not perform as well in terms of predicting each variable on a time and space basis. The evaluation also established that TAPM over-predicted the frequency of light winds less than 3.5 m/s and under-predicted the frequency of moderate wind speeds in the 3.5 – 5.5 m/s range.

As a result of the discrepancy in wind speeds between the observed and predicted distributions, the CALMET model was run in Hybrid Mode, with hourly wind speed and direction surface observations from Narrabri Airport incorporated into the model with the three-dimensional TAPM wind field. This approach significantly improved the model's overall performance to simulate the local wind fields, thereby making it suitable for use in the air dispersion modelling.

7.3 Analysis of dispersion meteorology across the project area

7.3.1 Wind direction and speed

The annual distribution of predicted wind direction and speed at Leewood, Bibblewindi, Wilga Park and Narrabri, based on the TAPM-CALMET simulation, are presented as wind rose diagrams in Figure 7-3. For the main project area at Leewood, the distribution used in the modelling indicates that:

- 40 % of winds blow from between the south-east and south.
- 25 % of winds blow from between the north-north-west and north-north-east.
- 26 % of winds blow from the eastern quadrant between the north-east and south-east.
- 17 % of winds blow from the western quadrant between the south-west and north-west.
- 42 % of winds are light and below 2 m/s, 52 % are moderate between 2-5 m/s and only 6 % are strong and greater than 5 m/s.

The comparison of winds at each modelled location indicates that there are a higher proportion of light winds in the more sheltered Leewood and Bibblewindi areas, when compared to the more exposed cleared pastoral areas around Narrabri and Wilga Park. This is to be expected as the greater surface roughness generated by the trees in the forest has the effect of reducing surface wind speeds. Modelling of the meteorology in the aforementioned four areas of the project was conducted to account for this variability in the assessment of separation distances for infrastructure that is not in a fixed location or is subject to further project design such as new roads, access tracks, pipeline corridors and well pads. The buffer assessment has been conducted based on the worst case findings of meteorological conditions in the various project areas.

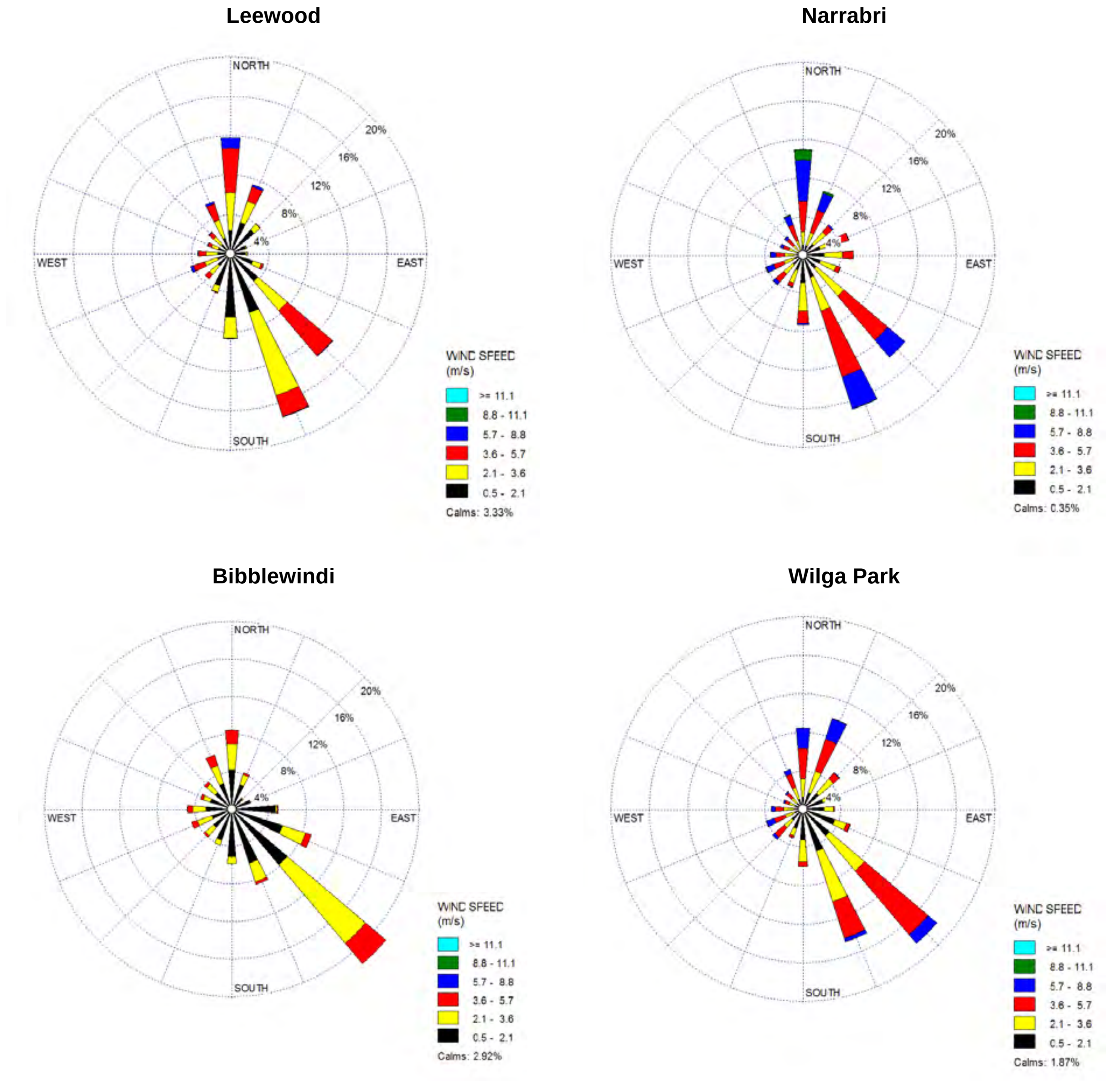


Figure 7-3 Annual frequency distributions of wind speed and direction at four locations used in the dispersion modelling

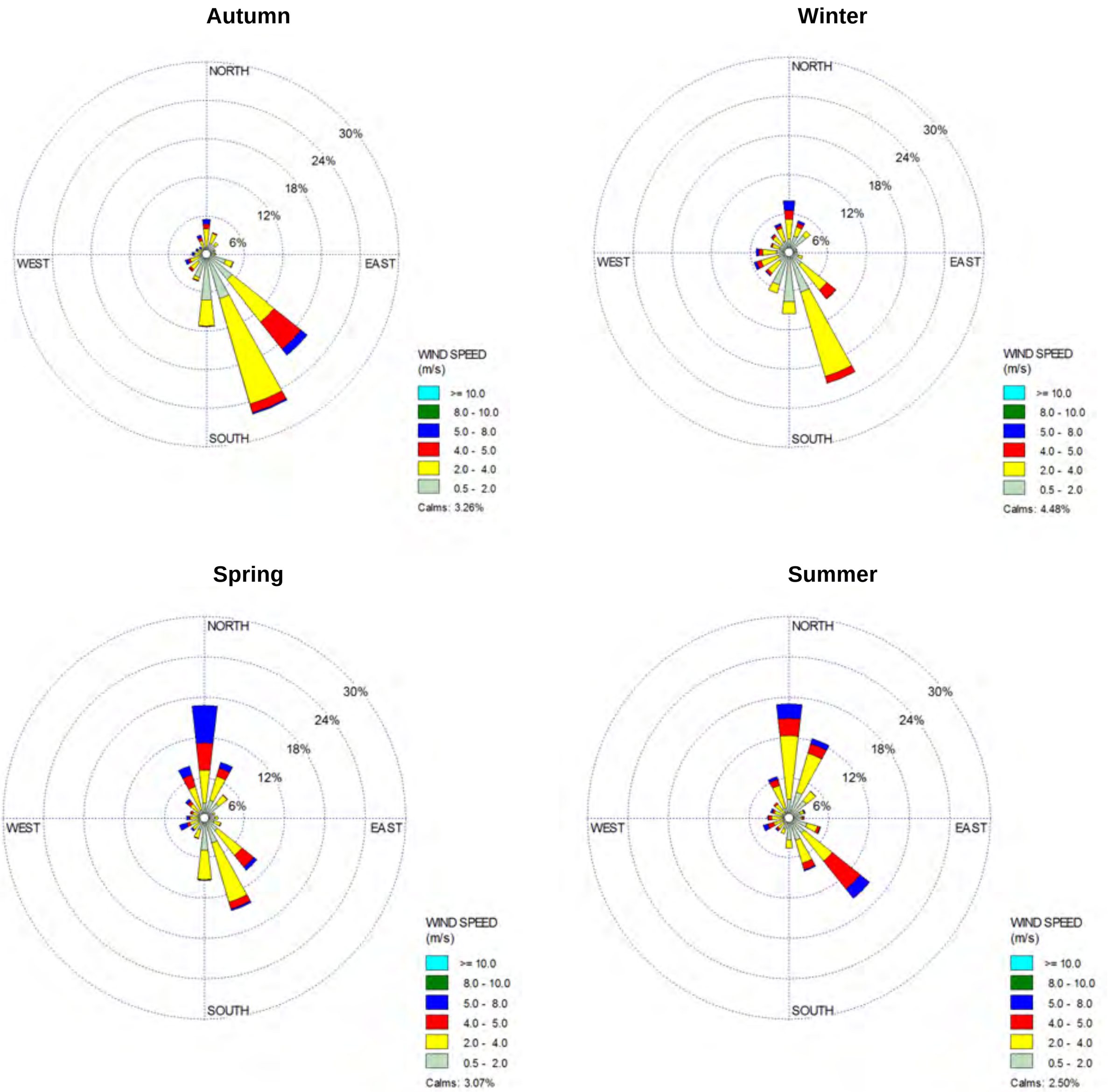


Figure 7-4 Seasonal frequency distributions of wind speed and direction at Leewood

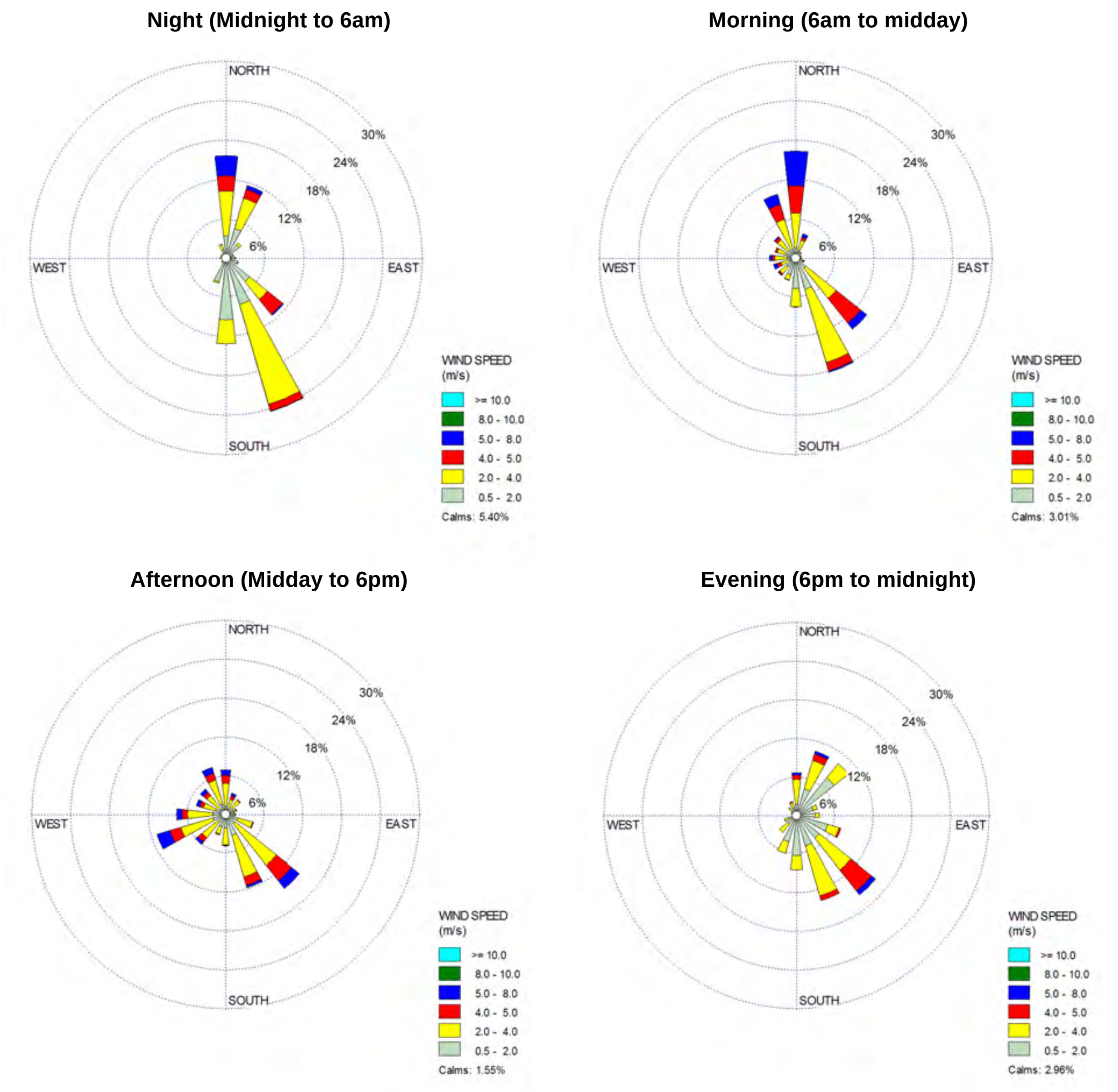


Figure 7-5 Daily frequency distributions of wind speed and direction at Leewood

The ratio of light (<2 m/s) to moderate (2-<5 m/s) and strong (>5 m/s) winds by wind direction at Leewood is presented in Figure 7-6. The histogram indicates that:

- Winds from between the north-east and east-south-east are two to six times more likely to be lights winds than moderate to strong.
- Winds from between the south-east and south-south-east are two to three and a half times more likely to be lights winds than moderate to strong.
- The wind is more likely to be moderate to strong than light for all other directions.

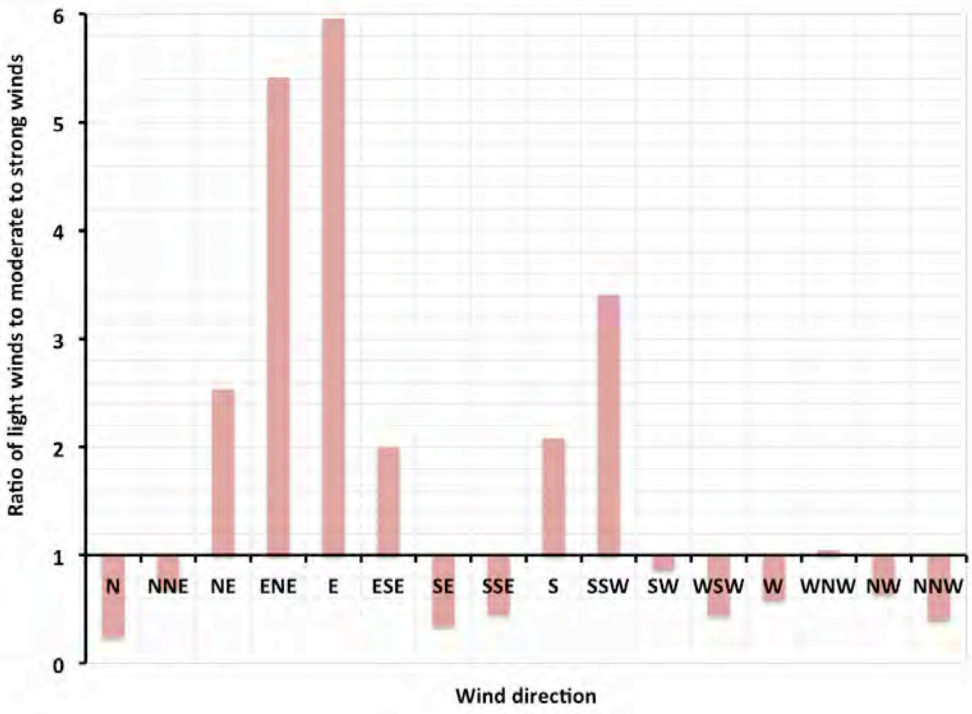


Figure 7-6 Ratio of light to moderate/strong winds by wind direction at Leewood

7.3.2 Atmospheric stability and mixing height

Stability is a term applied to the properties of the atmosphere that govern the acceleration of the vertical motion of an air parcel. The acceleration is positive in an unstable atmosphere (turbulence increases), zero when the atmosphere is neutral, and negative (deceleration) when the atmosphere is stable (turbulence is suppressed). There are six main atmospheric stabilities designated as:

- A (highly unstable or convective),
- B (moderately unstable),
- C (slightly unstable),
- D (neutral),
- E (slightly stable), and
- F (stable).

This is known as the Pasquill-Gifford atmospheric stability classification scheme and is widely used in atmospheric modelling to define the turbulent state of the atmosphere.

Unstable conditions (Class A-C) are characterised by strong solar heating of the ground that induces turbulent mixing in the atmosphere close to the ground. This usually results in material from a plume reaching the ground closer to the source than for neutral or stable conditions. Turbulent mixing is the main driver of dispersion during unstable conditions. Dispersion processes for neutral conditions (Class D) are dominated by mechanical turbulence generated as the wind passes over irregularities in the local surface, such as terrain features, stands of trees and building structures.

During the night, the atmospheric conditions are neutral or stable (Class D, E and F). During stable conditions, plumes from short stacks or fugitive releases will be subject to minimal atmospheric turbulence. A plume released below an inversion layer during stable conditions that has insufficient vertical momentum or thermal buoyancy to penetrate the inversion will be trapped beneath it and result in elevated ground-level concentrations. Conversely, a plume that is hotter than its surroundings and emitted above, or is able to penetrate the nocturnal inversion through momentum, will remain relatively undiluted and will not reach the ground unless it encounters elevated terrain.

The frequency distributions of Pasquill-Gifford stability classes based on the CALMET model Leewood, Bibblewindi, Narrabri Town and Wilga Park are presented in

Figure 7-7.

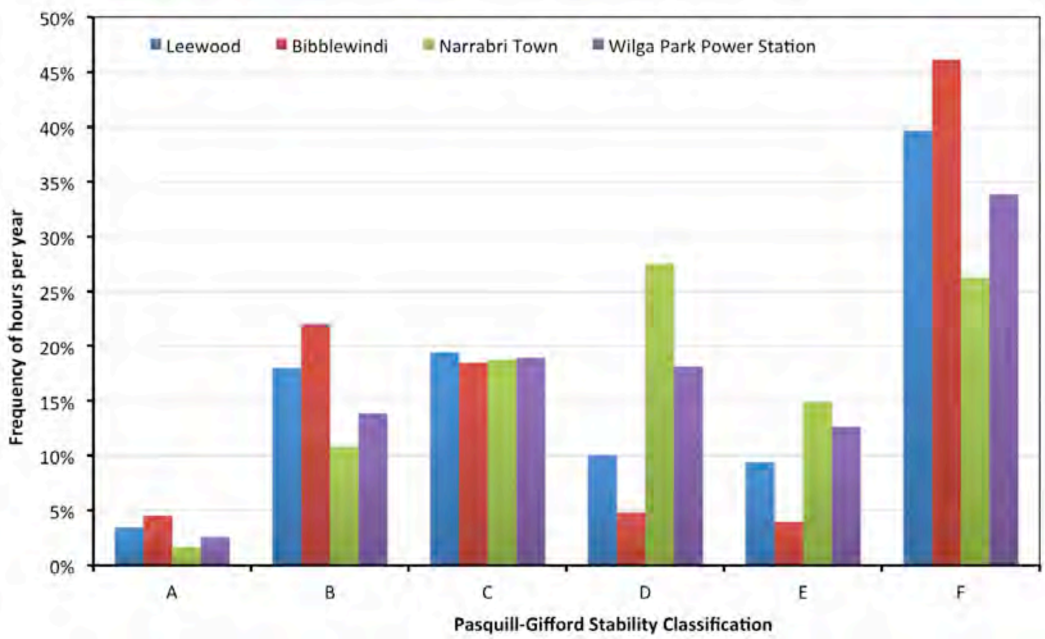


Figure 7-7 Frequency distributions of hourly Pasquill-Gifford atmospheric stability classifications at the four sites

The mixing height refers to the height above ground within which the plume can mix with ambient air. During stable atmospheric conditions at night, the mixing height is often quite low. During the day, solar radiation heats the air at ground level and causes the mixing height to rise through the growth of convection cells. The air above the mixing height during the day is generally colder. The growth of the mixing height is dependent on how well the air can mix with the cooler upper levels of air and therefore depends on meteorological factors such as the intensity of solar radiation and wind speed. During strong wind speed conditions the air will be well mixed, resulting in a high mixing height.

The hourly distributions of mixing height at the Leewood, Bibblewindi, Wilga Park and Narrabri sites from the CALMET model is presented as a box and whisker plot in Figure 7-8.

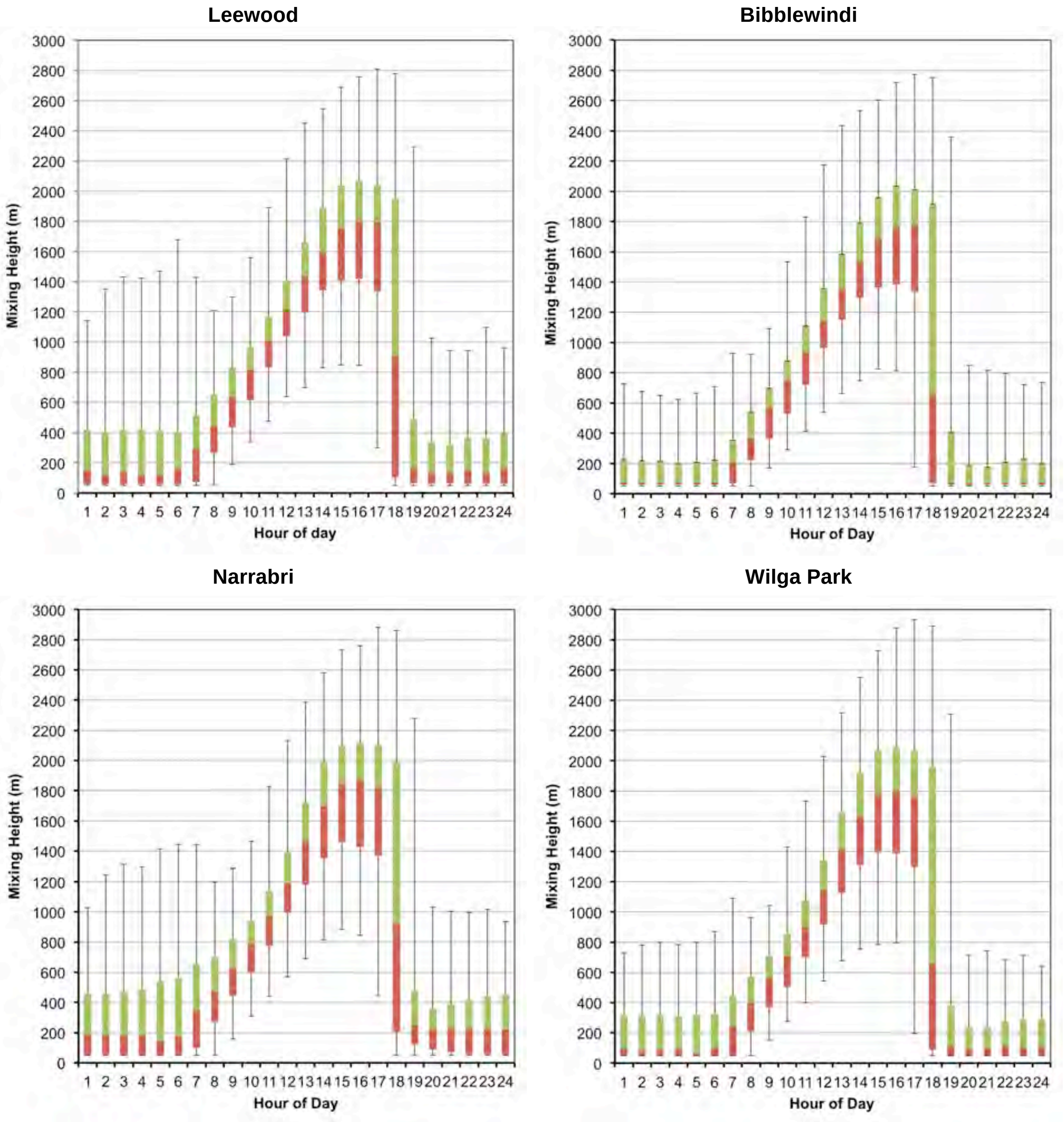


Figure 7-8 Hourly distributions of mixing height at the four sites

The main project sites where air emissions will be generated (being Leewood and Bibblewindi), are well separated from sparsely located residences. Fifteen receptor locations were identified within five kilometres of Leewood, while no receptors were identified within the same distance of Bibblewindi. Bibblewindi is surrounded by forest and by contrast, Leewood has forest adjacent to the south-east and south-west quadrants and primarily open pasture to the north. The effect on plume dispersion of tall stands of trees in the forest is to reduce surface wind speeds and increase turbulence (or mechanical mixing) of airflow as it passes through and over the rough surface features.

For gaseous emissions, this will tend to result in higher near-field ground-level concentrations of fugitive and low buoyancy short stack emissions due to the light winds. In addition, there will be approximately 60 percent frequency of neutral to very stable atmospheric stability conditions. However, for the power generation plant at Leewood, the high plume buoyancy factor of emissions due to the thermal and mechanical buoyancy of the stack emissions, when considered along with the tall stack, will create good dispersion conditions. The plume is to be released near the top of the tree canopy with significant velocity and temperature, causing it to rise through neutral or stable boundary layers. At night, once the plume rises above the stable layer, or temperature inversion, it is unlikely to come to ground unless encountering elevated terrain.

Conversely, during the day as the ground heats up, a more convective atmosphere develops, increasing atmospheric instability and causing the plume to loop and come to ground. Such daytime unstable conditions are more conducive to generating ground level impacts for the power generation plant.

7.4 Dispersion modelling

Atmospheric dispersion modelling was carried out using the CALPUFF and AUSPLUME dispersion models, as addressed below.

7.4.1 CALPUFF dispersion model

CALPUFF is a non-steady-state, Lagrangian puff dispersion model. It is accepted for use by the Office of Environment and Heritage for application in environments where wind patterns and plume dispersion is strongly influenced by complex terrain and the land-sea interface. While the regional terrain surrounding Narrabri appears to be rolling rural and not too complex, the standard definition of complex terrain in dispersion modelling is a situation where the local terrain has a higher elevation than stack sources at the facility being assessed. This is the case in the wider area of this assessment.

For this assessment, the CALPUFF dispersion model was used to predict ground-level concentrations of air contaminants downwind of the fixed facilities at Leewood and Bibblewindi. The grid size used in the CALPUFF model was equivalent to the CALMET domain. The same grid resolution of 500 m used for the CALMET run was used in CALPUFF.

7.4.2 AUSPLUME dispersion model

AUSPLUME is a steady-state, Gaussian dispersion model accepted for use by the OEH for application in non-complex environments and for assessing near field impacts.

For this assessment, AUSPLUME has been used to assess the impact of emissions from well pad gas- and diesel-fired engines, to determine an appropriate source-receptor separation distance, as the engines will be strategically located across the gas field. Given that the well pad locations are not known at this stage and likely to change throughout the life of the project as the gas supply and demand changes, this was determined to be the most appropriate, efficient and flexible method to assess the impact of well pad engine emissions.

7.5 Impact assessment scenarios

The potential for impacts to air quality have been assessed for the following air emission scenarios:

- The construction of the:
  - central gas processing facility, power generation plant and water treatment plant at Leewood,
  - in-field gas compression facility at Bibblewindi,
  - gas well pads,
  - gas and water pipeline and below ground electricity transmission line trenches, and
  - access tracks and roads.

- The operation of the project under power supply option 1:
  - ten gas-fired generators at the 100 MW_e gas-fired power generation plant at Leewood,
  - four hot oil boilers at the central gas processing facility at Leewood,
  - flare at Leewood,
  - flare at Bibblewindi,
  - gas and diesel-fired well head generator engines at the well pads,
  - pilot well flare at the well pad, and
- The operation of the project under power supply option 2:
  - four hot oil boilers at the central gas processing facility at Leewood,
  - flare at Leewood,
  - flare at Bibblewindi,
  - gas and diesel-fired well head generator engines at the well pads,
  - pilot well flare at the well pad, and

For the air quality assessment operational phase, the assessment has also been separated into routine and non-routine operations. Routine operations are defined as the sources that release emissions to air on a regular and continuous basis such as the power generation plant and hot oil boilers at Leewood and the generators at the well pads. This infrastructure is considered critical to the continuous operation of the project. Non-routine operations are defined as the sources that release emissions to air on an irregular and intermittent basis such as the operation of the flares at Leewood and Bibblewindi, beyond the minimal flow requirements, and pilot well flares as required. This infrastructure is a necessary element of the project design for maintenance and safety management. Consequently, it would only be utilized intermittently.

A summary of the air pollutants, emission sources, modelling method and scenarios assessed is presented in Table 7-1. The most important air pollutants in terms of the ratio of their emission rate to impact assessment criteria are also shown.

Table 7-1 Impact assessment scenarios and methods

Phase	Source	Scenario	Air pollutants	Modelling assessment method
Construction	Leewood facility	All construction activities combined	Buffer limiting pollutant - PM_{10}	AUSPLUME buffer assessment
	Bibblewindi facility	All construction activities combined	Buffer limiting pollutant - PM_{10}	AUSPLUME buffer assessment
	Well pad area	All construction activities combined	Buffer limiting pollutant - PM_{10}	AUSPLUME buffer assessment
	Gas, water and electricity transmission pipeline trenches / access tracks	All construction activities combined	Buffer limiting pollutant - PM_{10}	AUSPLUME buffer assessment
	Roads	All construction activities combined	Buffer limiting pollutant - PM_{10}	AUSPLUME buffer assessment
Operation - power supply option 1	100 MW_e power generation plant at the Leewood	Routine operations	NO_2, CO, PM_{10}, acrolein, formaldehyde, acetaldehyde	CALPUFF impact assessment
	Hot oil boilers	Routine operations	NO_2, CO, PM_{10}, acrolein, formaldehyde, cadmium, nickel	CALPUFF impact assessment
	Gas flare at the Leewood central gas processing facility	Non-routine or emergency operations	NO_2	CALPUFF impact assessment
	Gas flare at the Bibblewindi in-line compressor station	Non-routine or emergency operations	NO_2	CALPUFF impact assessment
	Gas-fired engine at the well pad	Routine operations	Buffer limiting pollutant - NO_2	AUSPLUME buffer assessment
	Diesel-fired engine at the well pad	Routine operations	Buffer limiting pollutant - NO_2	AUSPLUME buffer assessment
	Pilot well flare at the well pad	Non-routine or emergency operations	Buffer limiting pollutant - NO_2	AUSPLUME buffer assessment
Operation - power supply option 2	Hot oil boilers at Leewood central gas processing facility	Routine operations	NO_2, CO, PM_{10}, acrolein, formaldehyde, cadmium, nickel	CALPUFF impact assessment
	Gas flare at the Leewood central gas processing facility	Non-routine or emergency operations	NO_2	CALPUFF impact assessment
	Gas flare at the Bibblewindi in-line compressor station	Non-routine or emergency operations	NO_2	CALPUFF impact assessment
	Gas-fired engine at the well pad	Routine operations	Buffer limiting pollutant - NO_2	AUSPLUME buffer assessment
	Diesel-fired engine at the well pad	Routine operations	Buffer limiting pollutant - NO_2	AUSPLUME buffer assessment
	Pilot well flare at the well pad	Non-routine or emergency operations	Buffer limiting pollutant - NO_2	AUSPLUME buffer assessment

7.6 Background concentrations used in the cumulative assessment

Representative background concentrations of the criteria air pollutants have been determined from the assessment of the existing air quality and the ambient air monitoring program conducted as part of the study. Background concentrations of nitrogen dioxide, ozone and PM_{10} used in the assessment are presented in Table 7-2. The assessment of principal and individual air pollutants has been undertaken in isolation of the background in accordance with DEC (2005). As discussed in Section 4.3.2, the 70th percentile concentration of PM_{10} has been used in the cumulative assessment based on guidance documents from EPAV (2007).

Table 7-2 Background concentrations used in the assessment

Air pollutant	Background concentration			
	1-hour	4-hour	24-hour	Annual
Nitrogen dioxide	18.5	N/A	N/A	18.5
Ozone	74.2	72.0	N/A	N/A
PM_{10}	N/A	N/A	24.1[1]	16.3

Table note: N/A: No criterion, not assessed
[1] Highest 70th percentile concentration of all years at Tamworth has been used, based on guidance from EPAV (2007).

7.7 Conversion of nitrogen oxides to nitrogen dioxide

As a conservative estimate, a level 1 assessment of nitrogen dioxide has been undertaken in accordance with the methods outlined in DEC (2005). For the purposes of the assessment, it has been assumed that 100 percent of the nitrogen oxides released from various project emission sources are converted to nitrogen dioxide in the atmosphere. In reality, this is considered to be highly conservative as the in-plume nitrogen dioxide concentration:

- Is typically less than 10 per cent of the combustion source emission concentration when released.
- Diminishes with distance due to mixing and dispersion processes.
- Increases with distance due to the reaction rate of nitric oxide to nitrogen dioxide. The rate of this reaction is dependent on the ambient concentrations of ozone and other oxidizing substances such as peroxy radicals and the season or available solar insolation.

Notwithstanding this, in the first instance, the NSW Approved Methods level one assessment approach has been used.

7.8 Assessment of ozone

Ozone is not directly released from the project as a primary pollutant but generated through the oxidation of nitrogen oxides in the presence of volatile organic compounds and sunlight in the atmosphere. The exhausts from the project engines and boilers contain approximately 90-95 percent of nitrogen oxides in the form of nitric oxide. Once the nitric oxide has been transformed into nitrogen dioxide, ozone may be produced via a multi-stage process. The rate at which ozone is generated is a function of:

- the in-plume concentration of nitrogen oxides,
- the concentration and reactivity of VOCs in the ambient air,
- the rate of plume dispersion, and

- the prevailing atmospheric conditions, including temperature and solar radiation fluxes.

Due to the low emissions of nitrogen oxides from the project in comparison to a large urban airshed such as the Sydney Greater Metropolitan Region, which has ozone formation issues, modelling of ozone generation has not been conducted for this assessment. In order to assess the potential of the project to cause air quality impacts in relation to ozone, a conservative method has been applied.

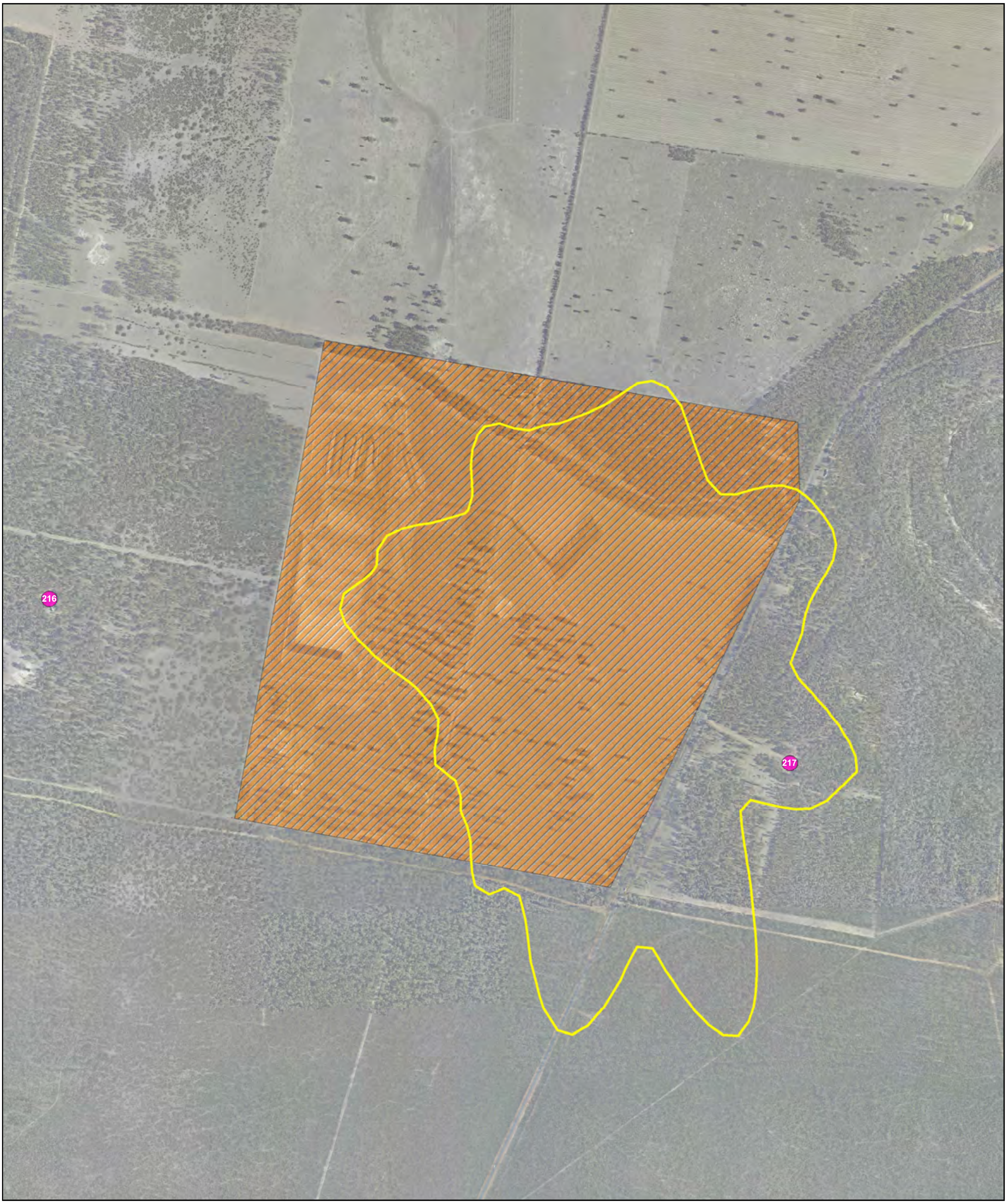
The assessment has assumed that 100 percent of the predicted maximum 1-hour and 4-hour average incremental ground-level concentrations of nitrogen dioxide, associated with emissions from the project, beyond the Leewood site boundary will be transformed in to ozone. The cumulative assessment has been calculated by adding the 1-hour and 4-hour average incremental predictions to the maximum 1-hour and 4-hour average ozone concentrations recorded during the monitoring program and compared to the impact assessment criterion. This is considered to be a conservative approach.

8 Impact Assessment

8.1 Assessment of construction phase air quality impacts

The assessment of construction related air quality impacts determined that PM_{10} would be the buffer-limiting particulate size fraction. The predicted maximum 24-hour average ground-level concentrations of PM_{10}, due to construction activities, nearest to sensitive receivers at the eastern and western boundaries of the Leewood facility, are presented as concentration contour plots in Figure 8-1 and Figure 8-2, respectively. The predicted maximum 24-hour average ground-level concentrations of PM_{10} due to construction activities at Bibblewindi are presented as concentration contour plots in Figure 8-3.

For other construction areas that will vary in location as the project develops, separation distances to sensitive receptors have been assessed based on the construction activity and area of construction. Construction area boundary to receptor separation distances are provided in Table 8-1, and are illustrated as concentration versus distance relationship graphs in Figure 8-4 to Figure 8-6. The assessment shows the appropriate buffer distance for the well pads, gas, water and electricity transmission pipeline trenching, access track and road construction areas.



LEGEND

Leewood

Sensitive receivers

50 $\mu g/m^3$

0 0.125 0.25 0.5

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Leewood central gas processing facility construction area predicted maximum 24-hour average concentration of PM10, with background for construction at the eastern boundary nearest to receptor 217

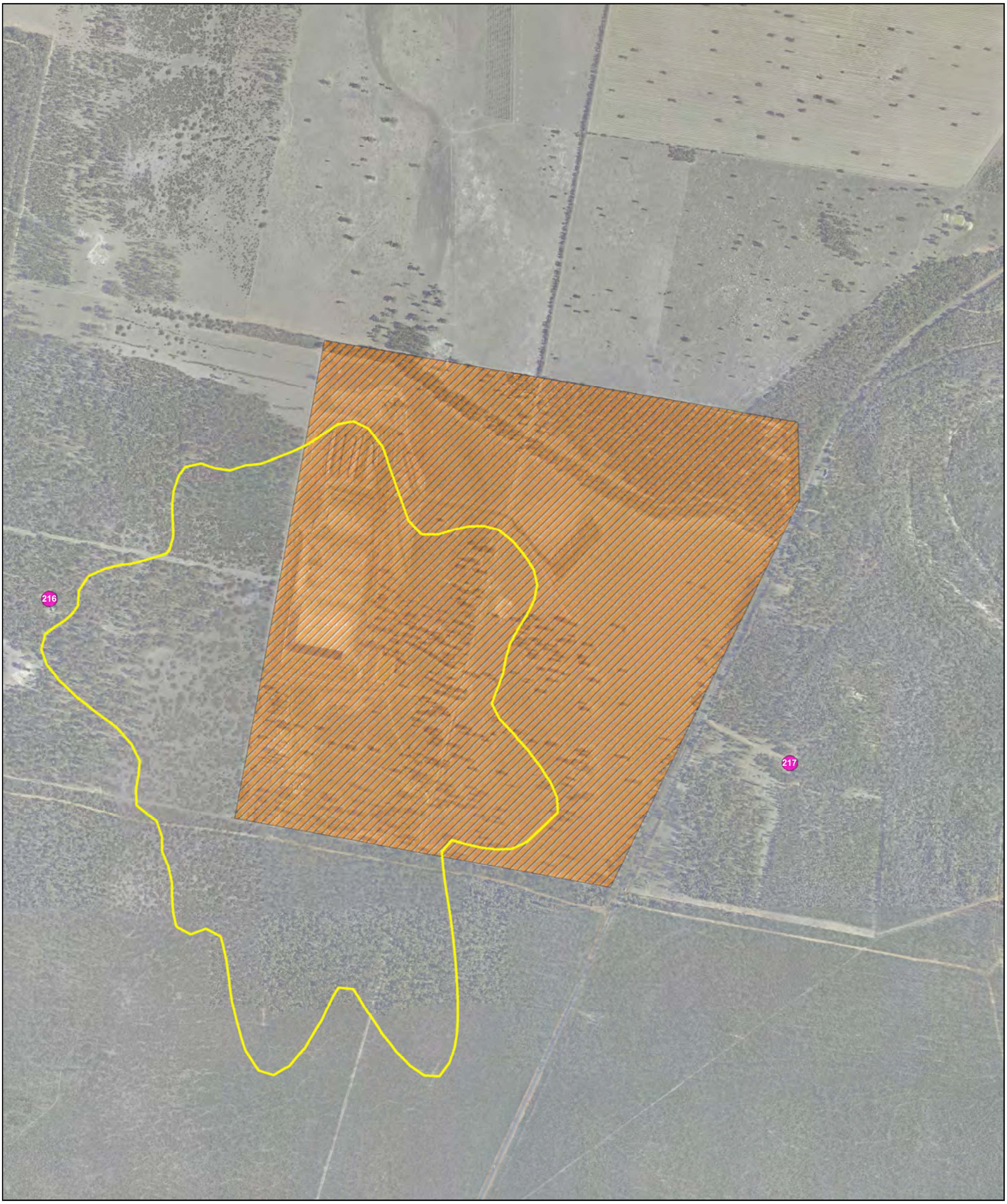
Job Number 21-22463
Revision A
Date Feb 2015

Figure 8-1

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 139]

Level 15, 133 Castlereagh Street Sydney NSW 2000 T 61 2 9239 7100 F 61 2 9239 7199 E sydmail@ghd.com.au W www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Created by: afoddy



LEGEND
Leewood
Sensitive receivers
50 µg/m^3

0 0.125 0.25 0.5
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Leewood central gas processing facility construction area predicted maximum 24-hour average concentration of PM10, with background for construction at the south-western boundary nearest to receptor 216

Job Number	21-22463
Revision	A
Date	Feb 2015

Figure 8-2

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 139]

Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

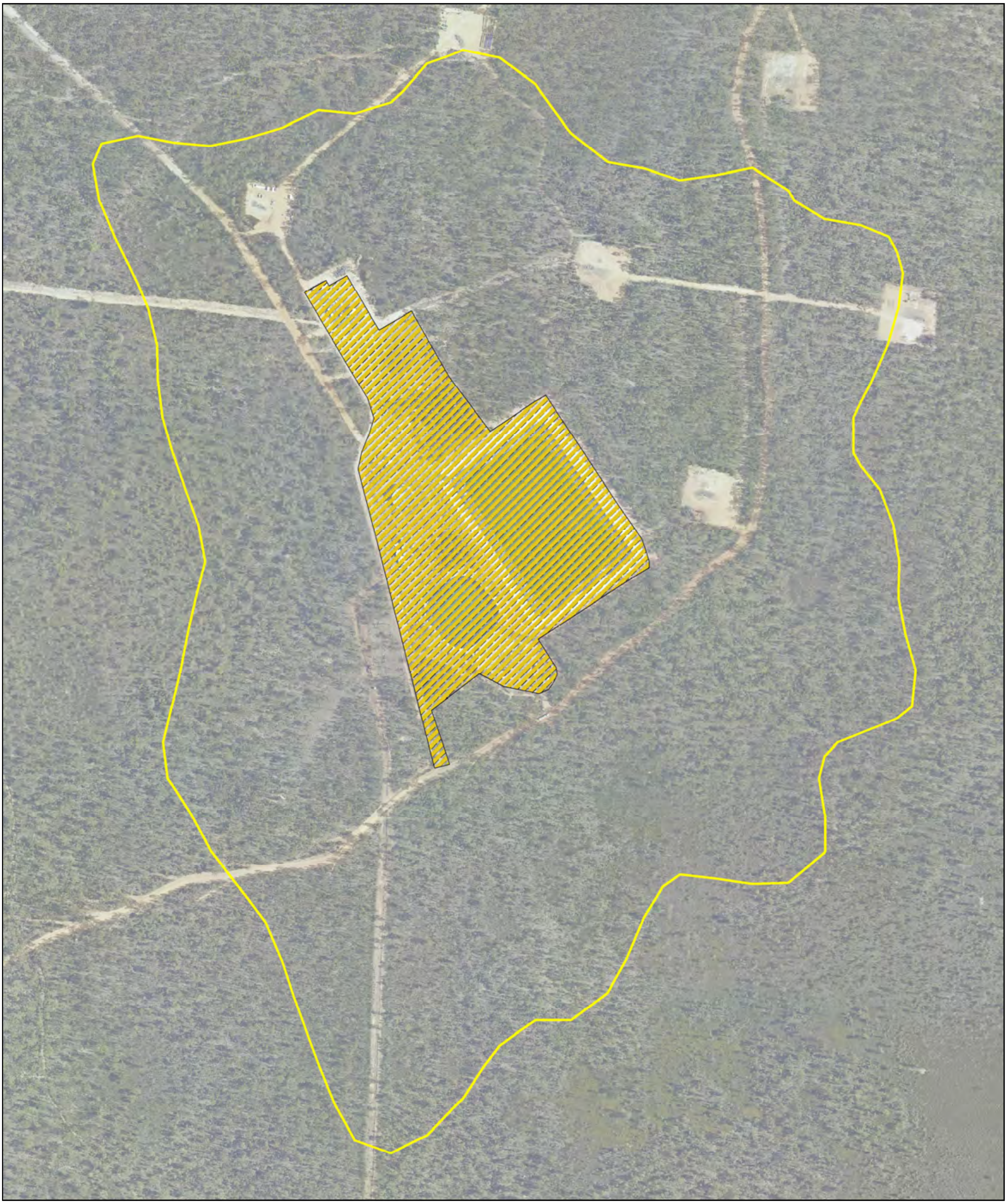
Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Created by: afoddy

As the construction footprint at the Leewood facility will move around the site as various infrastructure is developed, the assumed 500 metre by 500 metre construction area and its associated dust contours were relocated around the site to assess the impact at the nearest residences, i.e., receiver 216 (adjacent to the western boundary) and receiver 217 (adjacent to the eastern boundary). The assessment determined that daily concentrations of PM_{10} are expected to be below the air quality criterion of 50 µg/m^3 at receiver 216 during construction of the Brine Management Ponds in the southwest corner of the site. This is also expected to be a conservative estimate as the assumed construction footprint and associated dust emissions are expected to be less than that which has been modelled in this area.

The assessment of PM_{10} associated with dust emissions from the construction of the gas processing facility area adjacent to the eastern boundary of Leewood determined that the 24-hour average PM_{10} criterion is predicted to be exceeded at receiver 216 on one day per year (with a maximum cumulative concentration of 78 µg/m^3). The second highest daily PM_{10} concentration was determined to be considerably less and below the criterion at 47.8 µg/m^3. The highest daily concentration was determined to occur under relatively infrequent northwest to north-northwesterly winds below 3.5 m/s, until 6pm when the winds shifted to the north and north-northeast, remaining between 2.8 to 3.6 m/s. This prediction is considered to be conservative as the dust emission modelling methodology did not take into consideration a wind speed factor in the dust emission estimation and consequently a uniform dust emission was estimated for each hour of the year based on the area of construction. In addition to this, as a conservative estimate, plume depletion was not modelled.

In reality, the dust emissions will be a mix of wind speed dependent lift off from exposed surfaces and the handling of dusty materials. While the dust emission estimation did assume level 1 watering was applied, dust is unlikely to be lifted from exposed surfaces at such moderate winds, as that which were predicted on the day. Consequently, if the dust emissions were lower, the predicted concentration at receiver 217 would be expected to be lower. Factoring in plume depletion with the distance travelled would also reduce ground-level concentrations at receiver 217.

Notwithstanding the assumptions made in the modelling assessment, receiver 217 is located within the forest and surrounded by tall stands of trees. These trees are expected to provide a useful screen to disrupt the dispersion of dust by reducing wind speeds, increasing turbulence and further depleting plume concentrations through dust settling. Further application of dust management strategies on days when the wind blows at moderate to strong speeds toward nearby receivers will also help to mitigate dust impacts.



LEGEND
Bibblewindi
Sensitive receivers
50 µg/m³

0 0.05 0.1 0.2
Kilometers
Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
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Predicted maximum 24-hour average ground-level concentrations of PM10 for the Bibblewindi construction area, with background

Figure 8-3

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 140]

Level 15, 133 Castlereagh Street Sydney NSW 2000 T 61 2 9239 7100 F 61 2 9239 7199 E sydmail@ghd.com.au W www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Created by: afoddy

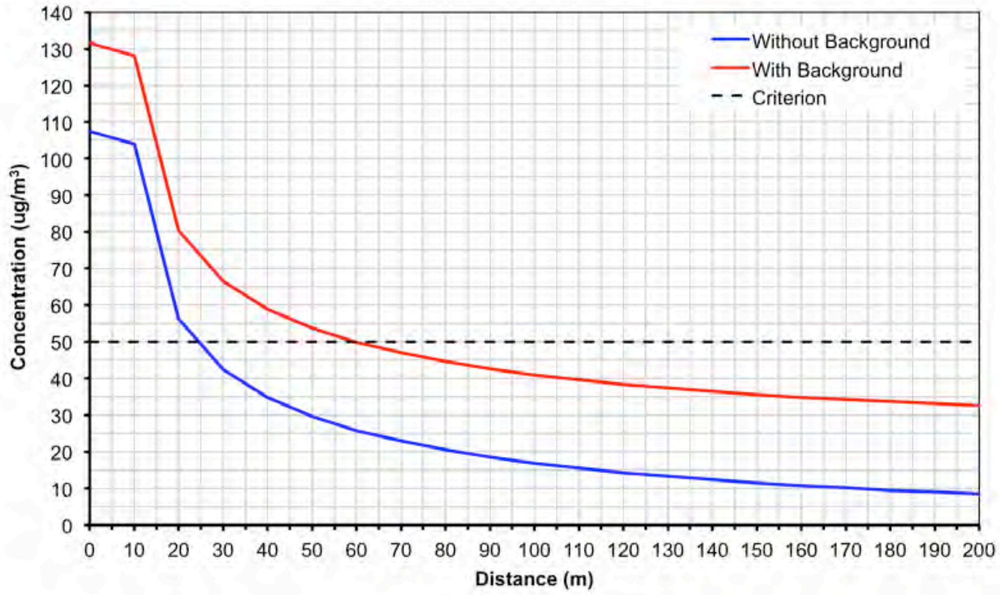


Figure 8-4 Daily PM_{10} concentration versus distance relationship from the boundary of the well pad construction area

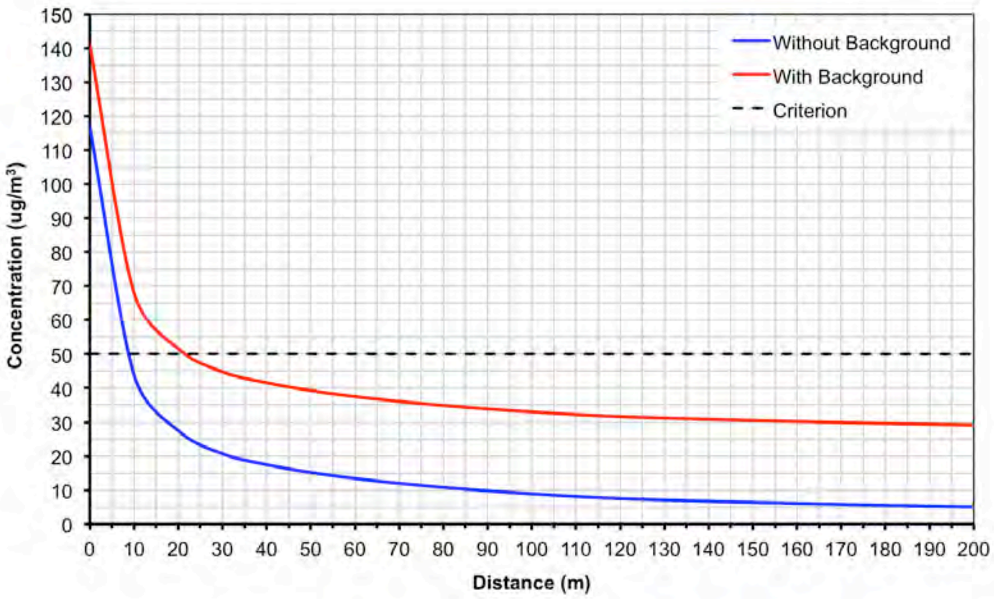


Figure 8-5 Daily PM_{10} concentration versus distance relationship from the boundary of the pipeline trenching and access track construction area

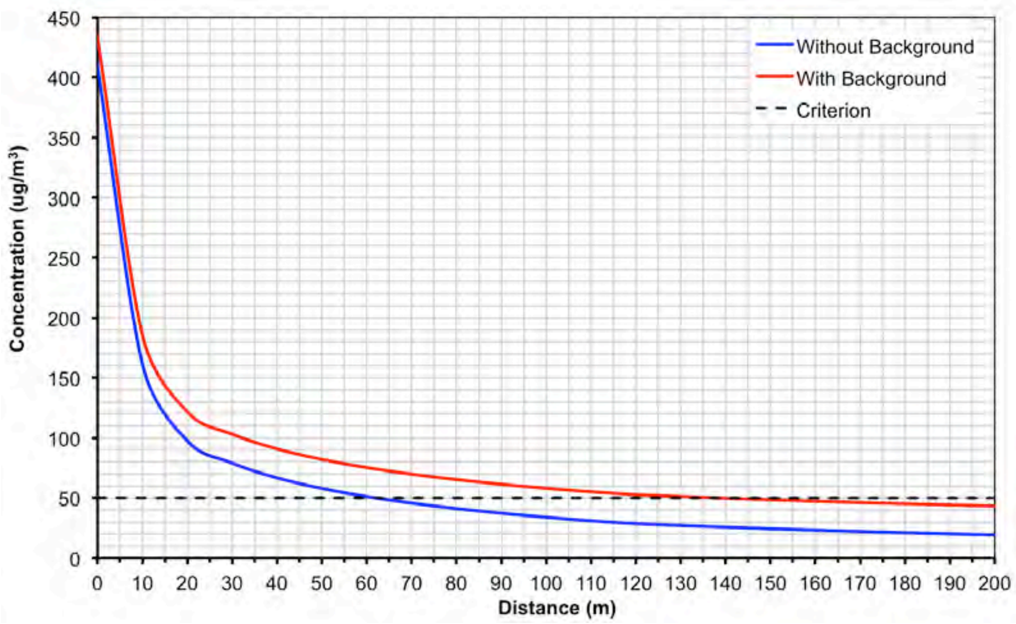


Figure 8-6 Daily PM_{10} concentration versus distance relationship from the boundary of a road construction area

Table 8-1 Separation distances by construction source due to daily PM_{10} emissions

Source	Distance at which criterion is reached - in isolation (m)	Distance at which criterion is reached - with background (m)
Well pad	30	60
Gas, water and electricity transmission pipeline trenches / access track	10	30
Access road	60	140

Table note: 24-hour average assessment criterion of PM_{10} is 50 µg/m^3.
Background 24-hour average PM_{10} concentration is 24.1 µg/m^3.

Construction dusts impacts of the Westport Accommodation Camp were not modelled for the impact assessment as the minimal ground disturbance and different construction methods were considered to generate significantly less dust emissions than that generated from other routine construction activities. In addition to this, the total area of disturbance is estimated to be only marginally larger than a well pad area. When applying a buffer distance for a well pad area to the accommodation camp, the area of potential impact is predicted to be within the surrounding fire protection zone. Consequently, no sensitive receptors are likely to be affected.

8.2 Assessment of operational phase air quality impacts

Nitrogen dioxide was considered to be the most important air pollutant in terms of the ratio between its emission rate and impact assessment criterion for the overall project due to the combustion of coal seam gas fuel in engines and boilers. The following section details the results of the air quality impact assessment for the following operating scenarios:

- Power supply option 1 – power generated at Leewood:
  - Routine conditions (Leewood), and
  - Non-routine conditions (Leewood and Bibblewindi).
- Power supply option 2 – power sourced from the national electricity grid:
  - Routine conditions (Leewood), and
  - Non-routine conditions (Leewood and Bibblewindi).
- Well pad power generation – power generated locally from gas or diesel-fired engines.
  - Routine conditions, and
  - Non-routine conditions.

The assessment has focused on the impacts around the Leewood and Bibblewindi facilities, as well as the separation distance required between well pads and sensitive receivers. This is due to these facilities being the focus of this environmental approval process. The Wilga Park Power Station is currently operating intermittently and under a separate environmental approval, up to approximately 16 MW_e of generation capacity. Notwithstanding this approval, nitrogen oxide emissions associated with Wilga Park's maximum licensed generation capacity of 40 MW_e have been used to determine background nitrogen dioxide concentrations to determine whether there are cumulative effects with project emissions on ground-level concentrations of nitrogen dioxide in sensitive receiver areas.

The assessment has determined that the significant separation distance of approximately 15 kilometres between Wilga Park and Leewood means the cumulative impact is predicted to be low. Consequently, the concentration contour isopleths and maximum pollutant concentrations presented in this report illustrate the ground level impact around Leewood and Bibblewindi only. The predicted incremental (i.e. the impact of the project's emissions in isolation) and cumulative (i.e. the project's emissions plus measured local background plus the impacts due to Wilga Park operating at maximum load (40 MW_e) ground level concentrations have both been presented and assessed. In accordance with the approach prescribed in the NSW Approved Methods (DEC, 2005), the cumulative impact is assessed against the ambient air quality criteria.

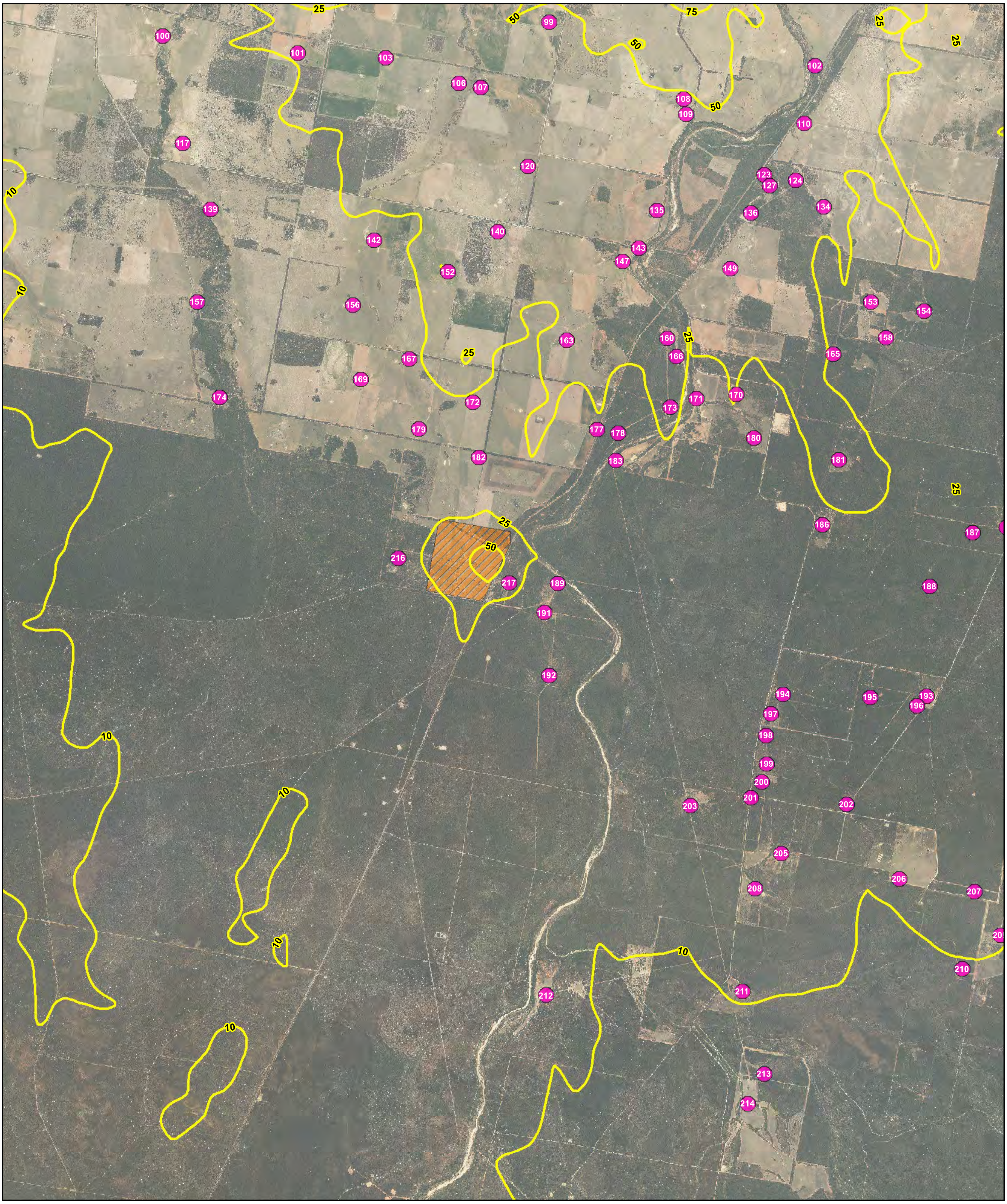
8.2.1 Power supply option 1 - routine operations

Leewood area

The predicted maximum 1-hour and annual average ground-level concentrations of nitrogen dioxide across the project area during routine operations are presented in isolation and with background air quality in Figure 8-7 to Figure 8-10, respectively. Predicted maximum ground-level concentrations of nitrogen dioxide and ozone beyond the Leewood boundary are also presented in isolation and with background in Table 8-2 and Table 8-3, respectively. Nitrogen dioxide concentration contours are based on actual engine nitrogen oxide emissions at a 100 per cent NO_2/NO_X ratio. Predicted maximum concentrations are also based on a 100 per cent NO_2/NO_X ratio. Ozone concentrations are based on 100 per cent conversion of nitrogen oxides to ozone.

The predicted maximum 1-hour average and 4-hour average ground-level concentrations of ozone in the Leewood area have been presented in Table 8-3. The predicted highest ground-level concentrations of carbon monoxide, PM_{10}, acrolein, formaldehyde and acetaldehyde for the relevant impact assessment criteria in the Leewood area are presented in Table 8-4.

Based on the air pollutant hierarchy for the Leewood operations, the top five minor pollutants after nitrogen dioxide and ozone for the engines and boilers have also been assessed. The predicted highest ground-level concentrations of carbon monoxide, PM_{10}, acrolein, formaldehyde and acetaldehyde for the relevant impact assessment criteria beyond the boundary, for each pollutant in isolation, are presented in Table 8-4.



LEGEND

Leewood

Sensitive receivers

NO_2 concentration µg/m³ (1 hour average)

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

Narrabri Gas Project
EIS Technical Appendix Air Quality

Predicted maximum incremental 1-hour average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 1 routine operations, no background

Job Number	21-22463
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Date	Feb 2015

Figure 8-7

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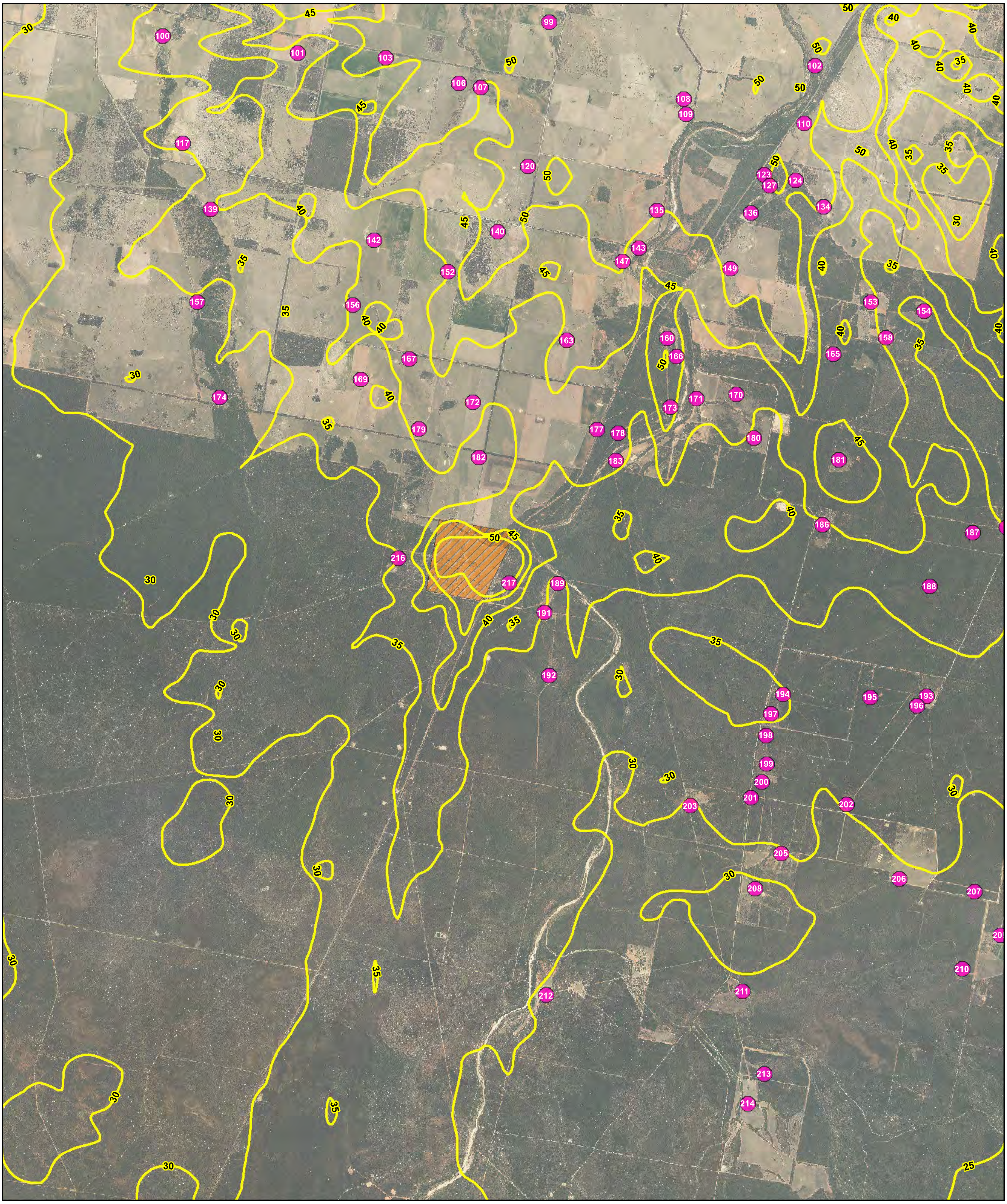
Level 15, 133 Castlereagh Street Sydney NSW 2000 T 61 2 9239 7100 F 61 2 9239 7199 E sydmail@ghd.com.au W www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy



LEGEND

Leewood

Sensitive receivers

NO_2 concentration µg/m^3 (1 hour average)

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

Narrabri Gas Project
EIS Technical Appendix Air Quality

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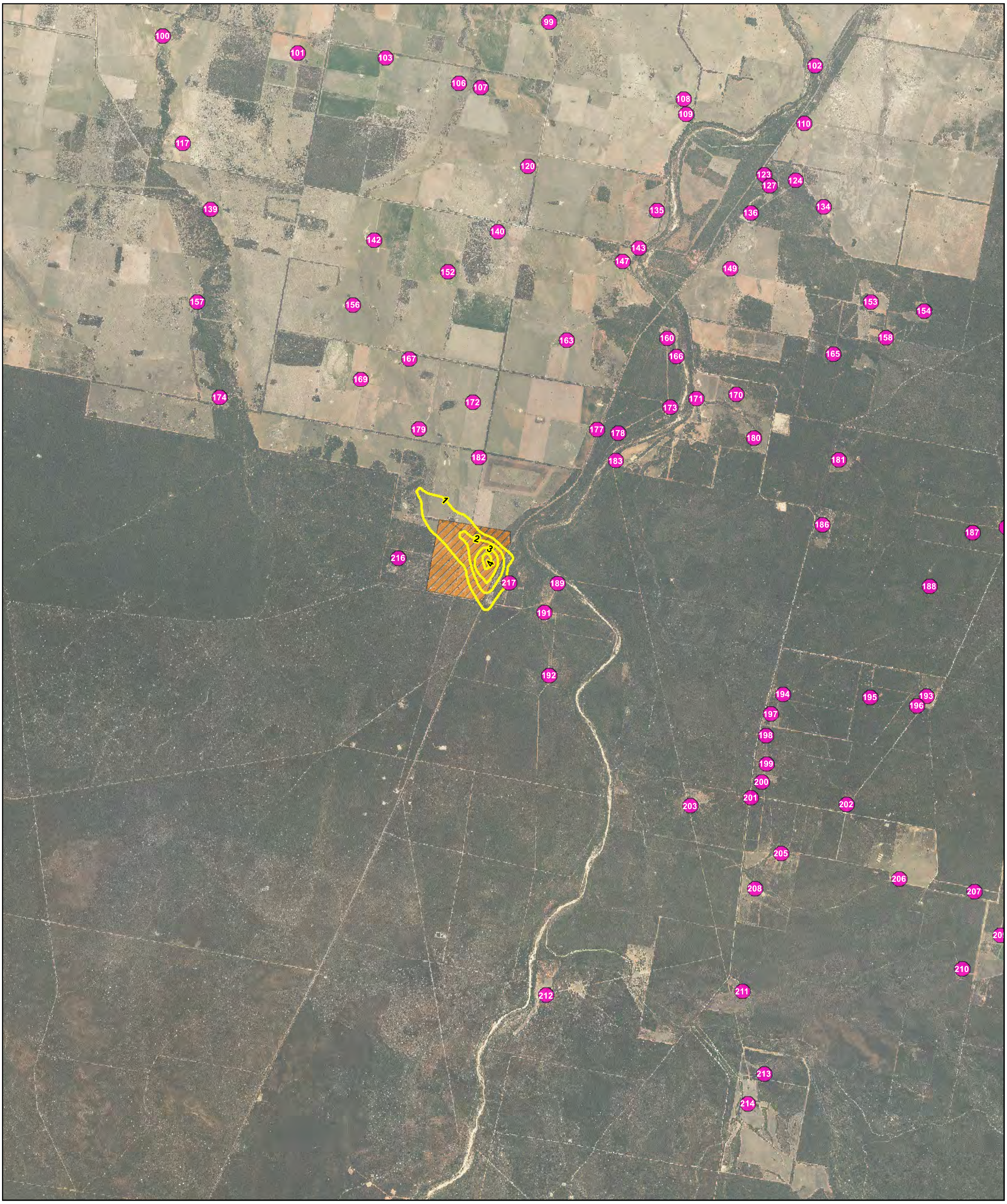
Predicted maximum cumulative 1-hour average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 1 routine operations, with background

Figure 8-8

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 157]

Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy



LEGEND

Leewood

Sensitive receivers

NO_2 concentration µg/m^3(Annual average)

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

Narrabri Gas Project
EIS Technical Appendix Air Quality

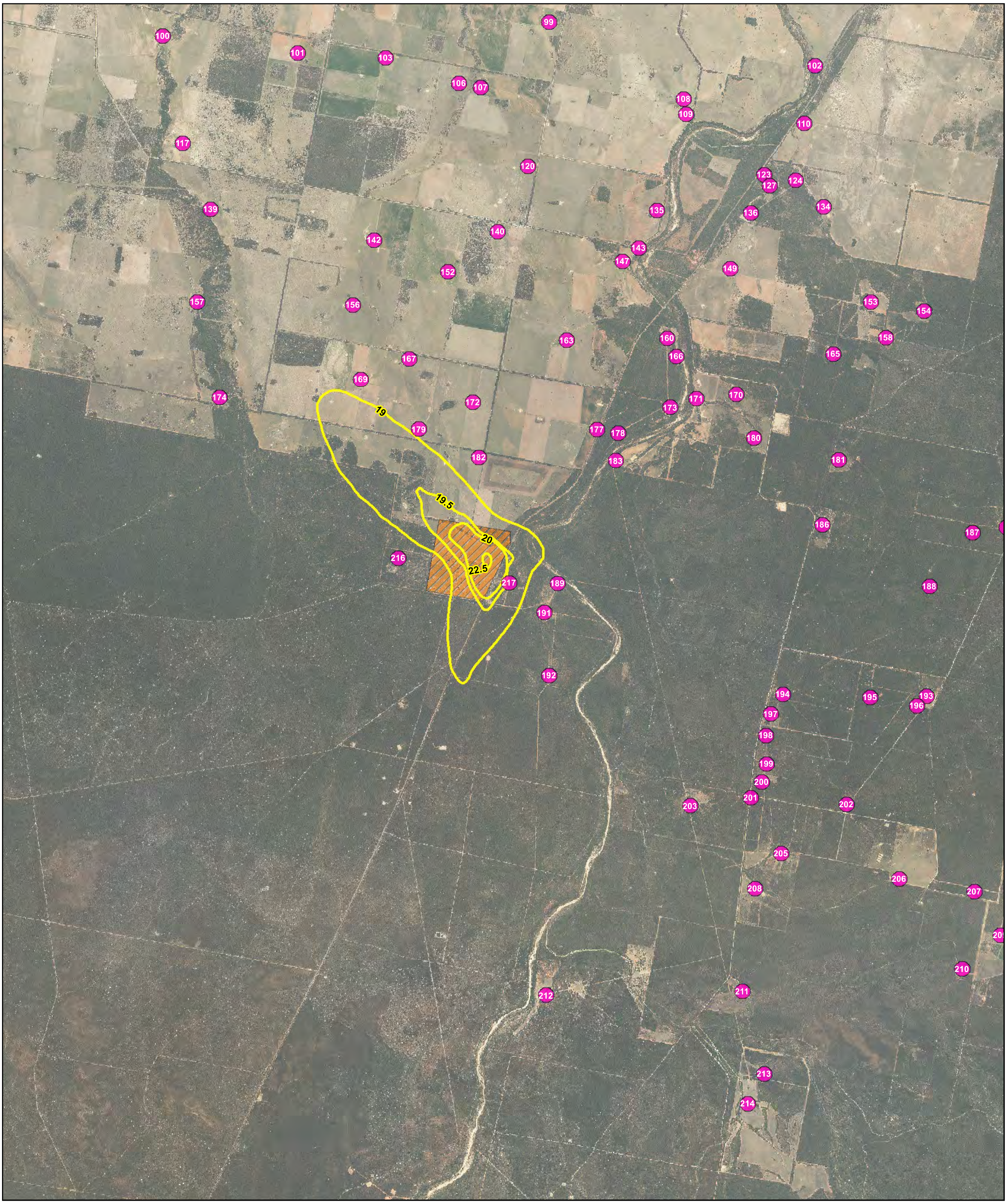
Predicted incremental annual average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 1 routine operations, no background

Job Number	21-22463
Revision	A
Date	Feb 2015

Figure 8-9

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 158]

Level 15, 133 Castlereagh Street Sydney NSW 2000 T 61 2 9239 7100 F 61 2 9239 7199 E sydmail@ghd.com.au W www.ghd.com.au



LEGEND

Leewood

NO_2 concentration µg/m^3(Annual average)

Sensitive receivers

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

Narrabri Gas Project
EIS Technical Appendix Air Quality

Predicted cumulative annual average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 1 routine operations, with background

Job Number 21-22463
Revision A
Date Feb 2015

Figure 8-10

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 159]

Level 15, 133 Castlereagh Street Sydney NSW 2000 T 61 2 9239 7100 F 61 2 9239 7199 E sydmail@ghd.com.au W www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy

Table 8-2 Predicted maximum ground-level nitrogen dioxide concentrations beyond the boundary at Leewood

Emission data source	Averaging period	Impact assessment criterion (µg/m³)	Concentration, in isolation[1] (µg/m³)	Percent of criterion[3] (%)	Concentration, with background[2] (µg/m³)	Percent of criterion[3] (%)
Nominal engine and boiler data	1-hour	246	51	21	70	28
NSW emission standard	1-hour	246	98	40	117	47
Nominal engine and boiler data	Annual	62	3	4	21	34
NSW emission standard	Annual	62	4	7	23	37

Table note: [1] The concentration in isolation depicts the predicted contribution of the project to ambient air quality.
[2] The concentration with background depicts the predicted worst case state of the ambient air quality.
[3] The percent of criterion presents the predicted ambient air quality in relation to the criterion for the protection human health.

Table 8-3 Predicted maximum ground-level ozone concentrations beyond the boundary at Leewood

Emission data source	Averaging period	Impact assessment criterion (µg/m³)	Concentration, in isolation[1] (µg/m³)	Percent of criterion[3] (%)	Concentration, with background[2] (µg/m³)	Percent of criterion[3] (%)
Nominal engine and boiler data	1-hour	214	53	25	127	60
NSW emission standard	1-hour	214	102	48	176	82
Nominal engine and boiler data	4-hour	171	28	25	102	48
NSW emission standard	4-hour	171	53	13	127	60

Table note: [1] The concentration in isolation depicts the predicted contribution of the project to ambient air quality.
[2] The concentration with background depicts the predicted worst case state of the ambient air quality.
[3] The percent of criterion presents the predicted ambient air quality in relation to the criterion for the protection human health.

Table 8-4 Predicted maximum incremental ground-level pollutant concentrations beyond the boundary for minor pollutants

<table>
<tr><th>Air pollutant</th><th>Emission data source</th><th>Averaging period</th><th>Impact assessment criterion (µg/m³)</th><th>Concentration, in isolation (µg/m³)</th><th>Percent of criterion (%)</th></tr>
<tr><td>Acrolein</td><td>AP-42</td><td>1-hour</td><td>0.42</td><td>0.3</td><td>70</td></tr>
<tr><td>Formaldehyde</td><td>AP-42</td><td>1-hour</td><td>20</td><td>1.6</td><td>8</td></tr>
<tr><td>Acetaldehyde</td><td>AP-42</td><td>1-hour</td><td>42</td><td>0.2</td><td>0.6</td></tr>
<tr><td rowspan="2">Carbon monoxide</td><td>AP-42</td><td rowspan="2">1-hour</td><td rowspan="2">30,000</td><td>305</td><td>1</td></tr>
<tr><td>NSW emission standard</td><td>11</td><td>0.1</td></tr>
<tr><td rowspan="2">Carbon monoxide</td><td>AP-42</td><td rowspan="2">8-hour</td><td rowspan="2">10,000</td><td>87</td><td>0.3</td></tr>
<tr><td>NSW emission standard</td><td>3.2</td><td>0.03</td></tr>
<tr><td rowspan="2">PM_{10}</td><td rowspan="2">Engine data</td><td>24-hour</td><td>50</td><td>0.9</td><td>0.1</td></tr>
<tr><td>Annual</td><td>30</td><td>0.2</td><td>0.01</td></tr>
<tr><td>Cadmium</td><td>NPI</td><td>1-hour</td><td>0.018</td><td>5.59E-04</td><td>3.1</td></tr>
<tr><td>Nickel</td><td>NPI</td><td>1-hour</td><td>0.18</td><td>1.06E-03</td><td>0.6</td></tr>
</table>

Table note: Carbon monoxide and PM_{10} results are based on the 100^{th} percentile value. Acrolein, formaldehyde and acetaldehyde concentrations based on the 99.9^{th} percentile, as per the Approved Methods (DEC 2005).
The predicted impacts of carbon monoxide and PM_{10} are presented in isolation to illustrate the negligible incremental impact. The predicted impacts of acrolein, formaldehyde, acetaldehyde, cadmium and nickel are presented in isolation as per the Approved Methods requirement.

The results indicate that there are no exceedances of the air quality impact assessment criteria predicted beyond the Leewood facility boundary during routine operations for power supply option 1. All predicted ground-level pollutant concentrations are well below the assessment criteria.

8.2.2 Power supply option 1 - non-routine operations

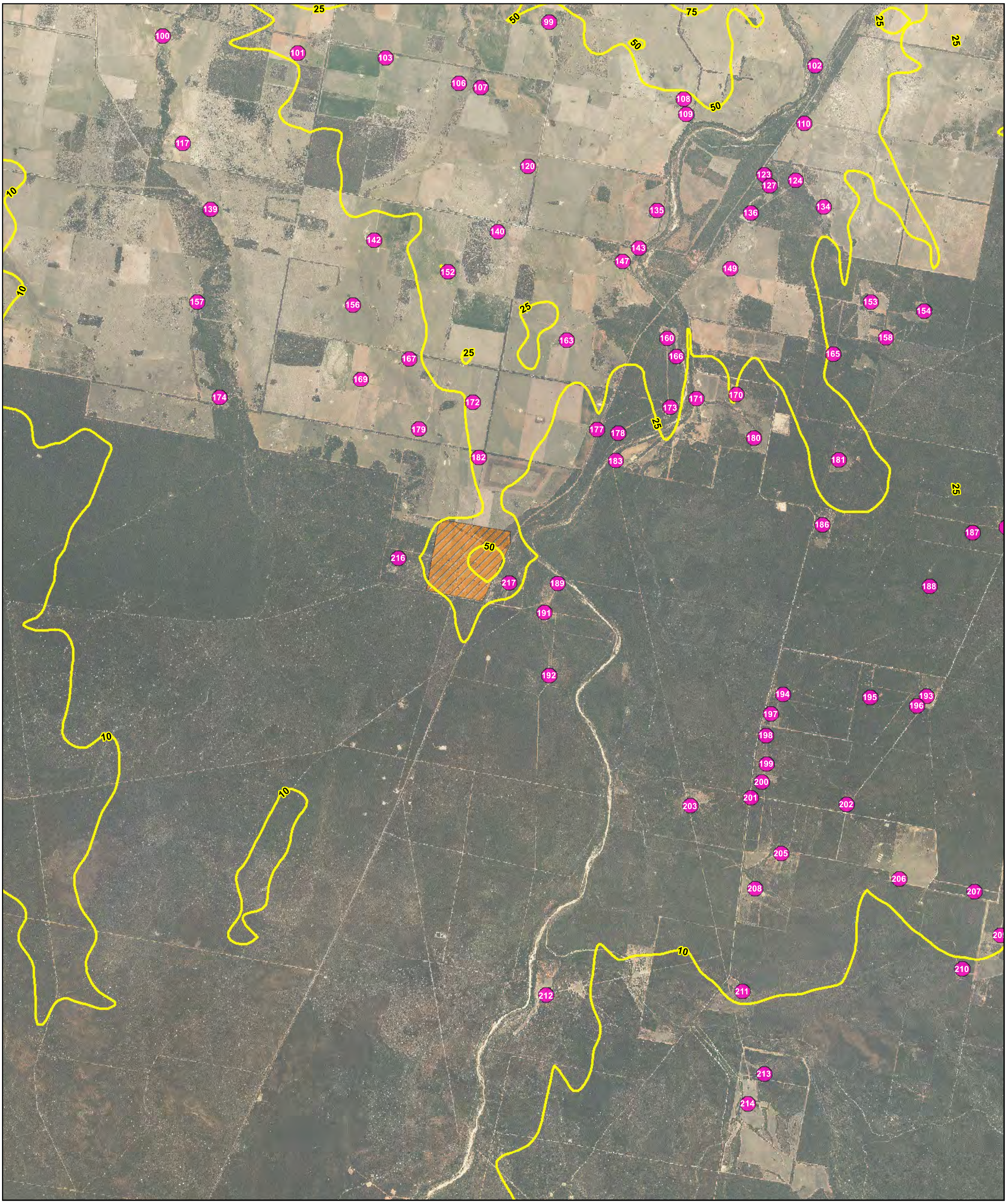
Leewood area

The predicted maximum 1-hour average ground-level concentrations of nitrogen dioxide across the project for non-routine flare operation is presented in Figure 8-11. The assessment of non-routine flaring at Leewood is assessed with the power plant and hot oil boilers operating simultaneously. This is considered to be a worst case scenario, as not all gas-fired engines and boilers would be expected to be operating during operations that require flaring beyond the minimal flow. Predicted maximum ground-level pollutant concentrations beyond the site boundaries at Leewood during flaring are presented in Table 8-5.

Table 8-5 Predicted maximum incremental 1-hour average ground-level pollutant concentrations beyond the boundary at Leewood during flaring

Pollutant	Concentration, in isolation (µg/m^3)	Criterion (µg/m^3)	Percent of criterion (%)
Nitrogen dioxide	51	246	21
Carbon monoxide	146	30,000	0.5
Acetylene	3	26,600	0.01
Ethane	4	12,000	0.03
Propane	4	18,000	0.02
Propylene	13	8,750	0.1

Table note: Predicted ground-level concentrations of nitrogen dioxide and carbon monoxide for total impact.



LEGEND

Leewood

Sensitive receivers

NO_2 concentration µg/m^3(1 hour average)

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

Narrabri Gas Project
EIS Technical Appendix Air Quality

Predicted 1-hour average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 1 non-routine flare operations, no background

Job Number	21-22463
Revision	A
Date	Feb 2015

Figure 8-11

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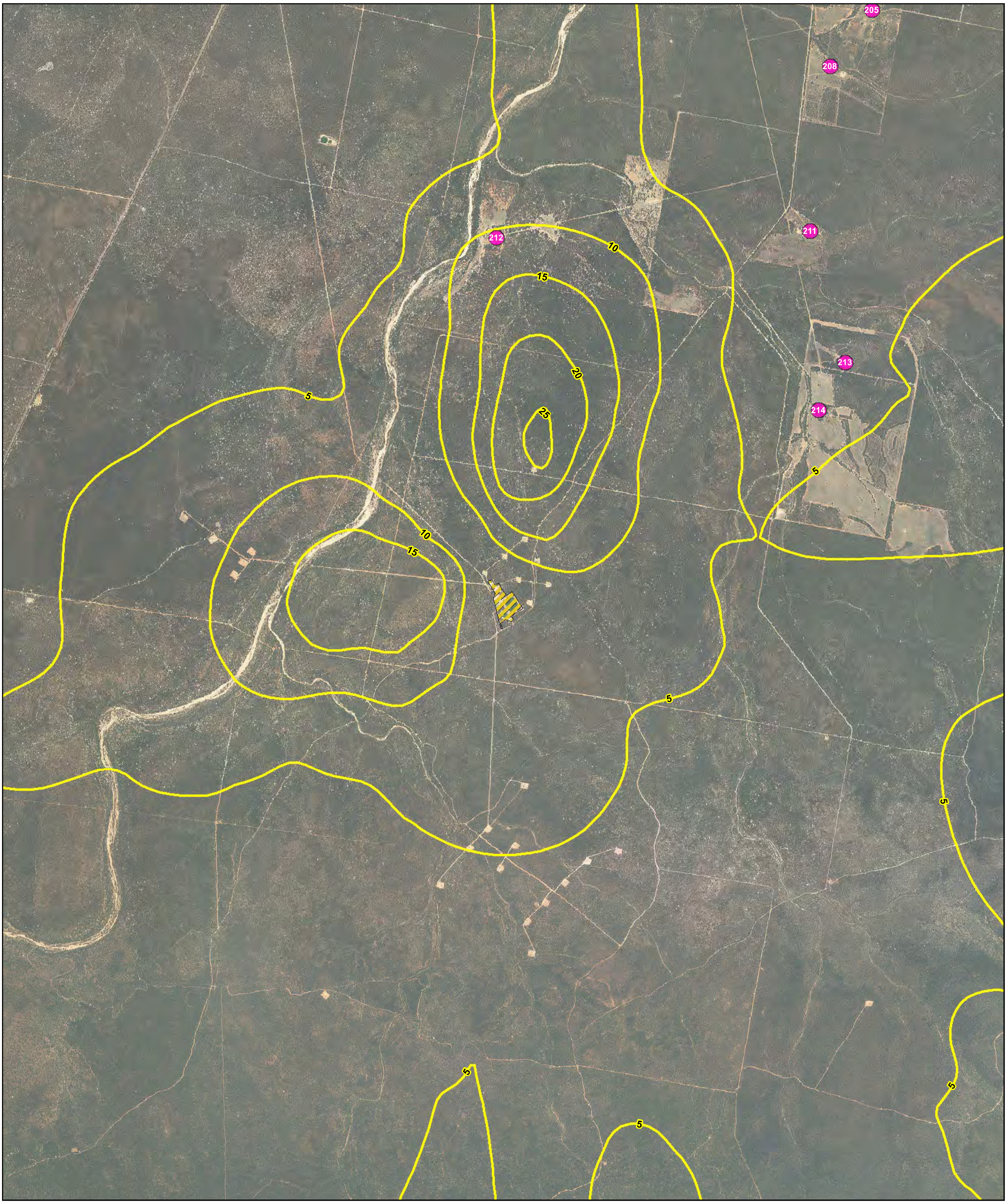
Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy

The results indicate that there are no exceedances of the air quality impact assessment criteria predicted beyond the Leewood facility boundary during non-routine operations. In addition to this, the contribution of the flare to ground-level concentrations of all pollutants is predicted to be negligible. Ground-level concentrations of all pollutants associated with emissions from the power generation plant, hot oil boilers and flare at Leewood are predicted to be well below the ambient air quality impact assessment criteria.

Bibblewindi area

The predicted maximum 1-hour average ground-level concentrations of nitrogen dioxide across the project area during non-routine flare operation is presented in Figure 8-12. Predicted maximum ground-level pollutant concentrations beyond the site boundaries at Bibblewindi during flaring are presented in Table 8-6.

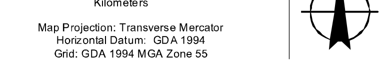


LEGEND

Bibblewindi

NO_2 concentration µg/m^3(1 hour average)

Sensitive receivers



Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

Narrabri Gas Project
EIS Technical Appendix Air Quality

Predicted 1-hour average ground-level concentrations of nitrogen dioxide around Bibblewindi for power supply option 1 non-routine flare operations, no background

Job Number	21-22463
Revision	A
Date	Feb 2015

Figure 8-12

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 161]

Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy

Table 8-6 Predicted maximum incremental 1-hour average ground-level pollutant concentrations beyond the boundary at Bibblewindi during flaring

Pollutant	Concentration, In isolation (µg/m³)	Criterion (µg/m³)	Percent of criterion (%)
Nitrogen dioxide	25	246	10.2
Carbon monoxide	135	30,000	0.5
Acetylene	2.4	26,600	0.01
Ethane	3.8	12,000	0.03
Propane	3.4	18,000	0.02
Propylene	12.0	8,750	0.1

Table note: Predicted ground-level concentrations of nitrogen dioxide and carbon monoxide for total impact, i.e. flare emissions only due to no engines at Bibblewindi.

The results indicate that ground-level concentrations of all pollutants emitted by the flare at Bibblewindi are predicted to be negligible and well below the ambient air quality impact assessment criteria.

8.2.3 Power supply option 2 - routine operations

Leewood area

The predicted maximum 1-hour and annual average ground-level concentrations of nitrogen dioxide across the project area during routine operations for power supply option 2 are presented in isolation and with background in Figure 8-13 to Figure 8-16, respectively. Predicted maximum 1-hour and annual average ground-level concentrations of nitrogen dioxide beyond the site boundaries at Leewood are presented in Table 8-7. Predicted maximum 1-hour and 4-hour average ground-level concentrations of ozone beyond the site boundaries at Leewood are presented in Table 8-8.

Table 8-7 Predicted maximum ground-level nitrogen dioxide concentrations beyond the boundary

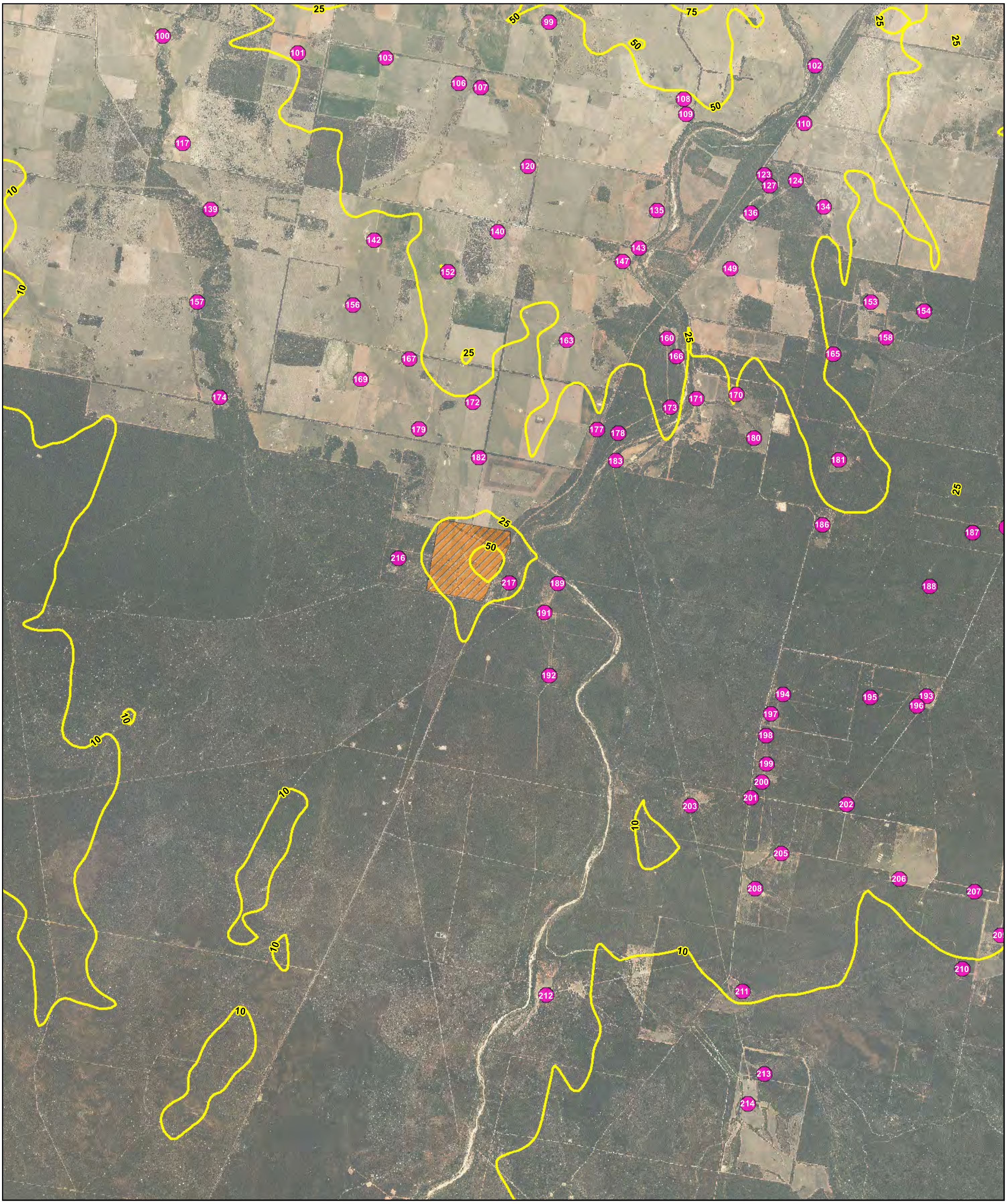
Emission data source	Averaging period	Impact assessment criterion (µg/m³)	Concentration, in isolation[1] (µg/m³)	Percent of criterion[3] (%)	Concentration, with background[2] (µg/m³)	Percent of criterion[3] (%)
Nominal boiler data	1-hour	246	51	21	70	28
NSW emission standard	1-hour	246	98	40	117	47
Nominal boiler data	Annual	62	3	4	21	34
NSW emission standard	Annual	62	4	7	23	37

Table note: [1] The concentration in isolation depicts the predicted contribution of the project to ambient air quality.
[2] The concentration with background depicts the predicted worst case state of the ambient air quality.
[3] The per cent of criterion presents the predicted ambient air quality in relation to the criterion for the protection human health.

Table 8-8 Predicted maximum ground-level ozone concentrations beyond the boundary

Emission data source	Averaging period	Impact assessment criterion (μg/m³)	Concentration, in isolation[1] (μg/m³)	Percent of criterion[3] (%)	Concentration, with background[2] (μg/m³)	Percent of criterion[3] (%)
Nominal boiler data	1-hour	214	53	25	127	60
NSW emission standard	1-hour	214	102	48	176	82
Nominal boiler data	4-hour	171	28	25	102	48
NSW emission standard	4-hour	171	53	13	127	60

Table note: [1] The concentration in isolation depicts the predicted contribution of the project to ambient air quality.
[2] The concentration with background depicts the predicted worst case state of the ambient air quality.
[3] The per cent of criterion presents the predicted ambient air quality in relation to the criterion for the protection human health.



LEGEND

Leewood

NO_2 concentration µg/m^3(1 hour average)

Sensitive receivers

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Predicted maximum incremental 1-hour average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 2 routine operations, no background

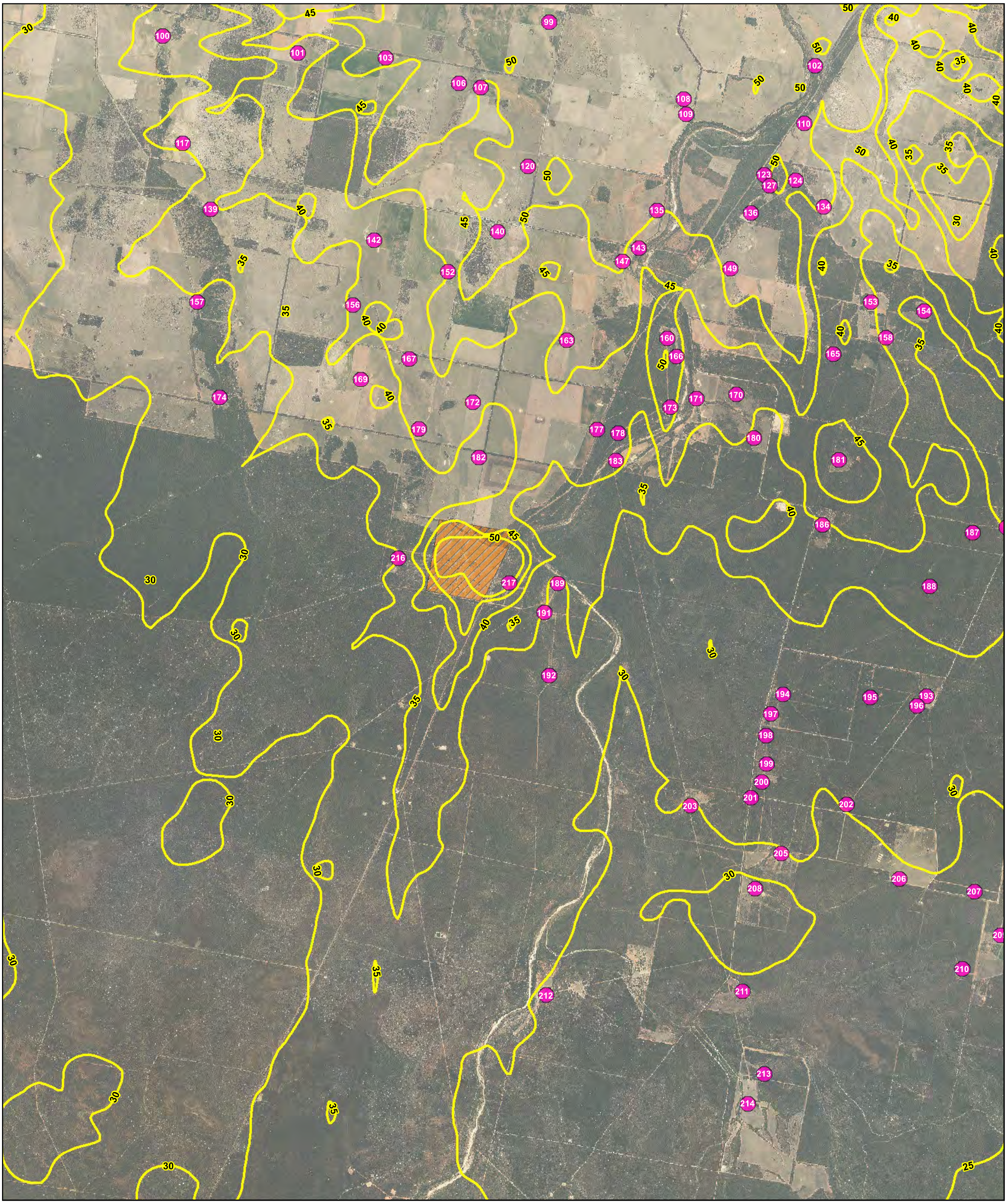
Job Number	21-22463
Revision	A
Date	Feb 2015

Figure 8-13

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 162]

Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy

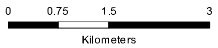


LEGEND

Leewood

NO$_2$ concentration µg/m^3(1 hour average)

Sensitive receivers



Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

Narrabri Gas Project
EIS Technical Appendix Air Quality

Job Number 21-22463
Revision A
Date Feb 2015

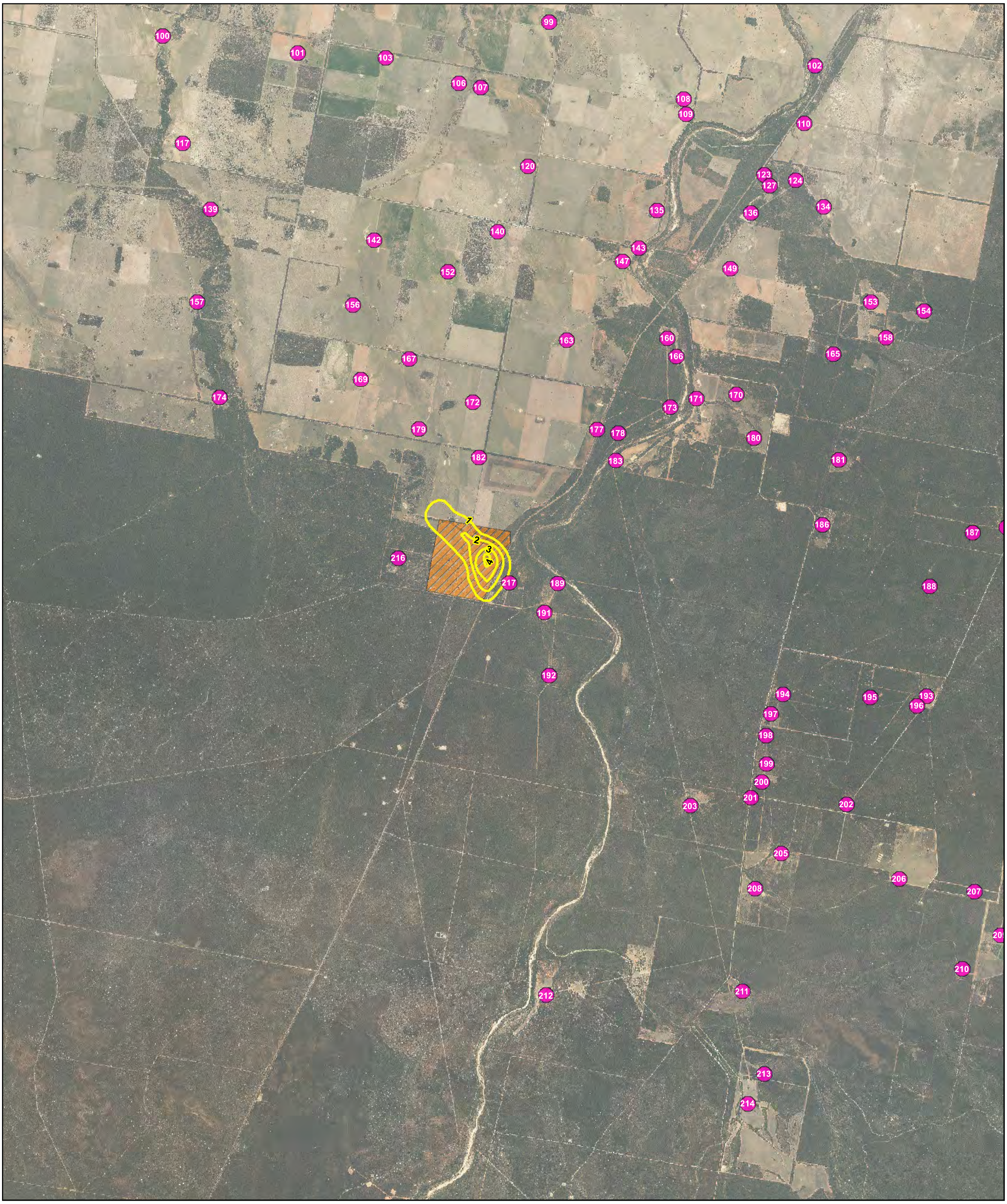
Predicted maximum incremental 1-hour average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 2 routine operations, with background

Figure 8-14

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 163]

Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy



LEGEND

Leewood

Sensitive receivers

NO_2 concentration µg/m^3(Annual average)

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Predicted incremental annual average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 2 routine operations, no background

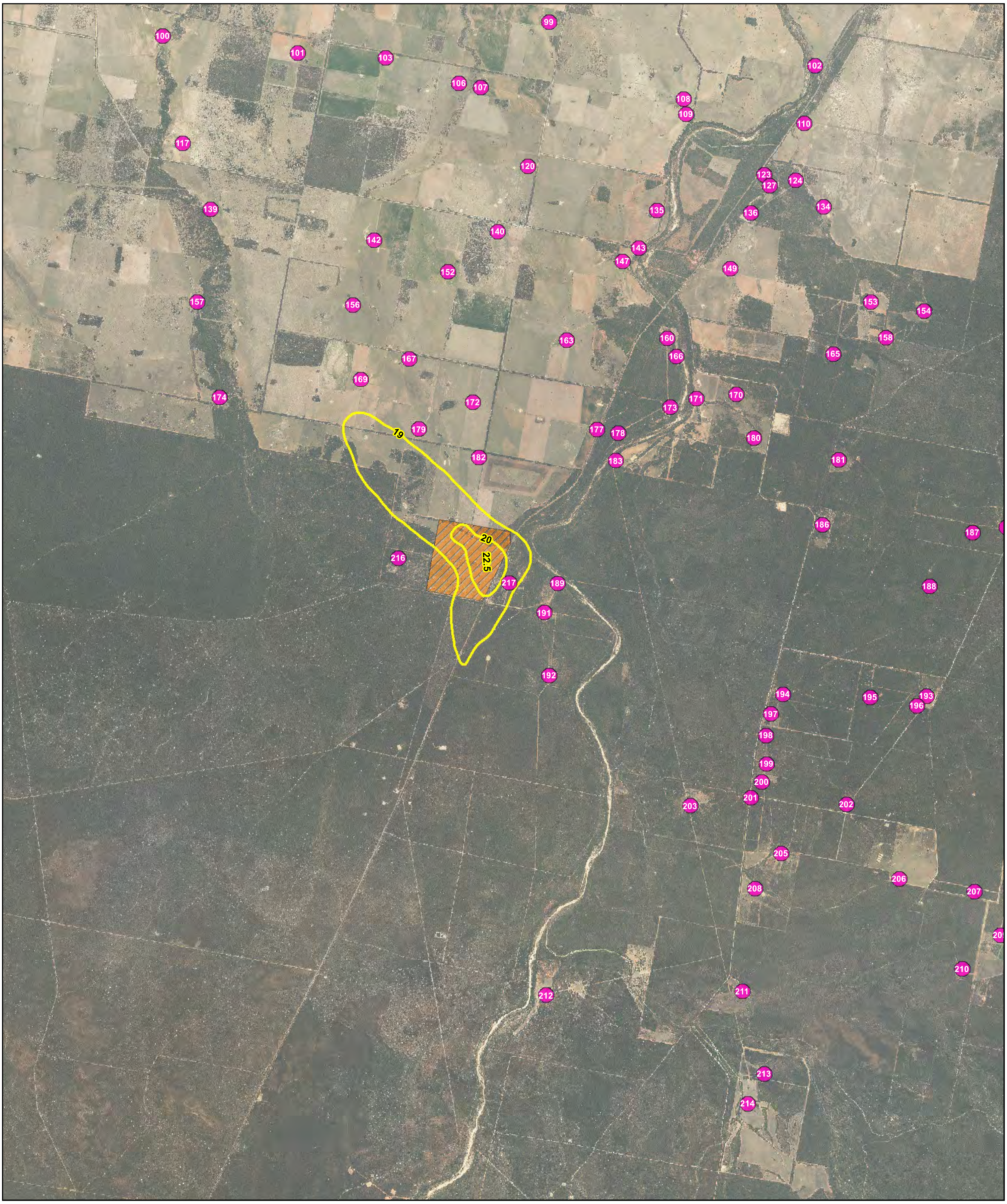
Job Number	21-22463
Revision	A
Date	Feb 2015

Figure 8-15

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 164]

Level 15, 133 Castlereagh Street Sydney NSW 2000 T 61 2 9239 7100 F 61 2 9239 7199 E sydmail@ghd.com.au W www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy



LEGEND

Leewood

Sensitive receivers

NO_2 concentration μg/m^3(Annual average)

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Job Number	21-22463
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Date	Feb 2015

Predicted incremental annual average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 2 routine operations, with background

Figure 8-16

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 165]

Level 15, 133 Castlereagh Street Sydney NSW 2000 **T** 61 2 9239 7100 **F** 61 2 9239 7199 **E** sydmail@ghd.com.au **W** www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy

The results indicate that there are no exceedances of the air quality impact assessment criteria predicted beyond the Leewood facility boundary during routine operations for power supply option 2. All predicted ground-level pollutant concentrations are well below the assessment criteria.

The results also indicate that the location of the maximum ground-level pollutant concentrations for the gas-fired power plant generators is in a very different location to that of the gas-fired hot oil boilers beyond the Leewood site boundary. This is due to significant differences in the source configuration, emission rates, plume buoyancy and dispersion characteristics of the two sources. As a result, there is no difference in the maximum ground-level concentrations of nitrogen dioxide between the power supply options due to the dominant ground level contribution of the boiler emissions which feature in both scenarios.

Bibblewindi area

The impact to air quality at Bibblewindi associated with the power supply option 2 routine operating scenario is expected to be the same as that during the option 1 scenario due to the operation of similar emission sources.

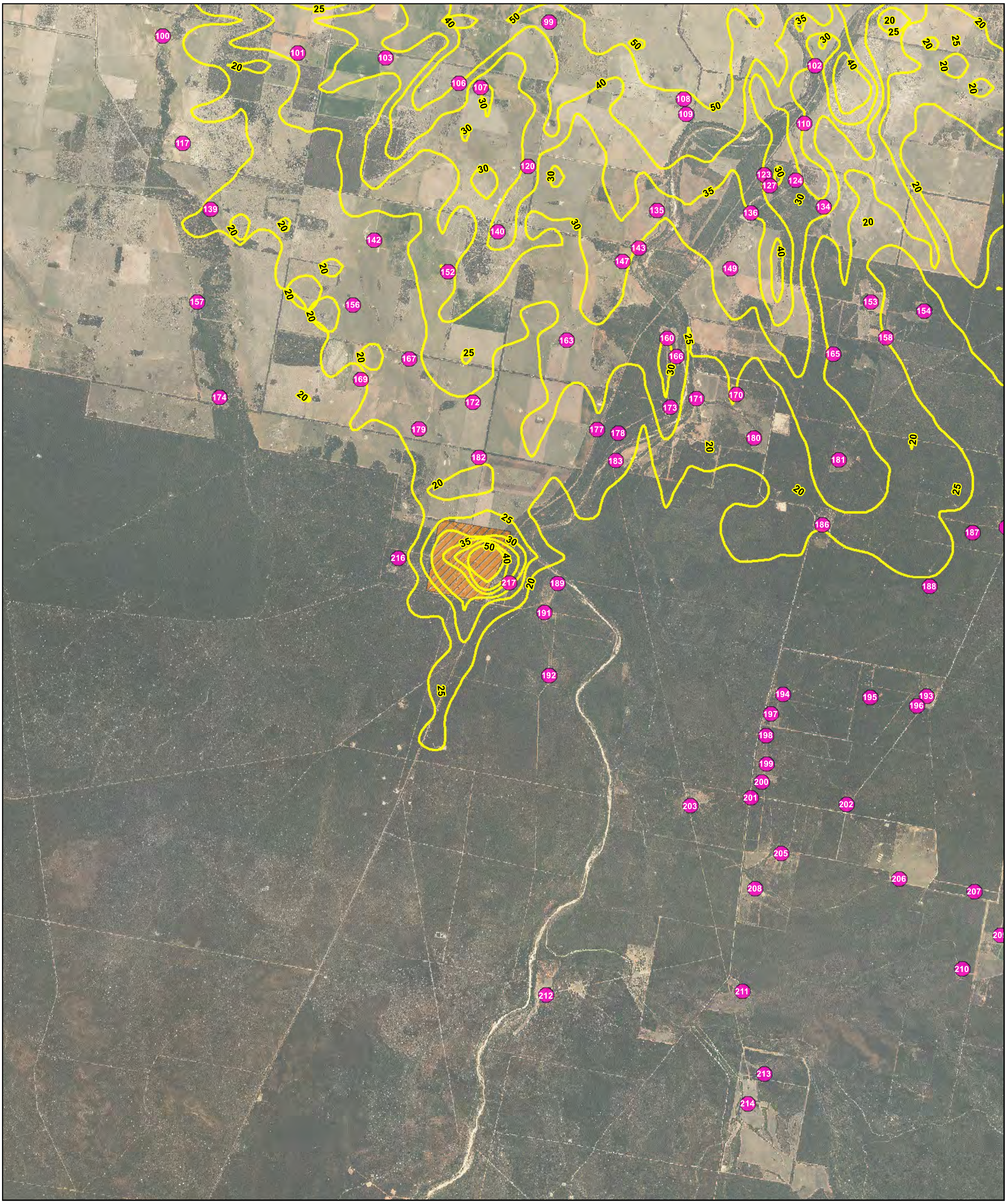
8.2.4 Power supply option 2 – non-routine operations

Leewood area

The predicted maximum 1-hour average ground-level concentrations of nitrogen dioxide across the project area during non-routine operations are presented in isolation in Figure 8-17. The assessment of non-routine flaring at Leewood is assessed with the hot oil boilers only operating simultaneously. This is considered to be a worst case scenario, as not all gas-fired boilers would be expected to be operating during an emergency flare event. Predicted maximum ground-level pollutant concentrations beyond the site boundaries at Leewood during flaring are presented in Table 8-9.

Table 8-9 Predicted maximum incremental 1-hour average ground-level pollutant concentrations beyond the boundary at Leewood during flaring

Pollutant	Concentration, in isolation (µg/m^3)	Criterion (µg/m^3)	Percent of criterion (%)
Nitrogen dioxide	51	246	21
Carbon monoxide	141	30,000	0.5
Acetylene	3	26,600	0.01
Ethane	4	12,000	0.03
Propane	4	18,000	0.02
Propylene	13	8,750	0.1



LEGEND

Leewood

Sensitive receivers

NO_2 concentration µg/m^3(1 hour average)

0 0.75 1.5 3

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Narrabri Gas Project
EIS Technical Appendix Air Quality

Predicted 1-hour average ground-level concentrations of nitrogen dioxide around Leewood for power supply option 2 non-routine flare operations, no background

Job Number	21-22463
Revision	A
Date	Feb 2015

Figure 8-17

G:\21\22463\GIS\Maps\21_22463_KBMAIR2.mxd [KBM: 166]

Level 15, 133 Castlereagh Street Sydney NSW 2000 T 61 2 9239 7100 F 61 2 9239 7199 E sydmail@ghd.com.au W www.ghd.com.au

Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Geoscience Australia: Topographic Base Map - 2014. Created by: afoddy

Bibblewindi area

The impact to air quality at Bibblewindi associated with the power supply option 2 non-routine operating scenario is expected to be the same as that during the option 1 scenario due to the operation of similar emission sources.

8.2.5 Well pad power generation – routine operations

The assessment of well pad generator engine nitrogen dioxide emissions is presented as concentration versus distance graphs in Figure 8-18 to Figure 8-21. The assessment is based on gas and diesel-fired engines at the NSW emission concentration standard limit and engine technical specifications or NPI emission factors.

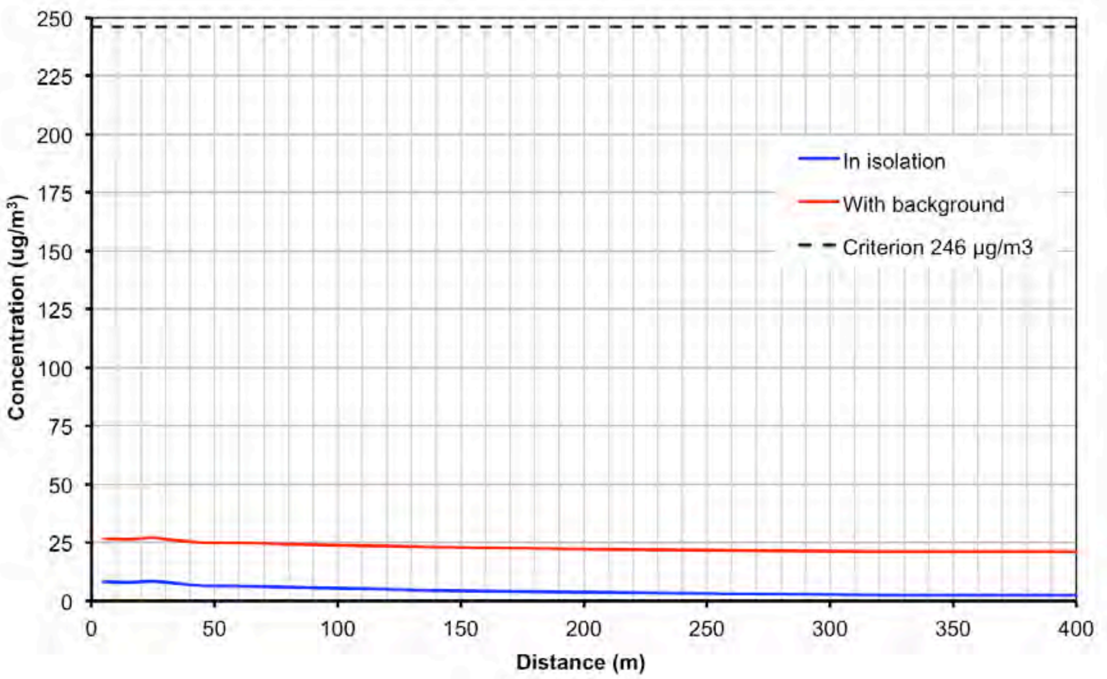


Figure 8-18 Concentration versus distance relationship for the 1-hour average of nitrogen dioxide from the stack of a gas engine at the well pad with emissions based on the nominal engine data

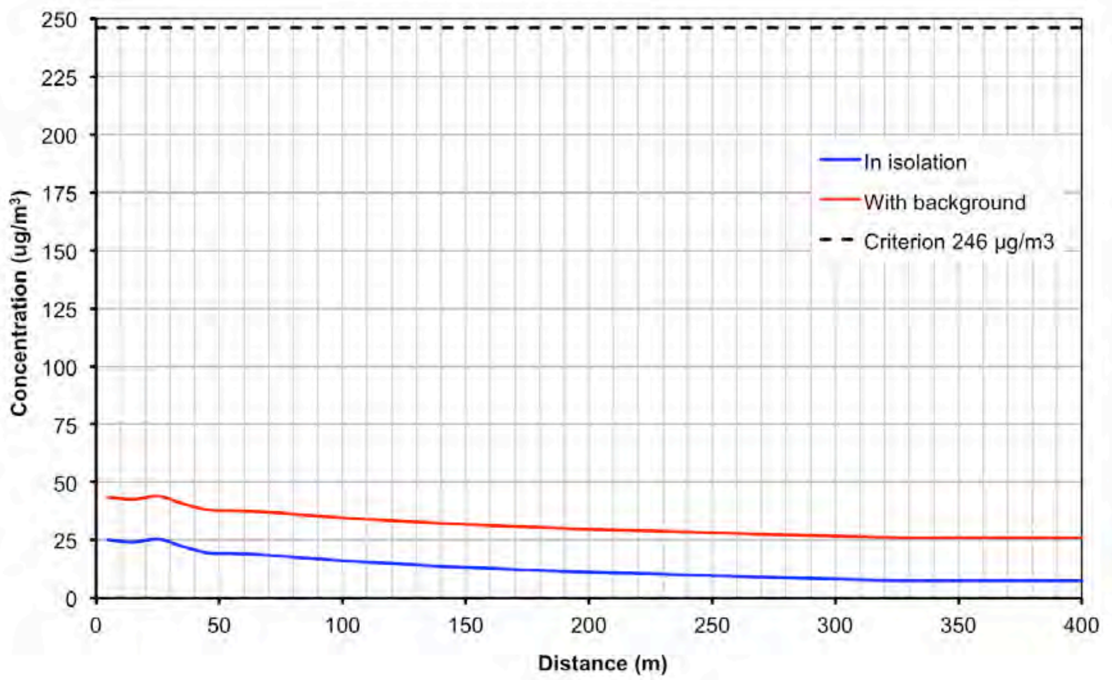


Figure 8-19 Concentration versus distance relationship for the 1-hour average of nitrogen dioxide from the stack of a gas engine at the well pad with emissions based on the NSW emission standards

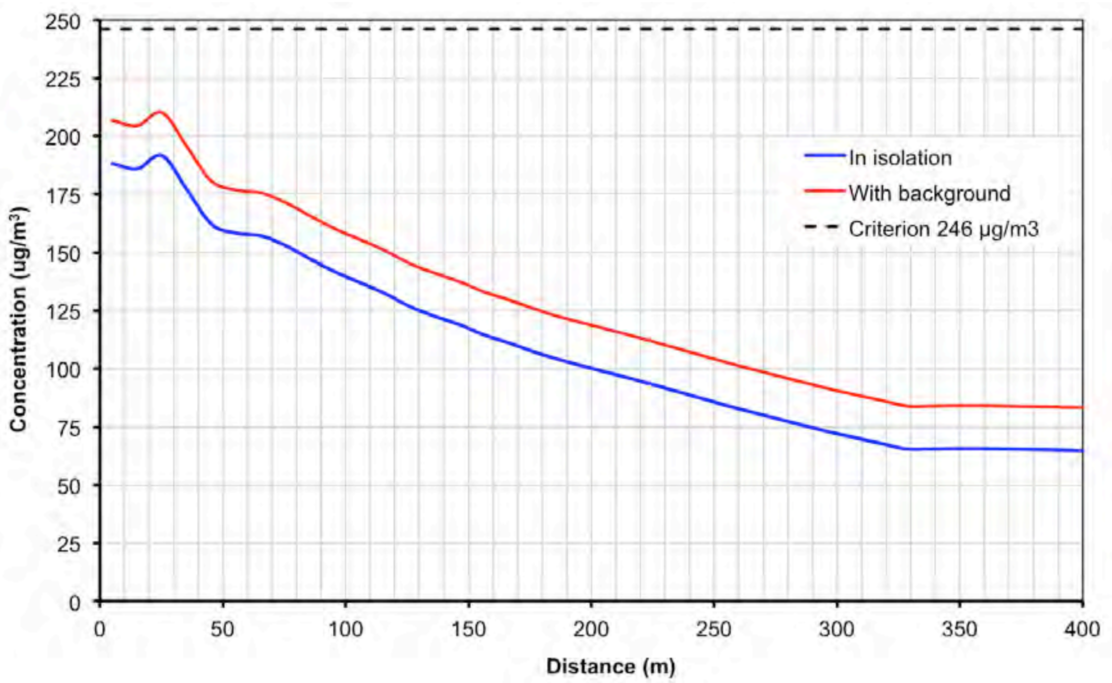


Figure 8-20 Concentration versus distance relationship for the 1-hour average of nitrogen dioxide from the stack of a diesel engine at the well pad with emissions based on the NPI emission factors

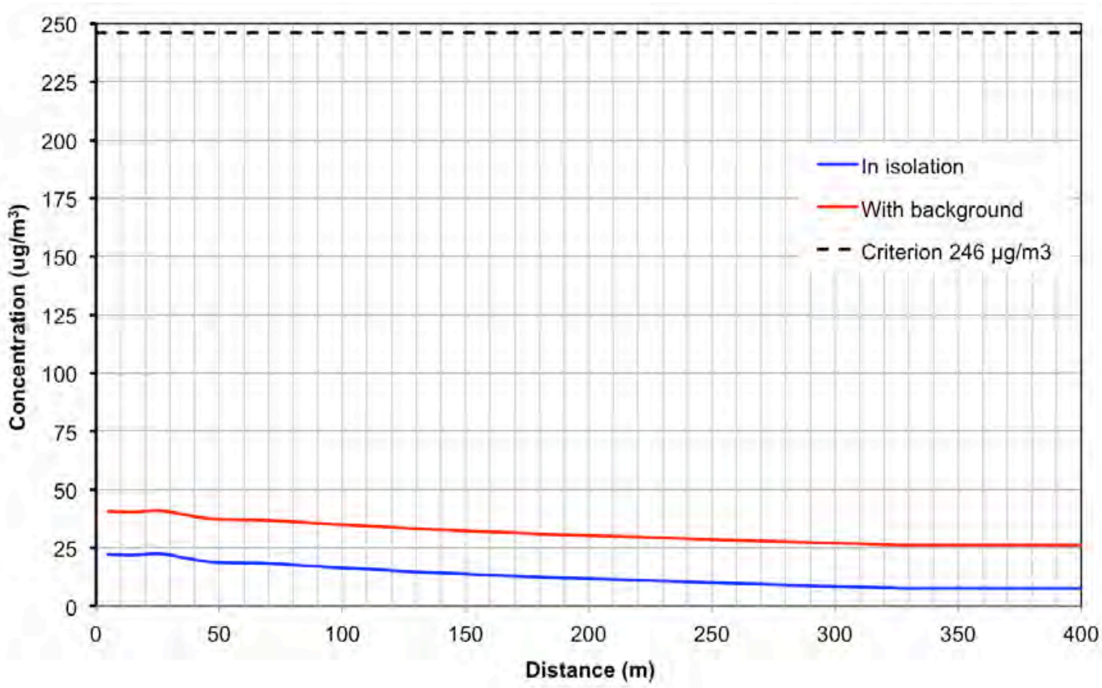


Figure 8-21 Concentration versus distance relationship for the 1-hour average of nitrogen dioxide from the stack of a diesel engine at the well pad with emissions based on the NSW emission standards

The results indicate that:

- Predicted ground-level concentrations of nitrogen dioxide associated with both the gas and diesel-fired generator engines are well below the ambient air quality impact assessment criterion at the boundary of the well pad.
- Emissions associated with the gas-fired well pad generator engines are below the NSW emission concentration standards of nitrogen dioxide.
- No additional separation beyond the boundary of the well pad is required for either generator engine operating on either fuel type.

In addition to the ground level concentrations assessed in the modelling, emissions associated with the diesel-fired well pad generator engines are not based on a specific engine emission concentration data, rather, they are based on NPI emission factors. This NPI data does not comply with the NSW emission concentration standards. The selection of well pad generator engines that meet the NSW emission standards will be part of the design criteria during the project's FEED process.

8.2.6 Well pad – non-routine operations

The maximum 1-hour average ground-level concentration of nitrogen dioxide for the pilot well pad flare, in isolation, is predicted to be extremely low at 3.2 µg/m^3, which is 1.3 percent of the assessment criterion. A graph illustrating the ground-level concentration of nitrogen dioxide versus distance relationship is presented Figure 8-22.

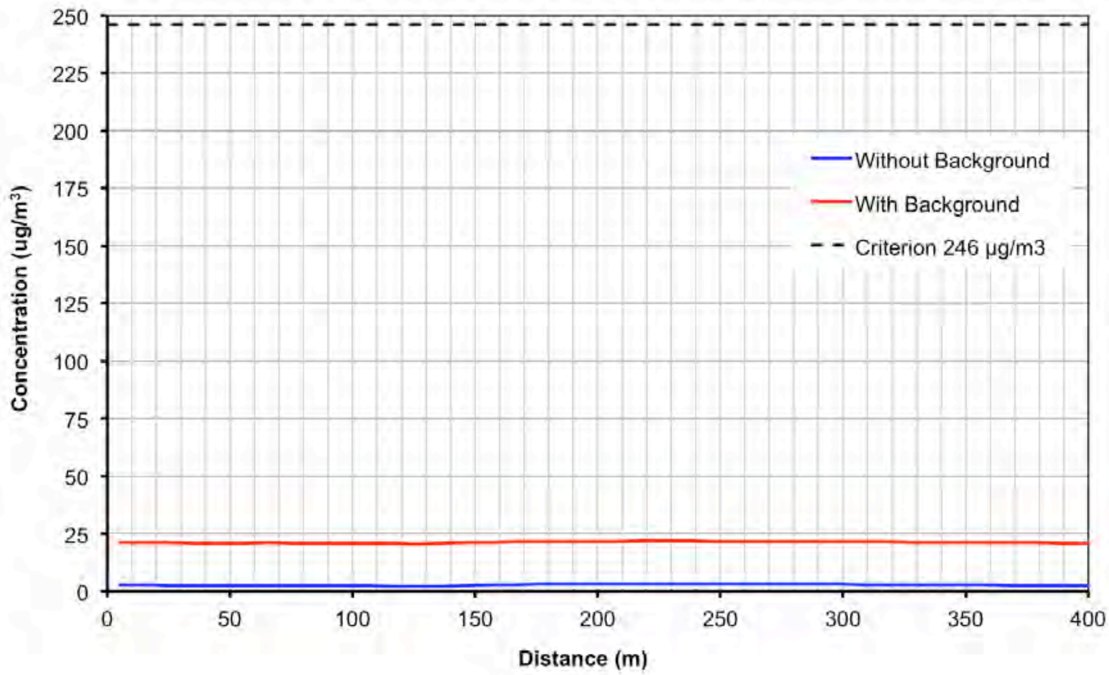


Figure 8-22 Concentration versus distance relationship for the 1-hour average of nitrogen dioxide from a pilot well flare with emissions based on AP-42 emission factors

The results indicate that 1-hour average ground-level concentrations of nitrogen dioxide based on pilot well flaring are predicted to be below 10 per cent of the assessment criterion.

8.2.7 Accommodation camp

The project's workforce accommodation camp is situated approximately four kilometres northeast of Bibblewindi. The maximum ground-level pollutant concentrations at the accommodation camp are predicted to occur if there is a need to flare at full flare capacity at Bibblewindi. Predicted maximum 1-hour average ground-level concentrations of nitrogen dioxide and carbon monoxide for the flare emissions are presented in Table 8-10.

Table 8-10 Predicted maximum 1-hour average ground-level pollutant concentrations at the accommodation camp due to flaring at Bibblewindi

Pollutant	Criterion (µg/m^3)	Concentration, in isolation (µg/m^3)	Percent of criterion (%)	Concentration, with background (µg/m^3)	Percent of criterion (%)
Nitrogen dioxide	246	5.3	2	23.8	9.7
Carbon monoxide	30,000	28.9	0.1	N/A[1]	N/A

Table note: [1] Background concentrations of carbon monoxide have not been used in the project due to the lack of available representative data and the very low impacts as a percentage of the assessment criteria. Background levels of carbon monoxide are also expected to be very low.

Odorous air emissions associated with the camp's sewage treatment facility will be managed through appropriate odour controls and in accordance with the project's environmental management plan. No odour impacts are expected.

9 Air quality monitoring and management strategy

The air quality impact assessment has predicted that the risk of impacts to air quality at sensitive receivers in the region are generally very low. Notwithstanding this, a separation distance between the non-fixed infrastructure and sensitive receivers will be implemented to ensure dust emissions from construction activities do not exceed ambient air quality assessment criteria.

In order to validate the assessment findings and to reduce the uncertainty in some of the assumptions made, it is recommended that an air quality monitoring and management program be implemented during the construction and operation phases. As the predicted impacts of each of the project's phases are different, the management strategies would identify and address each risk individually.

9.1 Management of construction phase air quality impacts

During project construction, the primary risk to air quality is associated with dust emissions, and in particular, the impact of PM_{10}. To manage and mitigate potential impacts to air quality during construction, the following mitigation measures would be considered:

- Wetting or covering of expose surfaces of stockpiled dirt.
- Application of water to unsealed road and construction area surfaces used for mobile plant and vehicle traffic.
- Application of misting water sprays in areas where earthworks are being conducted. Activities include loading and unloading of dirt from trucks and truck, front end loader, conveyor or excavator dumping.
- Limiting of dump heights by excavation equipment.
- Application of speed limits for all vehicles on unsealed roads.
- Limiting of vegetation cleared areas and revegitation of exposed areas upon completion of construction works.
- Erection of physical barriers around dust generating activities.
- Apply dust suppressants to stockpiled dirt if pile is inactive for extended periods.
- Apply surfactants to unsealed road surfaces if dust becomes an issue or is difficult to manage.
- Check weather reports daily. Closely observe weather patterns to enable action to be taken immediately if conditions change.
- Implement control measures that ensure that dust problems do not occur while the site is unattended, e.g. at night or on weekends.
- In locations where nearby sensitive receivers may be affected, adopt a site 'shut down and cover up' policy during periods of extreme weather conditions, e.g. high winds and low humidity. All site operations should cease and all exposed areas covered or treated to ensure dust does not become airborne.

In addition to mitigation measures, dust monitoring would be undertaken to proactively manage emissions from each construction site. This may include the following:

- Installation and operation of dust monitors.
- Monitors should have the ability to measure and record PM_{10} concentrations continuously in real-time.

- Wind speed and direction should be measured and recorded simultaneously with dust concentrations.
- Monitors would ideally be designed to collect dust samples both in real-time and concurrently in accordance with the Australian standard, *Method 9.9: Determination of suspended particulate matter – PM_{10} low volume air sampler – Gravimetric Method*. This will provide for the calibration of real-time measurements with the standard method.
- Monitors would be located in fixed positions around the construction site boundary, or alternatively deployed as mobile units that may be located in different locations each day depending on wind direction. Monitors would be located at both upwind and downwind boundaries.
- Monitors would be equipped with alert systems to inform operators when dust assessment thresholds have been breached. This would allow for additional management strategies to be initiated.
- If sensitive receivers were determined to be in close proximity to construction activities, or close to the pre-defined buffer perimeter, dust monitoring may be deployed at the sensitive receiver location.

9.2 Management of operational phase air quality impacts

9.2.1 Emissions at the source

It is recommended that stack emissions monitoring of combustion gases is conducted upon commissioning of the power generation plant and boiler units at Leewood. Combustion gases to be monitored would include, but not be limited to:

- Oxides of nitrogen (nitric oxide and nitrogen dioxide),
- Carbon monoxide,
- Carbon dioxide,
- Particulate matter,
- Formaldehyde,
- Acrolein, and
- Metals (from the boiler).

Other stack parameters to be measured to calculate the volume flow rate include:

- Stack internal diameter,
- Exhaust velocity,
- Exhaust temperature, and
- Exhaust oxygen and moisture content.

The results of stack monitoring tests would be used to revise the air quality impact assessment by reconfiguring and running the dispersion model with measured input parameters.

A representative proportion of stacks associated with each source type would be monitored on at least a biannual basis.

The destruction efficiency of gases combusted in the flares at Leewood, Bibblewindi and at pilot wells would also be determined through emission monitoring.

It is also recommended that a meteorological monitoring station be installed and operated at Leewood. The monitor should be set up in accordance with the Australian standard AS 3580.14-2011: *Methods for sampling and analysis of ambient air – Meteorological monitoring for ambient air quality applications*. The monitor would be used to inform operators of weather conditions and provide data for use in air quality modelling applications.

9.2.2 Ambient ground level pollutant concentrations in sensitive areas

The impact assessment has shown that ground-level concentrations of nitrogen dioxide beyond the boundary and at sensitive receivers is predicted to be well below air quality criteria. Consequently, ambient air monitoring of the key air pollutant, nitrogen dioxide, is not considered to be a priority. Any uncertainty in this assessment due to emission estimates will be reduced by re-assessing the modelled ground-level concentrations of nitrogen dioxide using actual stack emission data.

Notwithstanding this, monitoring of nitrogen dioxide is recommended at either the location of predicted maximum ground-level concentration beyond the boundary or at the location of the most affected sensitive receiver, for a period of two years after the commissioning of the project.

10 Conclusions

An air quality impact assessment of the proposed Narrabri Gas Project has been conducted for the construction and operations phases, including two project power supply options. The two options included local gas-fired power generation at Leewood and electricity supplied from the national grid.

The assessment found that during construction:

- Ground-level concentrations of dust associated with the Leewood and Bibblewindi sites are predicted to meet the impact assessment criteria at all sensitive receptors.

Separation distances between construction areas and sensitive receptors of 60, 30 and 140 metres for a well pad, gas, water and electricity transmission pipeline trenching area and access track, and road construction area, respectively, was found to be necessary to protect receptors from ground-level PM_{10} concentrations that may exceed the assessment criteria under worst case meteorological conditions during construction. Implementation of mitigation and management measures to minimise dust will reduce these buffer distances. Dust impacts from construction activities have been assessed on the basis of worst case meteorological conditions over a full year, however it is important to note that many construction activities are mobile, transient and intermittent and likely to take place over a shorter period than one year.

The assessment found that during routine operations:

- Air emissions from the Leewood facility are predicted to meet all relevant impact assessment criteria for both power options (power station and grid sourced electricity). This includes ambient air quality criteria beyond the boundary and stack emission concentration limits, based on typical gas-fired power generator and gas-fired boiler emission rates and the NSW Group 6 emission concentration standards.
- The nominal gas-fired well pad engines selected for the assessment met the NSW Group 6 emission concentration standard for nitrogen oxides and other substances. No buffer requirements were identified as ground-level pollutant concentrations were well below the assessment criteria.
- The diesel-fired well pad engines assumed for the assessment did not require a buffer as ground-level pollutant concentrations were well below the assessment criteria. The selection of well pad generator engines that meet the NSW emission standards will need to be considered as part of the design criteria during the project's FEED process.

The assessment determined that during non-routine flaring operations:

- The impact assessment criteria were met for all pollutants at all locations beyond the boundary of both the Leewood and Bibblewindi sites.

The assessment also determined that air quality impacts at the accommodation camp are likely to be negligible.

11 References

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Appendix A

Site Air Quality Monitoring Program

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1 Introduction

Air Environment Consulting and Ecotech were commissioned by GHD, on behalf of Santos, to undertake an ambient air quality monitoring program in the project area. The program was developed to assess the following key air quality parameters for the impact assessment:

- oxides of nitrogen, nitrogen dioxide, nitric oxide,
- ozone, and
- meteorology.

2 Background and Objectives of Air Monitoring Program

The air quality monitoring program was designed to investigate the background concentrations of oxides of nitrogen at the project site and surrounding local area. Oxides of nitrogen primarily comprise the nitrogen based compounds nitric oxide and nitrogen dioxide, with small quantities of nitrous oxide – a greenhouse gas, and nitrogen pentoxide. Nitrogen dioxide is considered to be the most important air pollutant associated with the project, in terms of the ratio of its emission rate to impact assessment criterion.

The objective of the air quality monitoring program was two-fold, and was commissioned to provide:

1. Site-specific data for the assessment of the existing environment (i.e. baseline air quality data).
2. Data for the cumulative impact assessment of nitrogen dioxide.

Combustion processes, such as gas-fired and diesel engines, generate nitrogen oxide emissions. Nitrogen dioxide typically comprises less than 10% of the total nitrogen oxide emissions from combustion sources, with the remaining portion being primarily nitric oxide. In addition to a direct point source release from engines, nitrogen dioxide also forms in the atmosphere during plume transport through the photochemical reaction of nitric oxide with partly oxidized organic compounds and ozone. The NSW *Approved Methods for the Modelling and Assessment of Air Pollutants 2005* (Approved Methods) prescribes a method for the atmospheric conversion of nitrogen oxides to nitrogen dioxide, which requires data on the atmospheric concentration of ozone. Consequently, the monitoring program included the measurement of ozone concentrations.

Meteorological monitoring has also been undertaken during the program to provide information on a range of site-specific parameters. The objective of the meteorological monitoring program was to measure the:

1. Parameters relevant to meteorological modelling, in order to supplement data obtained from the Bureau of Meteorology (BOM) automatic weather station (AWS) at Narrabri Airport. These parameters included wind direction, wind speed, temperature (at 2 and 10 m) and solar radiation; and
2. Wind conditions at any time a measured nitrogen dioxide and ozone concentration was considered to be significant.

3 Air Monitoring Station

The monitoring station setup supplied and operated by Ecotech meets the relevant Australian standards and comprises the equipment outlined below:

- Measurement of ozone concentrations by gas analyser to the Australian standard AS3580.6.1.
- Measurement of nitrogen oxide concentrations, including nitric oxide and nitrogen dioxide components, by gas analyser to the Australian standard AS3580.5.1.
- Wind speed and direction (by two-dimensional ultrasonic anemometer), relative humidity, rainfall and solar radiation to the Australian standard AS3580.14.
- Differential temperature at two and ten metres using paired sensors and aspirated temperature shields as per Australian standard AS3580.14.
- Automatic gas calibrator to AS3580.2.2.
- Data acquisition system and remote communications.

4 Monitoring Program

The air quality monitoring station has been located at coordinates 30^{o} 33' 18.15" S, 149^{o} 45' 31.16" E, as shown in the aerial image in Figure 1.

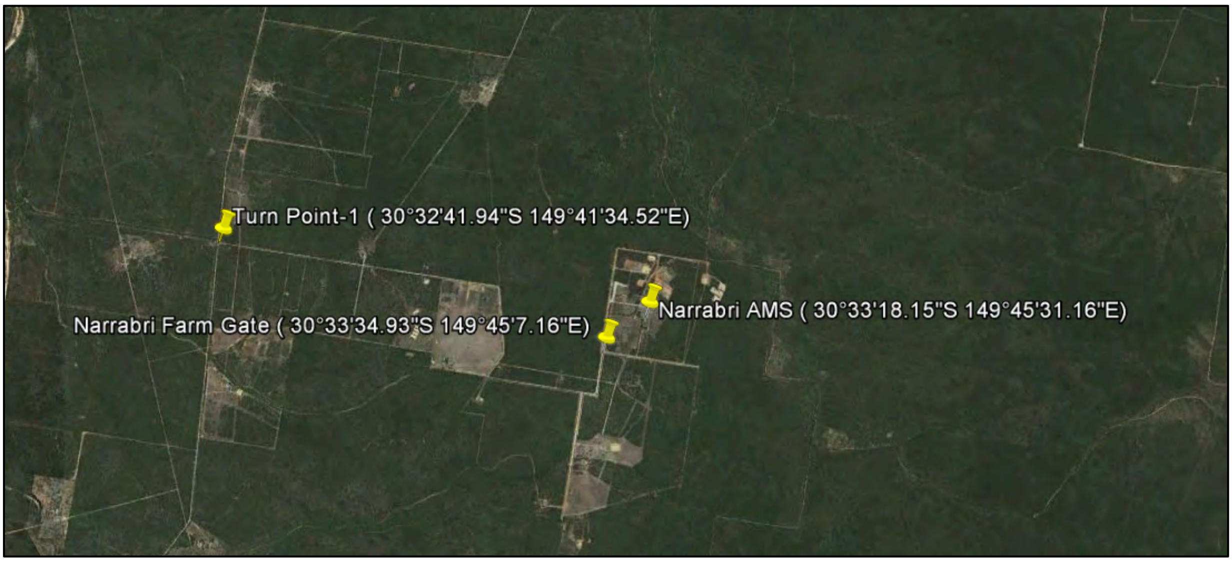

Figure 1 Aerial image of Air Monitoring Station (AMS) location

The monitoring station was installed and commissioned on 10 April 2014 at 4pm and decommissioned on 5 August 2014 at 10am. The monitoring station makes continuous observations of all parameters and records the data in five (5) minute average steps. The data has then been processed into 1-hour average concentrations for assessment against the 1-hour average impact assessment criteria of nitrogen dioxide and ozone. Ozone data has also been processed to assess a rolling 4-hour average for assessment against the 4-hour average criterion.

5 Ambient Air Quality Impact Assessment Criteria

Air quality impact assessment criteria for nitrogen dioxide and ozone in NSW are set out in the Approved Methods (2005), and presented in Table 1.

Table 1 Air quality impact assessment criteria for nitrogen dioxide and ozone

Pollutant	Averaging period	Concentration	Source
Nitrogen dioxide	1-hour	246	NEPC[2] (1998)
	Annual	62[1]	
Photochemical oxidants (as ozone)	1-hour	214	NEPC[2] (1998)
	4-hour	171	

Tablenote: Table is extracted from the document Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (2005)
[1] Not relevant to the short time period of this monitoring program.
[2] National Environment Protection Council. Assessment criterion is equivalent to the air quality standards promulgated in the National Environment Protection (Ambient Air Quality) Measure (Air NEPM, 1998).

6 Monitoring Results

6.1 Air Quality

6.1.1 Nitrogen dioxide

Concentrations of nitrogen dioxide during the monitoring period were found to be very low. Descriptive statistics of observed 1-hour average concentrations of nitrogen dioxide are presented in Table 2, while a time series plot of the 1-hour average concentrations are provided in Figure 2. The relationship between wind direction and nitrogen dioxide concentrations is explored through the pollution rose diagram in Figure 3.

Table 2 Descriptive statistics of 1-hour average concentrations of nitrogen dioxide

Statistic	Concentration (µg/m^3)	Percentage of criterion (%)
Mean	2.6	1.1%
Maximum	18.5	7.5%
99th percentile	10.7	4.3%
95th percentile	6.2	2.5%
90th percentile	4.8	1.9%
75th percentile	3.6	1.5%
50th percentile	2.1	0.8%
25th percentile	1.9	0.8%
Minimum	0.0	0.0%
Impact assessment criterion	246	N/A

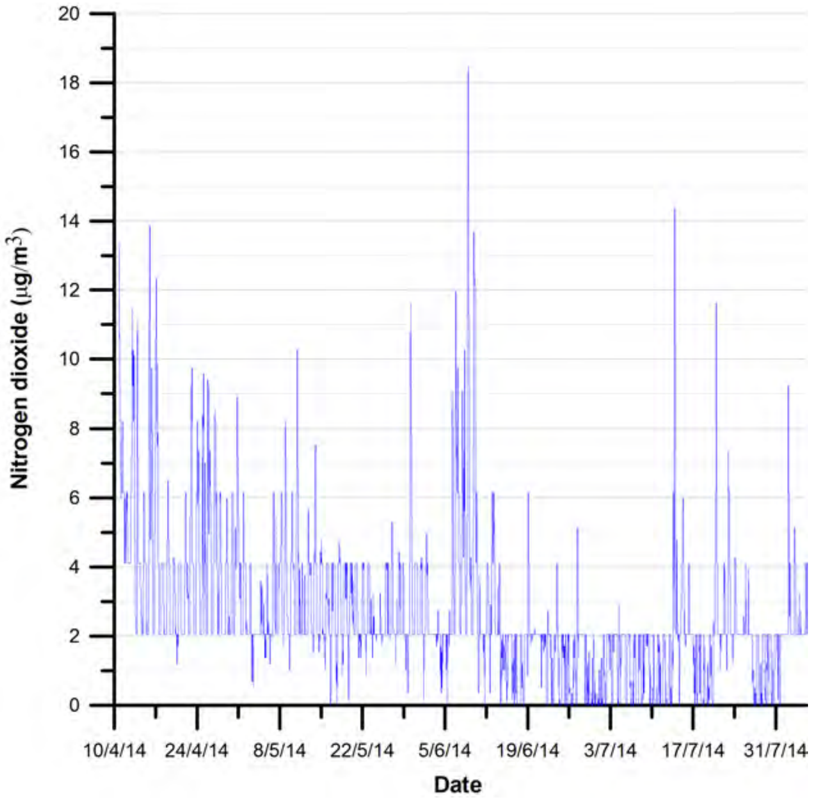

Figure 2 Time series of 1-hour average concentrations of nitrogen dioxide

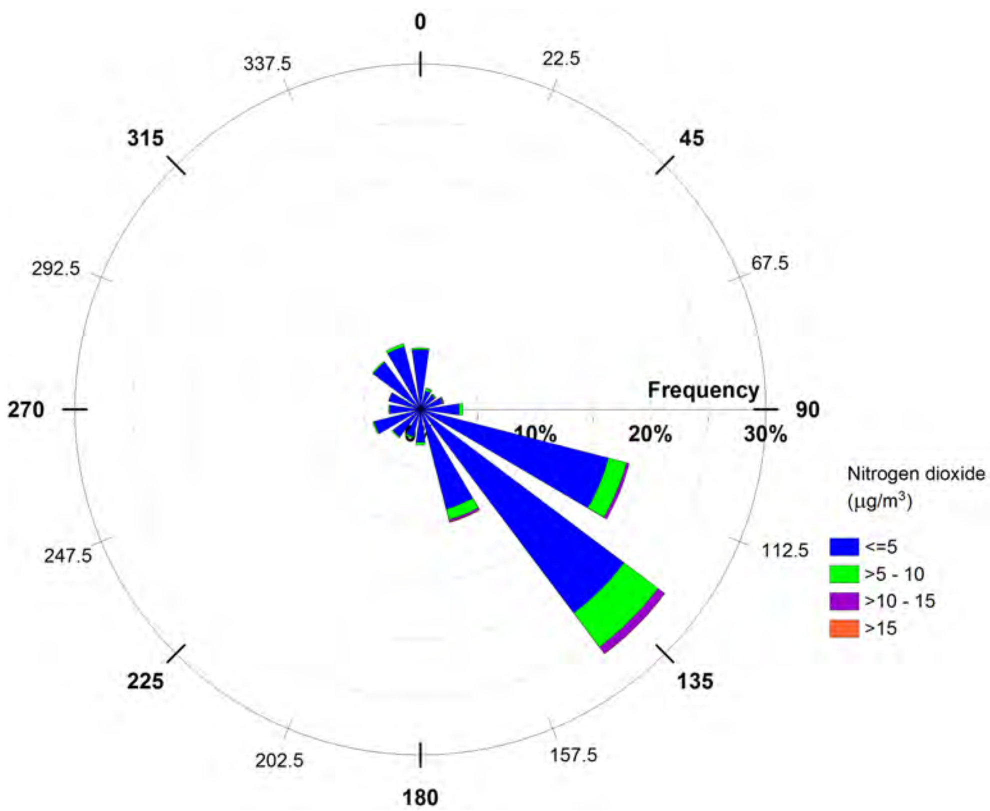

Figure 3 Rose diagram illustrating the relationship between nitrogen dioxide concentrations, frequency and the wind direction

Figure note: 0° is north

6.1.2 Ozone

Concentrations of ozone during the monitoring period were found to be low. Descriptive statistics of observed 1-hour and 4-hour average concentrations of ozone are presented in Table 3, while a time series plot of the 1-hour average concentrations are provided in Figure 4.

Table 3 Descriptive statistics of 1-hour and 4-hour average concentrations of ozone

Statistic	1-hour		4-hour	
	Concentration ($\mu g/m^3$)	Percentage of criterion (%)	Concentration ($\mu g/m^3$)	Percentage of criterion (%)
Mean	33.1	15.5%	32.5	19.0%
Maximum	74.2	34.7%	72.0	42.1%
99th percentile	68.7	32.1%	67.2	39.3%
95th percentile	61.2	28.6%	59.6	34.8%
90th percentile	58.7	27.4%	57.3	33.5%
75th percentile	52.3	24.4%	49.9	29.2%
50th percentile	36.0	16.8%	34.1	19.9%
25th percentile	12.0	5.6%	14.1	8.2%
Minimum	-1.6[1]	-0.8%	-0.5[1]	-0.3%
Impact assessment criterion	214	N/A	171	N/A

Table note: [1] Negative values are within the uncertainty range of the monitoring instrument.

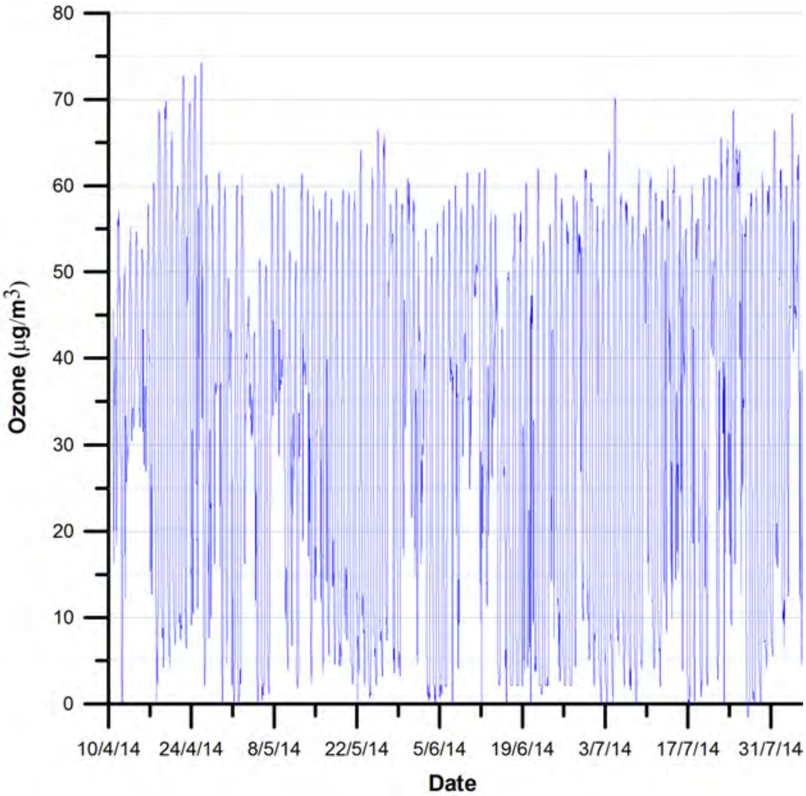

Figure 4 Time series of ozone concentrations between 10 April and 5 August 2014

6.2 Meteorology

The observed winds during the monitoring period indicate that the prevailing winds were from the southeast, with a less dominant reverse flow pattern from the northwest and north. The distribution of wind speed and direction is presented as a rose diagram in Figure 5.

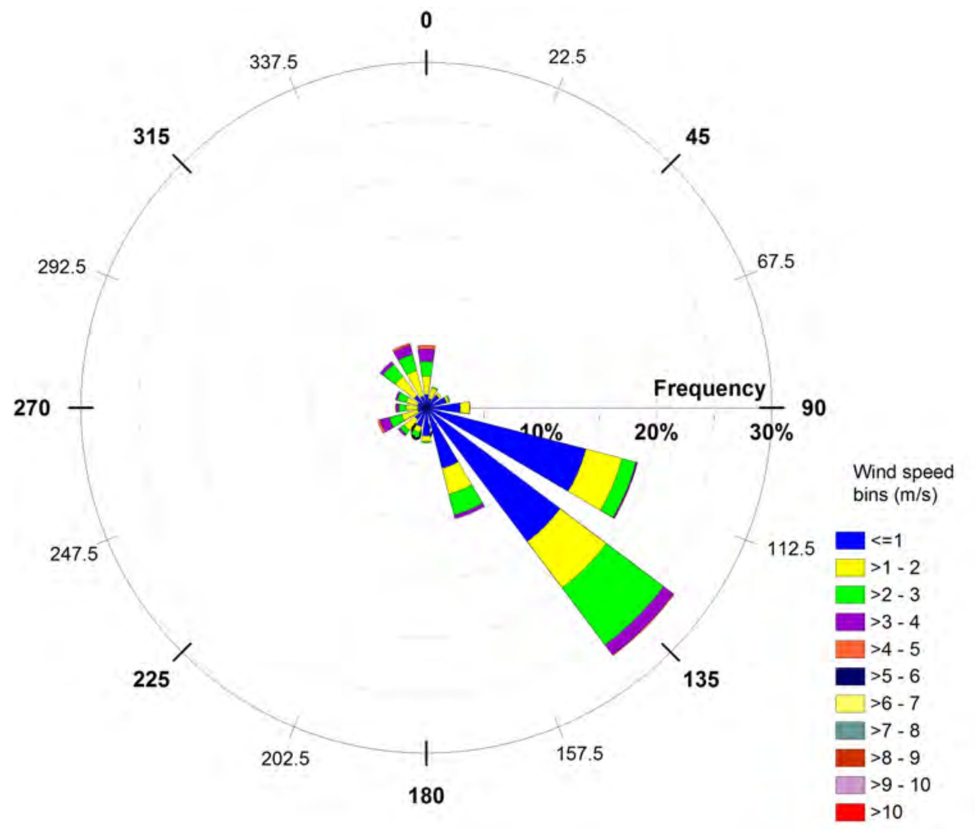

Figure 5 Distribution of 1-hour average wind speed and direction

Figure note: 0° is north

7 Discussion of Results

The findings of the monitoring program between 10 April and 5 August 2014 are summarised as follows:

- Ambient concentrations of nitrogen dioxide are considered to be very low, with a maximum 1-hour average concentration of 18.5 µg/m^3, which is 7.5 percent of the NSW impact assessment criterion.
- Ambient concentrations of ozone are considered to be low, with maximum 1-hour and 4-hour average concentrations of 74.2 and 72.0 µg/m^3, respectively, which are 34.7 and 42.1 percent of the NSW impact assessment criterion.
- While regional nitrogen dioxide and ozone concentrations are influenced by photochemical activity, and therefore likely to increase during the summer period due to strong solar insolation, the lack of significant urban and industrial background emission sources in the region suggest that the low concentrations observed during the monitoring period are highly unlikely to increase to levels near to, or in exceedance of, the impact assessment criteria.

- The wind directions in the area were predominantly from the southeast with a minor component from the northwest and north. Wind speeds tended to be light to moderate:
    - Maximum 5-minute average of 7.4 metres per second.
    - Mean 5-minute average of 1.3 metres per second.
    - Maximum 1-hour average of 4.8 metres per second.
    - Mean 1-hour average of 1.2 metres per second.

8 Conclusion

The air quality monitoring data collected provided for the characterisation of the background concentrations of nitrogen dioxide and ozone in the project area. This data supports the initial assumption that concentrations of nitrogen dioxide and ozone are expected to be low. The data provides for the description of the existing state of local air quality and may be used in the cumulative impact modelling assessment.

There is typically some variability in annual and inter-annual air quality in any given region due to the type and seasonality of emission sources and changes in meteorological conditions. However, the paucity of local air emission sources suggests that this variability is likely to be relatively low. Consequently, the risk that concentrations of nitrogen dioxide and ozone will significantly increase during the spring and summer months to levels that could affect the outcome of the air quality impact assessment is also low.

It is considered that the use of nitrogen dioxide and ozone concentration data from Office of Environment and Heritage monitoring sites in NSW, situated nearby to large industrial sources and urban populations, as a surrogate for background data at the site are likely to significantly over-estimate the background concentration when applied in the cumulative impact assessment. The application of the ambient nitrogen dioxide concentration data measured at the site in the cumulative impact assessment is considered reasonable.

Appendix B

Air Pollutant Hierarchy of Importance

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1 Methodology for the Assessment of Minor Air Pollutants

A broad suite of criteria and hazardous air pollutants are emitted from gas and diesel fired combustion engines during normal operation. In order to assess the most critical air pollutants emitted, the contaminants were ranked according to the ratio of their emission factor (in $g_{pollutant}/MJ_{energy\ used}$) to impact assessment criteria (in µg/m^3). The 1-hour average assessment criterion was used for all pollutants with the exception of PM_{10}, where the 24-hour average was used to be conservative.

As various engine types are proposed for the project, including lean-burn gas-fired, rich-burn gas-fired and diesel-fired engines, each engine type has been assessed and the pollutants ranked. Emissions for lean- and rich-burn gas engines have been ranked based on US EPA AP42 emission factors, while diesel engines have been ranked based on and combination of AP42 and Australian NPI emission factors. Air pollutant emission factors associated with lean-burn gas-fired, rich-burn gas-fired and diesel-fired engines, impact assessment criteria and the ranking of the most important substances for the assessment are presented in Table 1 to Table 3, respectively.

Table 1 Lean-burn gas-fired engine critical air pollutant ranking

Substance	Emission factor[1] (g/MJ)	Impact assessment criterion	Assessment criterion source	Ratio *EF[2]/IAC[3]*	Rank
Acrolein	2.21E-03	0.42	Approved Methods	5.26E-03	1
Nitrogen oxides	9.50E-01	246	Approved Methods	3.86E-03	2
Formaldehyde	2.27E-02	20	Approved Methods	1.14E-03	3
Acetaldehyde	3.59E-03	42	Approved Methods	8.56E-05	4
PM_{10}	4.09E-03	50	Approved Methods	8.17E-05	5
Carbon monoxide	1.60E+00	30000	Approved Methods	5.33E-05	6
Phenanthrene	4.47E-06	0.5	TCEQ	8.94E-06	7
Benzene	1.89E-04	29	Approved Methods	6.52E-06	8
Ethylene Dibromide	1.90E-05	4	TCEQ	4.76E-06	9
Biphenyl	9.12E-05	24	Approved Methods	3.80E-06	10
1,3-Butadiene	1.15E-04	40	Approved Methods	2.87E-06	11
Acenaphthene	5.38E-07	0.4	Approved Methods	1.34E-06	12
Carbon Tetrachloride	1.58E-05	12	Approved Methods	1.32E-06	13
Pyrene	5.85E-07	0.5	TCEQ	1.17E-06	14
Fluoranthene	4.77E-07	0.5	TCEQ	9.55E-07	15
Chrysene	2.98E-07	0.5	TCEQ	5.96E-07	16
Methylcyclohexane	5.29E-04	940	TCEQ	5.63E-07	17
Phenol	1.03E-05	20	Approved Methods	5.16E-07	18
Toluene	1.75E-04	360	Approved Methods	4.87E-07	19
2-Methylnaphthalene	1.43E-05	30	TCEQ	4.76E-07	20
Xylene	7.91E-05	190	Approved Methods	4.16E-07	21
Methanol	1.08E-03	3000	Approved Methods	3.58E-07	22
Benzo(e)pyrene	1.78E-07	0.5	TCEQ	3.57E-07	23
Butyr/Isobutyraldehyde	4.34E-05	140	TCEQ	3.10E-07	24
n-Pentane	1.12E-03	4100	TCEQ	2.73E-07	25
Vinyl Chloride	6.41E-06	24	Approved Methods	2.67E-07	26
1,3-Dichloropropene	1.14E-05	45	TCEQ	2.52E-07	27
1,1,2,2-Tetrachloroethane	1.72E-05	70	TCEQ	2.46E-07	28

Substance	Emission factor[1] (g/MJ)	Impact assessment criterion	Assessment criterion source	Ratio EF^2/IAC^3	Rank
Fluorene	2.44E-06	10	TCEQ	2.44E-07	29
Naphthalene	3.20E-05	200	TCEQ	1.60E-07	30
n-Hexane	4.77E-04	3,200	Approved Methods	1.49E-07	31
1,2-Dichloroethane	1.01E-05	70	Approved Methods	1.45E-07	32
Benzo(b)fluoranthene	7.14E-08	0.5	TCEQ	1.43E-07	33
Chlorobenzene	1.31E-05	100	Approved Methods	1.31E-07	34
Styrene	1.01E-05	120	Approved Methods	8.46E-08	35
n-Octane	1.51E-04	3500	TCEQ	4.31E-08	36
2,2,4-Trimethylpentane	1.08E-04	3130	TCEQ	3.43E-08	37
Cyclopentane	9.76E-05	3400	TCEQ	2.87E-08	38
1,2-Dichloropropane	1.16E-05	460	TCEQ	2.51E-08	39
Tetrachloroethane	1.07E-06	70	TCEQ	1.52E-08	40
1,1,2-Trichloroethane	1.37E-05	1000	Approved Methods	1.37E-08	41
Chloroform	1.23E-05	900	Approved Methods	1.36E-08	42
Acenaphthylene	2.38E-06	200	TCEQ	1.19E-08	43
1,3,5-Trimethylbenzene	1.45E-05	1250	TCEQ	1.16E-08	44
1,2,4-Trimethylbenzene	6.15E-06	700	TCEQ	8.78E-09	45
1,2,3-Trimethylbenzene	9.89E-06	1250	TCEQ	7.91E-09	46
n-Nonane	4.73E-05	10500	TCEQ	4.50E-09	47
Butane	2.33E-04	66000	TCEQ	3.52E-09	48
Methylene Chloride (Dichloromethane)	8.60E-06	3190	Approved Methods	2.70E-09	49
1,1-Dichloroethane	1.01E-05	4000	TCEQ	2.54E-09	50
Ethylbenzene	1.71E-05	8,000	Approved Methods	2.13E-09	51
Chloroethane	8.04E-07	900	Approved Methods	8.93E-10	52

Table note: [1] Emission ranking based on US EPA AP42 emission factors for uncontrolled emissions for 4-stroke lean-burn engines. US EPA AP42 Chapter 3.2 Table 3.2-2.
[2] EF: Emission factor.
[3] IAC: Impact assessment criterion.
[4] The PM_{10} 24-hour average criterion of 50 µg/m^3 has been used for comparison with the 1-hour average criteria as a conservative estimate.

Table 2 Rich-burn gas-fired engine critical air pollutant ranking

Substance	Emission factor[1] (g/MJ)	Impact assessment criterion	Assessment criterion source	Ratio EF^2/IAC^3	Rank
Oxides of nitrogen	1.75E+00	246	Approved Methods	7.13E-03	1
Acrolein	1.13E-03	0.42	Approved Methods	2.69E-03	2
Formaldehyde	8.82E-03	20	Approved Methods	4.41E-04	3
Acetaldehyde	1.20E-03	42	Approved Methods	2.86E-05	4
Benzene	6.79E-04	29	Approved Methods	2.34E-05	5
1,3-Butadiene	2.85E-04	40	Approved Methods	7.13E-06	6
Carbon monoxide	1.36E-01	30000	Approved Methods	4.54E-06	7
Toluene	2.40E-04	360	Approved Methods	6.67E-07	8
PM_{10}	3.32E-05	50[4]	Approved Methods	6.63E-07	9
Carbon Tetrachloride	7.61E-06	12	Approved Methods	6.34E-07	10
Xylene	8.39E-05	190	Approved Methods	4.41E-07	11

Substance	Emission factor[1] (g/MJ)	Impact assessment criterion	Assessment criterion source	Ratio EF^2/IAC^3	Rank
Methanol	1.32E-03	3000	Approved Methods	4.39E-07	12
Naphthalene	4.18E-05	200	TCEQ	2.09E-07	13
1,1,2,2-Tetrachloroethane	1.09E-05	70	TCEQ	1.55E-07	14
Butyr/Isobutyraldehyde	2.09E-05	140	TCEQ	1.49E-07	15
Vinyl Chloride	3.09E-06	24	Approved Methods	1.29E-07	16
1,3-Dichloropropene	5.46E-06	45	TCEQ	1.21E-07	17
1,2-Dichloroethane	4.86E-06	70	Approved Methods	6.94E-08	18
Chlorobenzene	5.55E-06	100	Approved Methods	5.55E-08	19
Styrene	5.12E-06	120	Approved Methods	4.26E-08	20
1,2-Dichloropropane	5.59E-06	460	TCEQ	1.22E-08	21
1,1,2-Trichloroethane	6.58E-06	1000	Approved Methods	6.58E-09	22
Chloroform	5.89E-06	900	Approved Methods	6.55E-09	23
Methylene Chloride (Dichloromethane)	1.77E-05	3190	Approved Methods	5.55E-09	24
1,1-Dichloroethane	4.86E-06	4000	TCEQ	1.21E-09	25

Table note: [1] Emission ranking based on US EPA AP42 emission factors for uncontrolled emissions for 4-stroke rich-burn engines. US EPA AP42 Chapter 3.2 Table 3.2-3.
[2] EF: Emission factor.
[3] IAC: Impact assessment criterion.
[4] The PM_{10} 24-hour average criterion of 50 µg/m^3 has been used for comparison with the 1-hour average criteria as a conservative estimate.

Table 3 Diesel-fired engine critical air pollutant ranking

Substance	Emission factor[1] (g/MJ)	Impact assessment criterion	Assessment criterion source	Ratio EF^2/IAC^3	Rank
Oxides of nitrogen	1.90E+00	246	Approved Methods	7.71E-03	1
PM_{10}	1.33E-01	50	Approved Methods	2.67E-03	2
Acrolein	3.98E-05	0.42	Approved Methods	9.47E-05	3
Formaldehyde	5.07E-04	20	Approved Methods	2.54E-05	4
Phenanthrene	1.26E-05	0.5	TCEQ	2.53E-05	5
Benzene	4.01E-04	29	Approved Methods	1.38E-05	6
Carbon monoxide	4.09E-01	30000	Approved Methods	1.36E-05	7
Propylene	1.11E-03	90	Approved Methods	1.23E-05	8
Acetaldehyde	3.30E-04	42	Approved Methods	7.85E-06	9
Fluoranthene	3.27E-06	0.5	TCEQ	6.54E-06	10
Pyrene	2.06E-06	0.5	TCEQ	4.11E-06	11
Acenaphthylene	2.18E-06	1	TCEQ	1.09E-08	12
Anthracene	8.04E-07	0.5	TCEQ	1.61E-06	13
Acenaphthene	6.11E-07	0.4	Approved Methods	1.53E-06	14
Benzo(a)anthracene	7.22E-07	0.5	TCEQ	1.44E-06	15
Fluorene	1.26E-05	10	TCEQ	1.26E-06	16
Xylenes	1.23E-04	190	Approved Methods	6.45E-07	17
Dibenz(a,h)anthracene	2.51E-07	0.5	TCEQ	5.01E-07	18
Toluene	1.76E-04	360	Approved Methods	4.89E-07	19
1,3-Butadiene	1.68E-05	40	Approved Methods	4.20E-07	20
Indeno(1,2,3-cd)pyrene	1.61E-07	0.5	TCEQ	3.23E-07	21

Substance	Emission factor[1] (g/MJ)	Impact assessment criterion	Assessment criterion source	Ratio *EF[2]/IAC[3]*	Rank
Chrysene	1.52E-07	0.5	TCEQ	3.04E-07	22
Benzo(a)pyrene	8.08E-08	0.3	TCEQ	2.69E-07	23
Naphthalene	3.65E-05	200	TCEQ	1.82E-07	24
Benzo(k)fluoranthene	6.67E-08	0.5	TCEQ	1.33E-07	25
Benzo(b)fluoranthene	4.26E-08	0.5	TCEQ	8.52E-08	26

Table note: [1] Emission ranking based on US EPA AP42 emission factors for uncontrolled emissions for diesel engines. US EPA AP42 Chapter 3.3 Table 3.3-3.

[2] EF: Emission factor.

[3] IAC: Impact assessment criterion.

[4] The PM_{10} 24-hour average criterion of 50 µg/m^3 has been used for comparison with the 1-hour average criteria as a conservative estimate.

Appendix C

Selection of a Representative Year of Meteorology for Model Simulation

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1 Methodology for the Assessment of Meteorological Inter-annual Variability

The nearest available meteorological monitoring station to the project area is operated by the Bureau of Meteorology at Narrabri Airport. This station is situated approximately 27 km to the northeast of the project's central gas processing plant at Leewood, on the northern edge of the Pilliga Forest.

Meteorological data collected at Narrabri Airport were analysed to determine a representative year for use in the dispersion modelling assessment. The meteorological parameters, dataset time period and analysis conducted are summarised in Table 1.

Table 1 Meteorological data assessed at Narrabri Airport

Parameter	Time period assessed	Data	Analysis
Wind speed Wind direction Wind vector U component Wind vector V component Temperature Relative humidity	March 2008 – February 2013	Half hourly data points from AWS	Comparisons of: • Frequency distributions (as probability density functions) as year on year and each year against the mean of all five years; • Frequency distribution anomaly (as a %) from the mean of all five years; • Correlation statistics (R^2).
Rainfall	2002 – 2013	Annual and monthly totals (mm)	Comparison of annual rainfall totals
El Nino Southern Oscillation (ENSO)	2008 – 2013	Annual classification	SOI classification and strength

The selection process was based on determining which years provided the closest representation of the average state of the climate based on the variation of each meteorological parameter from the mean and each other year. For meteorological modelling and air quality assessment purposes, the key parameters that influence pollutant dispersion are wind speed, wind direction and atmospheric stability, with stability a function of the atmosphere's vertical temperature profile and the wind speed. Notwithstanding this, these parameters are strongly influenced by the overall state of the climate such as ENSO, rainfall and the resulting soil and atmospheric moisture content. The analysis considered the following:

- A year with a moderate or strong ENSO classification should be avoided, where possible.
- A year with anomalously low or high rainfall should be avoided, where possible.
- The distributions of wind speed and direction should be as close to the mean distribution as possible, both in terms of the frequencies of low, moderate and high wind speeds, and in the overall correlation statistics. This includes the analysis of wind in its U and V vector components.

- The distributions of temperature should be as close to the mean distribution as possible, in terms of low nocturnal and daytime high temperatures.

2 Analysis of Meteorological Inter-annual Variability

2.1 Wind fields

2.1.1 Wind speed

The annual and mean frequency distributions (probability density function [pdf]) of wind speed and the anomaly of each year to the mean of the five-year period, March 2008 to February 2013, are presented in Figure 1 and Figure 2, respectively.

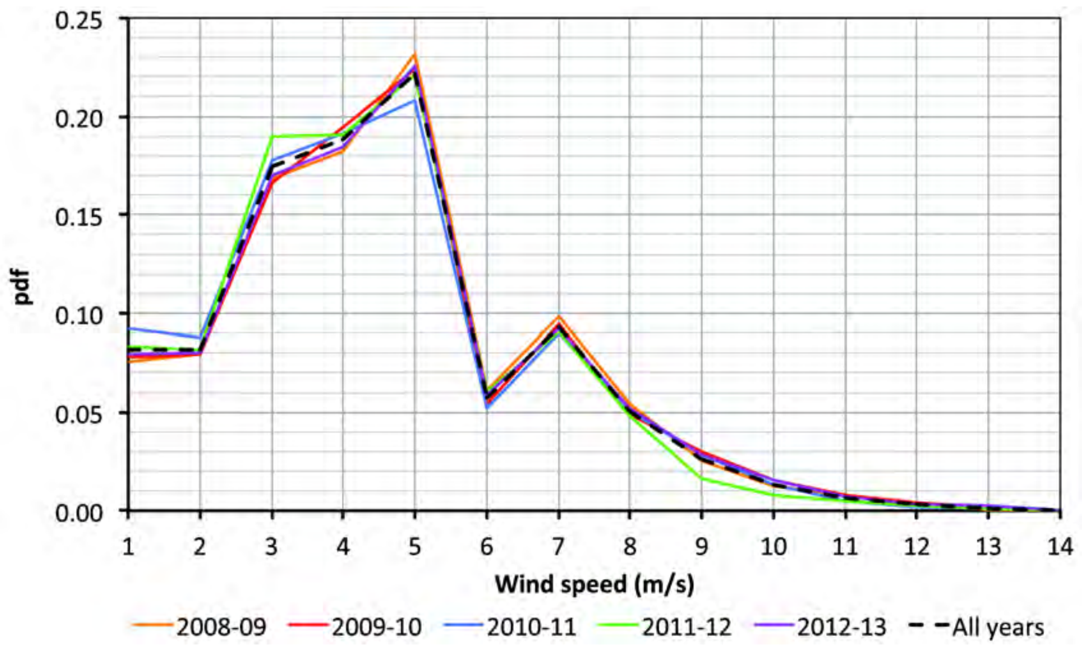

Figure 1 Comparison of annual observed wind speed frequency distributions to all years

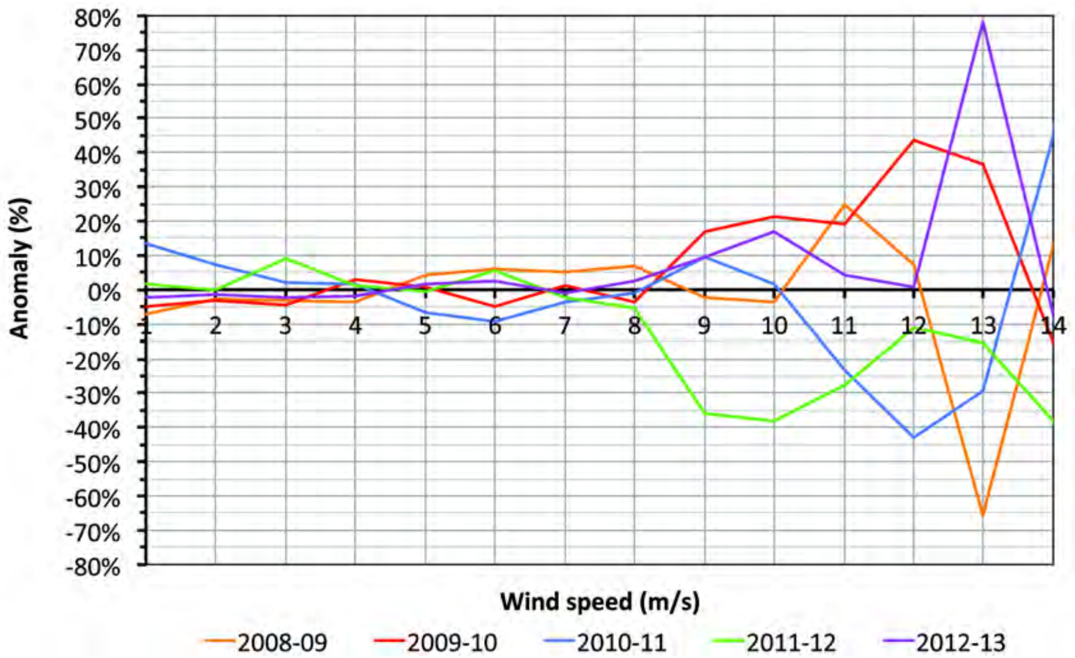

Figure 2 Annual observed wind speed distribution anomaly from the mean

The R^2 correlation statistics for each year on year, and each year versus the mean of all years, are summarised in Table 2.

Table 2 Correlation coefficients matrix of the distributions of wind speed

Period	2008-09	2009-10	2010-11	2011-12	2012-13	All years
2008-09	1	--	--	--	--	--
2009-10	0.9981	1		--	--	--
2010-11	0.9926	0.9956	1	--	--	--
2011-12	0.9954	0.9953	0.9969	1	--	--
2012-13	0.9993	0.9991	0.9957	0.9969	1	--
All years	0.9985	0.9990	0.9975	0.9983	0.9996	1

2.1.2 Wind direction

The annual and mean frequency distributions (probability density function [pdf]) of wind direction and the anomaly of each year to the mean of the five-year period, March 2008 to February 2013, are presented in Figure 3 and Figure 4, respectively.

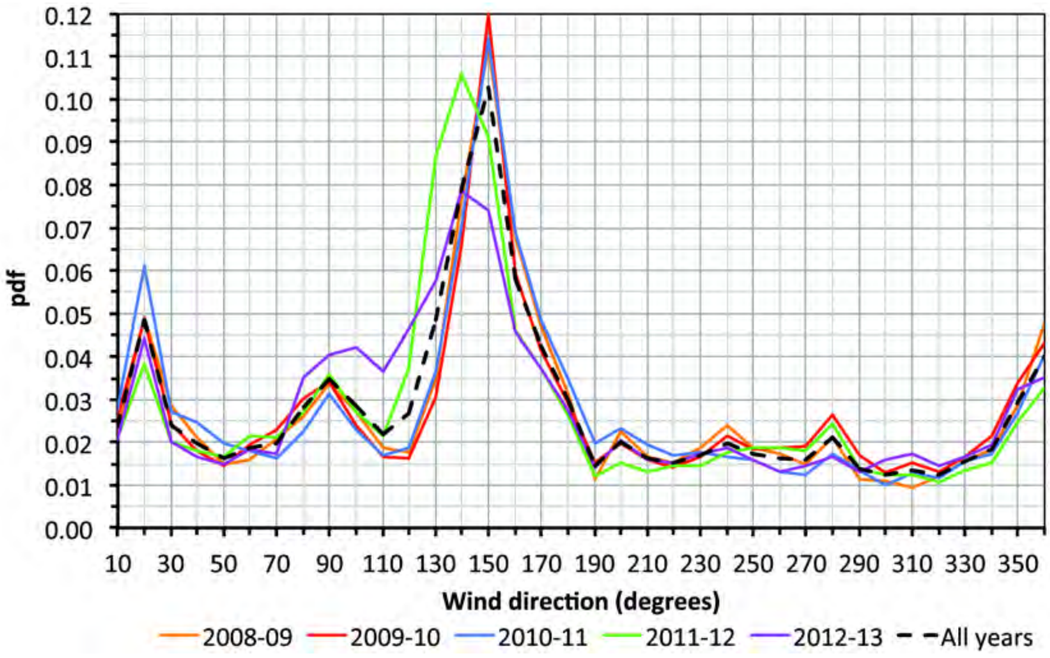

Figure 3 Comparison of annual observed wind direction frequency distributions to the mean

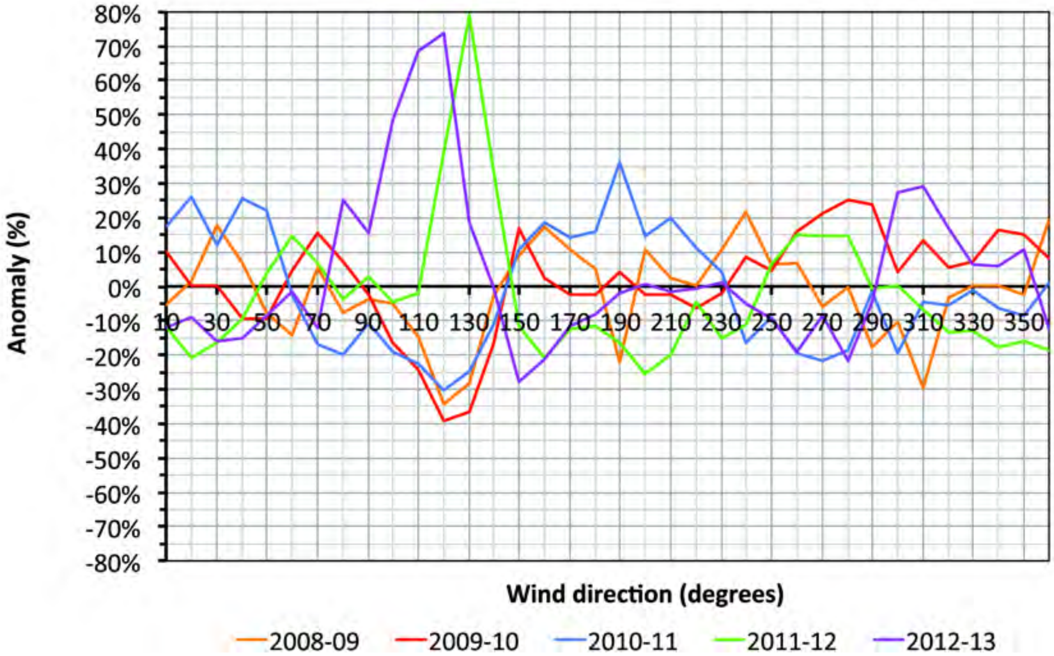

Figure 4 Annual observed wind direction distribution anomaly from the mean

The R^2 correlation statistics for each year on year, and each year versus the mean of all years, are summarised in Table 3.

Table 3 Correlation coefficients matrix of the distributions of wind direction

Period	2008-09	2009-10	2010-11	2011-12	2012-13	All years
2008-09	1	--	--	--	--	--
2009-10	0.9802	1	--	--	--	--
2010-11	0.9810	0.9689	1	--	--	--
2011-12	0.8287	0.7895	0.8038	1	--	--
2012-13	0.8401	0.7957	0.8173	0.9291	1	--
All years	0.9803	0.9614	0.9684	0.9128	0.9160	1

2.1.3 Wind vector U component

The annual and mean frequency distributions (probability density function [pdf]) of the wind vector U component and the anomaly of each year to the mean of the five-year period, March 2008 to February 2013, are presented in Figure 5 and Figure 6, respectively.

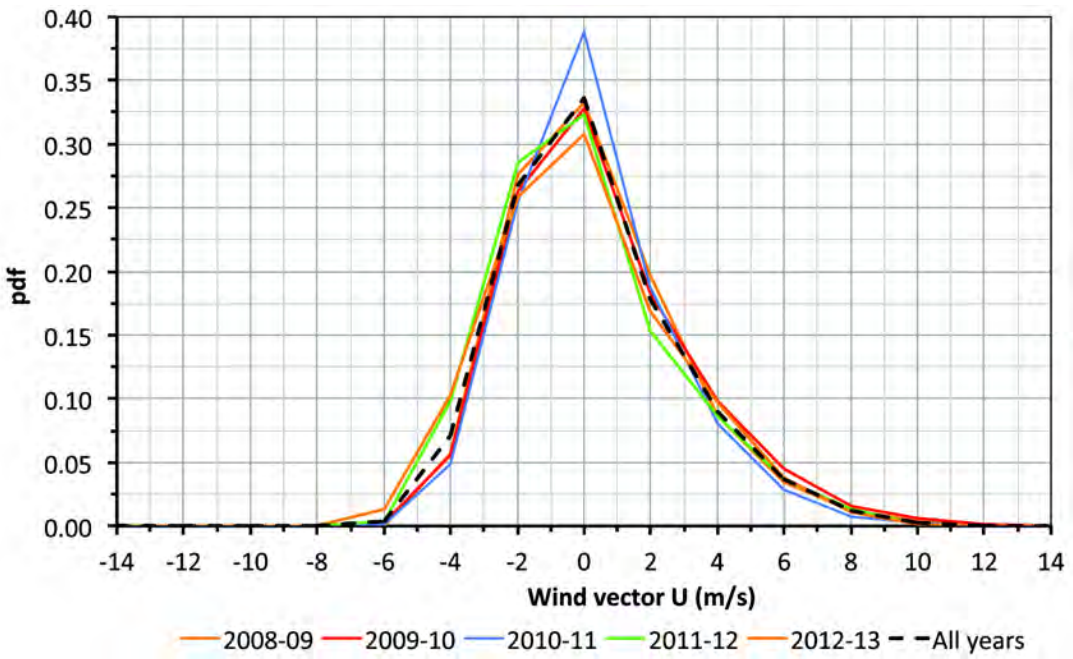

Figure 5 Comparison of annual observed wind vector U frequency distributions to the mean

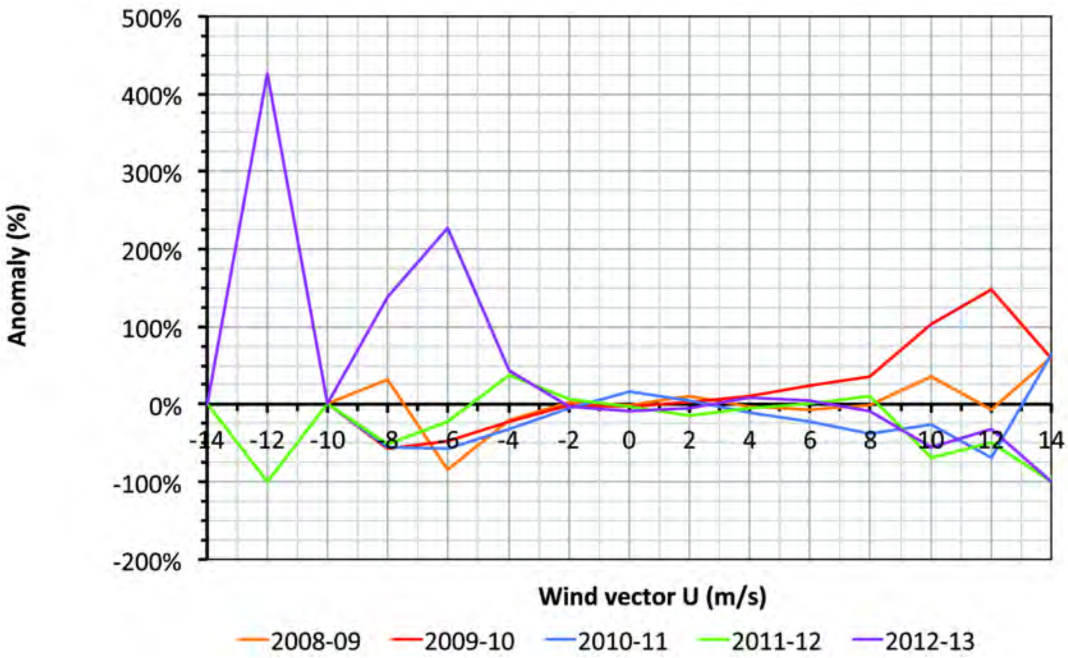

Figure 6 Annual observed anomaly of the wind vector U distribution from the mean

The R^2 correlation statistics for each year on year, and each year versus the mean of all years, are summarised in Table 4.

Table 4 Correlation coefficients matrix of the distributions of wind vector U component

Period	2008	2009	2010	2011	2012	All years
2008	1	--	--	--	--	--
2009	0.9988	1	--	--	--	--
2010	0.9924	0.9927	1	--	--	--
2011	0.9897	0.9900	0.9807	1	--	--
2012	0.9909	0.9917	0.9811	0.9969	1	--
All years	0.9983	0.9986	0.9937	0.9948	0.9955	1

2.1.4 Wind vector V component

The annual and mean frequency distributions (probability density function [pdf]) of the wind vector V component and the anomaly of each year to the mean of the five-year period, March 2008 to February 2013, are presented in Figure 7 and Figure 8, respectively.

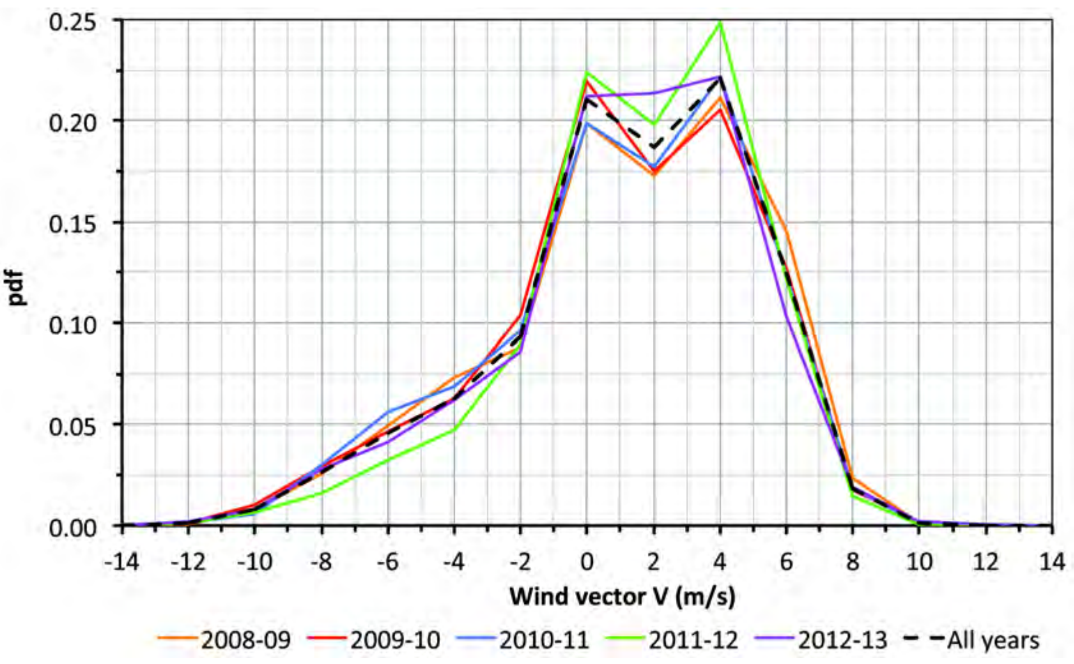

Figure 7 Comparison of annual observed wind vector V frequency distributions to the mean

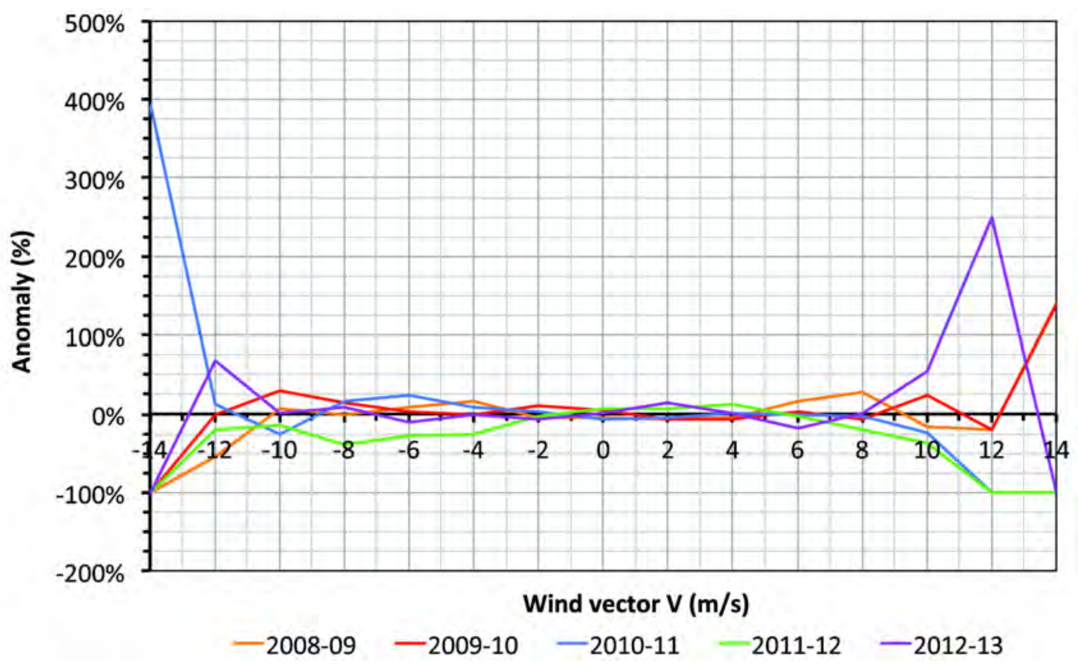

Figure 8 Annual observed anomaly of the wind vector V distribution from the mean

The R^2 correlation statistics for each year on year, and each year versus the mean of all years, are summarised in Table 5.

Table 5 Correlation coefficients matrix of the distributions of wind vector V component

	2008	2009	2010	2011	2012	All years
2008	1	--	--	--	--	--
2009	0.9943	1	--	--	--	--
2010	0.9964	0.9956	1	--	--	--
2011	0.9873	0.9906	0.9918	1	--	--
2012	0.9837	0.9887	0.9907	0.9936	1	--
All years	0.9959	0.9974	0.9984	0.9962	0.9948	1

2.2 Temperature

The annual and mean frequency distributions (probability density function [pdf]) of temperature and the anomaly of each year to the mean of the five-year period, March 2008 to February 2013, are presented in Figure 9 and Figure 10, respectively.

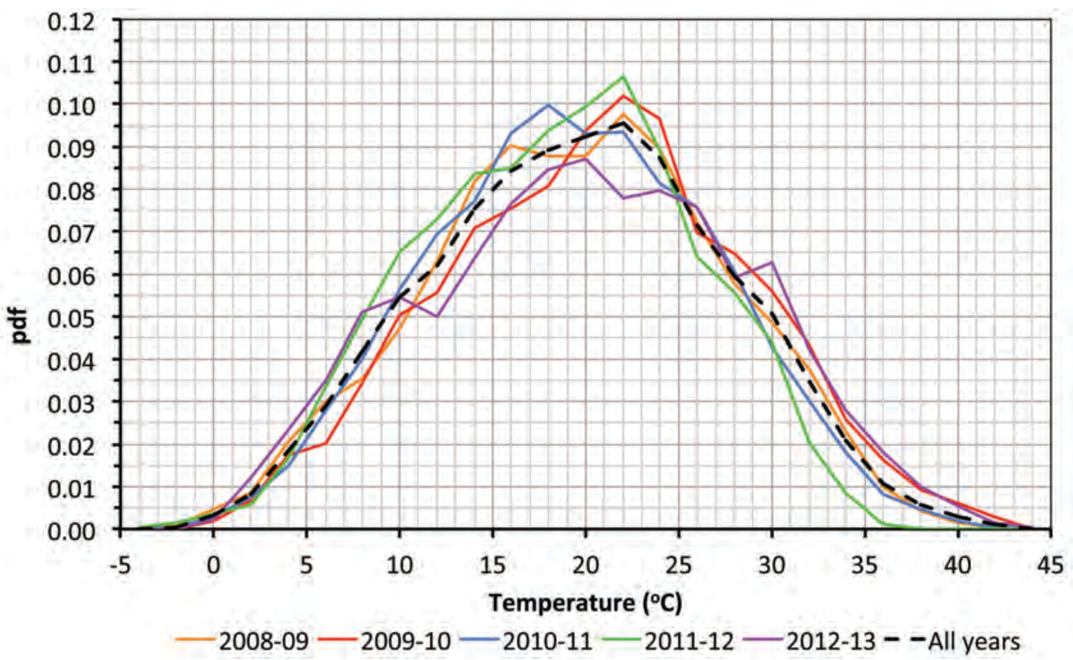

Figure 9 Comparison of annual observed temperature frequency distributions to the mean

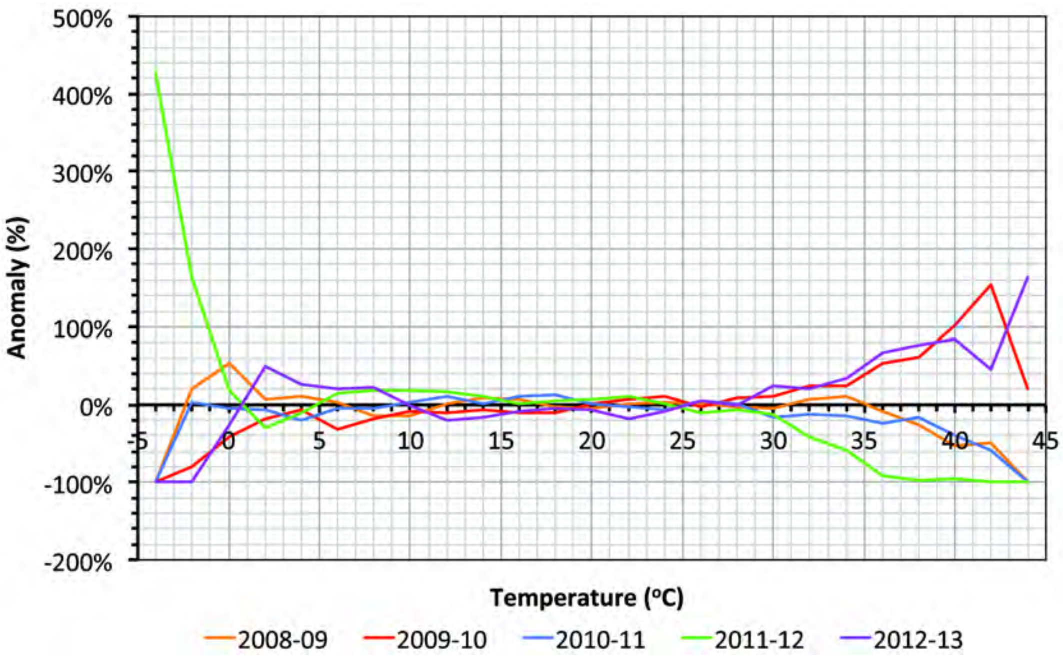

Figure 10 Annual observed temperature distribution anomaly from the mean

The R^2 correlation statistics for each year on year, and each year versus the mean of all years, are summarised in Table 6.

Table 6 Correlation coefficients matrix of the distributions of temperature

Period	2008-09	2009-10	2010-11	2011-12	2012-13	All years
2008-09	1	--	--	--	--	--
2009-10	0.9843	1	--	--	--	--
2010-11	0.9905	0.9697	1	--	--	--
2011-12	0.9785	0.9597	0.9852	1	--	--
2012-13	0.9710	0.9720	0.9685	0.9498	1	--
All years	0.9960	0.9877	0.9940	0.9862	0.9816	1

2.3 Relative humidity

The annual and mean frequency distributions (probability density function [pdf]) of relative humidity and the anomaly of each year to the mean of the five-year period, March 2008 to February 2013, are presented in Figure 11 and Figure 12, respectively.

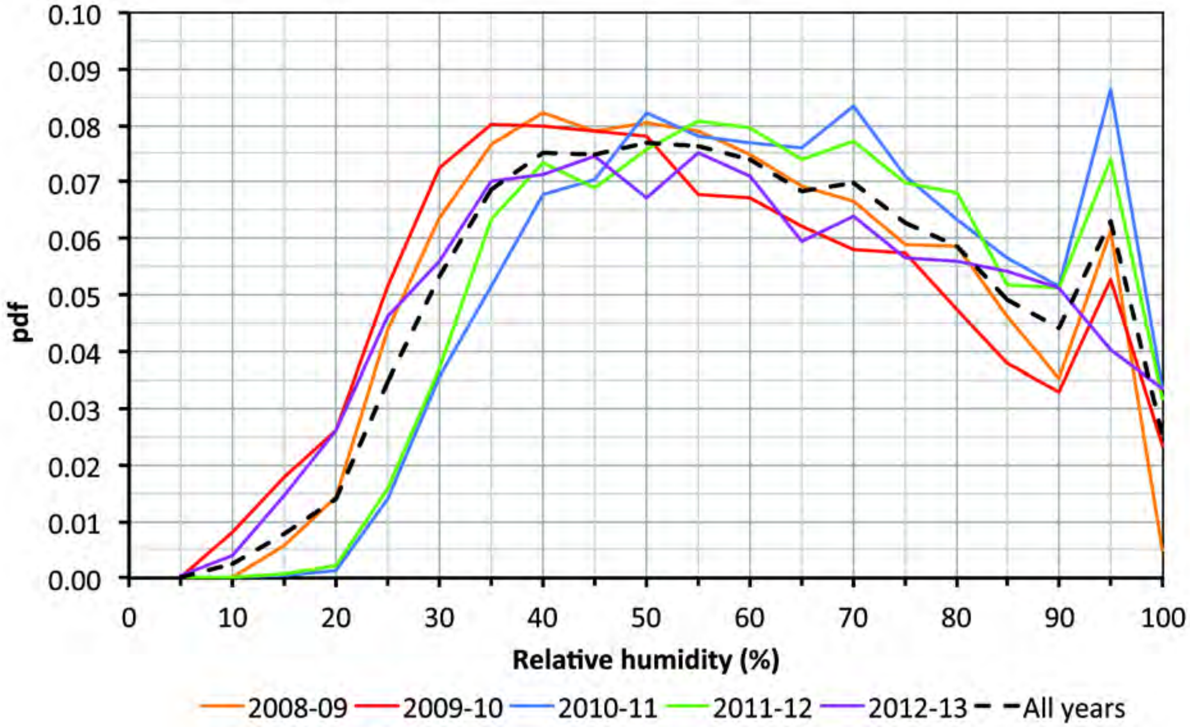

Figure 11 Comparison of annual observed relative humidity frequency distributions to the mean

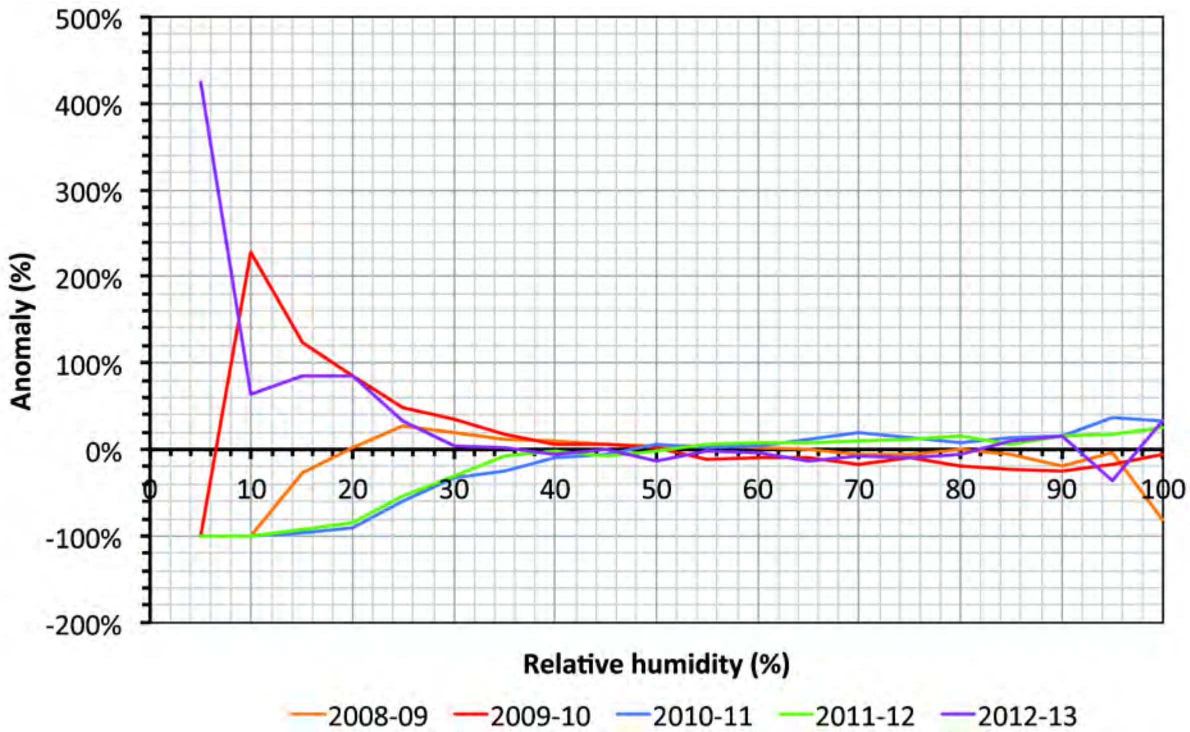

Figure 12 Annual observed relative humidity distribution anomaly from the mean

2.4 Rainfall

Variance in monthly rainfall over the five-year period is shown through the anomaly from the mean of each monthly mean for all years between 2002 and 2013, as shown in Figure 13.

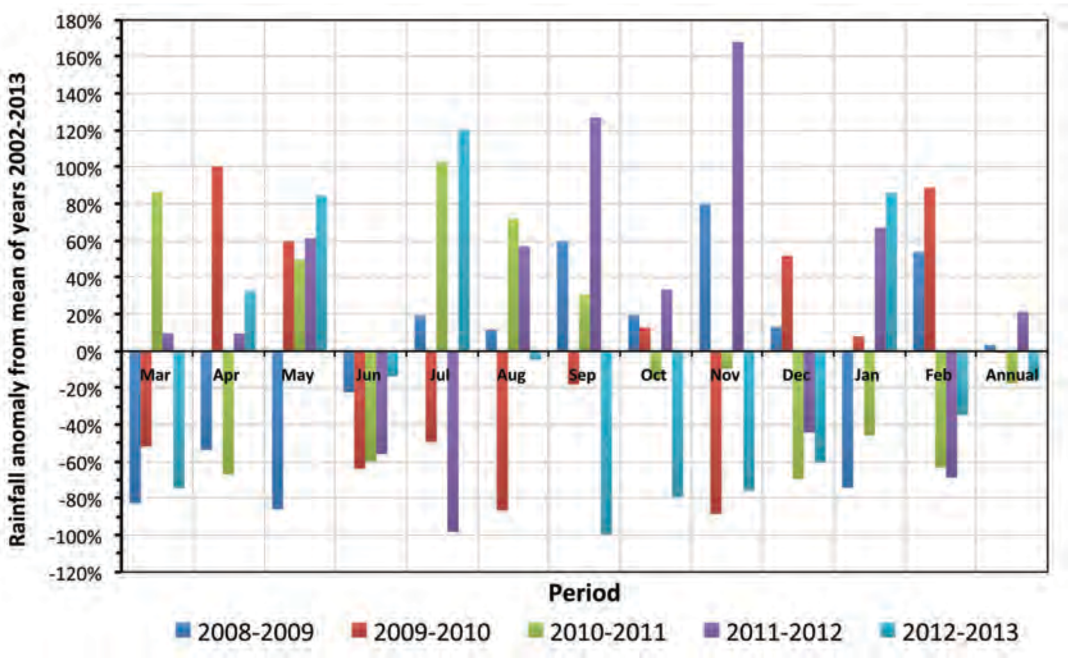

Figure 13 Monthly rainfall anomaly from the mean of all years during the period 2008 to 2013

2.5 El Nino Southern Oscillation

The El Nino Southern Oscillation (ENSO) classification and strength according to the Bureau of Meteorology for the period assessed, March 2008 – February 2013, are presented in Table 7.

Table 7 Annual El Nino Southern Oscillation classifications

Year	Classification
2008-09	La Nina (weak)
2009-10	El Nino (moderate)
2010-11	La Nina (strong)
2011-12	La Nina (weak)
2012-13	Neutral

2.6 Representative meteorological year selection

The most representative year of the five-year period investigated, March 2008 – February 2013, was selected by:

- ranking each of the key meteorological variables according to their correlation with the mean of the five year period,
- comparing the shape and fit of the distributions against that of the mean of the five year period,

- evaluating the variation of annual and monthly rainfall from the mean of all years of data, i.e. 2002-2013, and
- taking into consideration the ENSO classification for the year.

A summary of the rank of the correlation statistic (R^2) for each year against the mean of the five-year period is presented in Table 8.

Table 8 Meteorological variable correlation ranks

Year	Wind speed	Wind direction	Temperature	Relative humidity	Wind vector U component	Wind vector V component	Aggregate ranking	Final rank
2008-09	3	1	1	1	2	4	12	1
2009-10	2	3	3	5	1	2	16	2
2010-11	5	2	2	4	5	1	19	3
2011-12	4	5	4	2	4	3	22	5
2012-13	1	4	5	3	3	5	21	4

3 Conclusion

The analysis found that the:

- The years 2008-09 and 2009-10 were the closest to the mean in terms of wind field representation.
- The year 2008-09 had the closest correlation in terms of temperature and relative humidity.
- The year 2008-09 provided a reasonable representation of monthly rainfall patterns by comparison to the mean of all years between 2002 and 2013.
- The year 2008-09 was characterised by a weak strength La Nina, while the year 2009-10, which had a slightly higher correlation for winds, was characterised by a moderate strength El Nino.

Based on this assessment, the year March 2008 to February 2009 was selected as a representative period for the meteorological modelling simulation.

AIR ENVIRONMENT CONSULTING

Appendix D

Meteorological Model Performance Evaluation

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1 Methodology for the evaluation of meteorological model performance

1.1 Approach to the meteorological modelling

The meteorological modelling was conducted as a two-stage process once the year to model was selected. The modelling sequence was as follows:

1. Run TAPM in default mode with a standard mother domain with three nested daughter grids at 30 km, 10 km 3 km, and 1 km grid cell resolution. Evaluate output.
2. Run CALMET in Hybrid Mode, using three-dimensional output from TAPM as an 'initial guess' in the Step 1 Wind Field and assimilate surface meteorological information from Narrabri Airport automatic weather station (AWS) into the Step 2 Wind Field to nudge the three-dimensional TAPM Step 1 Wind Field. Evaluate output.

The analysis presented in this section is the model performance evaluation for these two stages.

1.2 Approach to the performance evaluation

For the evaluation of the TAPM and CALMET model performances to simulate the wind fields in the region, two statistical techniques were used:

1. Comparison of the distributions of key meteorological parameters through presentation of the modelled versus observed probability density functions for the BoM AWS site at Narrabri Airport –
   a. Wind speed.
   b. Wind direction.
   c. Temperature.
   d. U vector wind.
   e. V vector wind.

This analysis provides for the evaluation of the model's ability to predict the correct distributions of important parameters and is a reasonable approach to evaluating meteorological model performance.

2. Correlation of the observed and predicted wind speeds on a time and space basis including –
   a. Mean.
   b. Standard deviation.
   c. Index of Agreement.
   d. Root Mean Square Error (RMSE).
   e. Systematic Root Mean Square Error ($RMSE_S$).
   f. Unsystematic Root Mean Square Error ($RMSE_U$).
   g. Skill_E.
   h. Skill_V.
   i. Skill_R.

This analysis is more stringent and provides for the evaluation of the model's ability to predict the correct conditions during each hour of the year. In general for a model such as TAPM, it is unrealistic to expect that the model will accurately predict the surface conditions at a specific point in space at a specific point in time. The model is a regional-scale model that is skilled at computing the fluid dynamics of general synoptic-scale atmospheric circulations and predicting phenomena such as sea breezes, land breezes, large scale terrain affected flows and temperatures based on variable synoptic inputs, terrain and land use influences.

To evaluate the model's ability to predict the correct wind direction for each hour of the year, wind speed must be included in the analysis. Consequently, the entire wind field is broken down into its vector components, U (north-south) and V (east-west).

1.3 Correlation statistics for observed and predicted meteorology

Balch (2009) summarised the following statistical approach for the evaluation of meteorological model performance based on the methods described by Chang and Hanna (2005) and Wilmott (1982).

Root mean square error (RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}$$

Where:

N = number of observed and predicted hours in analysis (i.e. one year)

P = hourly prediction

O = hourly observation

The RSME can be described as the standard deviation of the difference for hourly predicted and observed pairings at a specific point. The RMSE is a quadratic scoring rule, which measures the average magnitude of the error. The difference between predicted and corresponding observed values are each squared and then averaged over the sample. Finally, the square root of the average is taken. Since the errors are squared before they are averaged, the RMSE gives a relatively high weight to large errors. This means the RMSE is most useful when large errors are particularly undesirable. Overall, the RSME is a good overall measure of model performance, but since large errors are weighted heavily (due to squaring), its value can be distorted. RMSE is equal to the unit of the values being analysed i.e., an RMSE of 1.2 for wind speed = 1.2 m/s.

Systematic root mean square error ($RMSE_S$)

$$\text{RMSE}_S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{P}_i - O_i)^2}$$

Where:

N = number of observed and predicted hours in analysis (i.e. one year)

$\hat{P}$ = mean of predictions

O = hourly observation

The $RMSE_s$ is calculated as the square root of the mean square difference of hourly predictions from the regression formula and observation pairings, at a specific point. The regressed predictions are taken from the least squares formula. The $RMSE_s$ estimates the model's linear (or systematic) error. The systematic error is a measure of the bias in the model due to user input or model deficiency, i.e., data input errors, assimilation variables, and choice of model options. The $RMSE_s$ is a metric for the model's accuracy.

Unsystematic root mean square error ($RMSE_u$)

$$\mathrm{RMSE_U} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{P}_i - P_i)^2}$$

Where:

N = number of observed and predicted hours in analysis (i.e. one year)

$\hat{P}$ = mean of predictions

O = hourly prediction

The $RMSE_u$ is calculated as the square root of the mean square difference of hourly predictions from the regression formula and model prediction value pairings, at a specific point. The $RMSE_u$ is a measure of how much of the difference between predictions and observations result from random processes or influences outside the legitimate range of the model. This error may require model refinement, such as new algorithms or higher resolution grids, or that the phenomena being simulated cannot be fully resolved by the model. The $RMSE_u$ is a metric for the model's precision.

Ultimately, for good model performance, the RMSE should be a low value, with most of the variation explained in the observations. Here, the systematic error $RMSE_s$ should approach zero and the unsystematic error, $RMSE_{u,}$ should approach the RMSE since:

$$\mathrm{RMSE}^2 = \mathrm{RMSE_S^2} + \mathrm{RMSE_u^2}$$

Mean error and mean absolute error

The Mean Error (ME) is simply the average of the hourly modelled values minus the hourly observed values. It contains both systematic and unsystematic errors and is heavily influence by high and low errors.

The Mean Absolute Error (MAE) measures the average magnitude of the errors in a set of predictions, without considering their direction. It measures accuracy for continuous variables. Expressed in words, the MAE is the average of the absolute values of the differences between predictions and the corresponding observation. The MAE is a linear score, which means that all the individual differences are weighted equally in the average. The MAE and the RMSE can be used together to diagnose the variation in the errors in a set of predictions. The RMSE will always be larger or equal to the MAE; the greater difference between them, the greater the variance in the individual errors in the sample. If the RMSE = MAE, then all the errors are of the same magnitude. Both the MAE and RMSE can range from 0 to ∞. They are negatively-oriented scores, i.e., lower values are better.

Index of agreement

The Index of Agreement (IOA) is defined as:

$$\text{IOA} = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i - O_{mean}| + |O_i - O_{mean}|)^2}$$

The IOA is calculated using a method described in Willmott (1982). The IOA can take a value between 0 and 1, with 1 indicating perfect agreement. The IOA is the ratio of the total RMSE to the sum of two differences, i.e., the difference between each prediction and the observed mean, and the difference between each observation and observed mean. From another perspective, the IOA is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean. A value of 0.5 is considered acceptable and >0.6 is considered good performance for time and space predictions.

Where:

N is the number of observations,

P_i are the hourly model predictions,

O_i are the hourly observations,

O_{mean} is the observed observation mean, and $\hat{P}_i = a + bO_i$ is the linear regression fitted with intercepts a and slope b.

Skill measures

Skill measure statistics are given in terms of a score, rather than in absolute terms. A model's skill can be measured by the difference in the standard deviation of the modelled and observed values (Chang and Hanna, 2004).

The **Skill_E (se)** is indicative of how much of the standard deviation in the observations is predicted to be due to random/natural processes (unsystematic) in the atmospheric boundary layer. i.e., turbulence/chaos. For good model performance, the value for Skill_E should be less than one, i.e.:

SKILL_E = (RMSE_U/ STDEV OBS) < 1 shows skill

Skill_V (sv) is ratio of the standard deviation of the model predictions to the standard deviation of the observations. For good model performance, the value for Skill_V should be close to one, i.e.:

SKILL_V = (STDEV_MOD/ STDEV _OBS) close to 1 shows skill

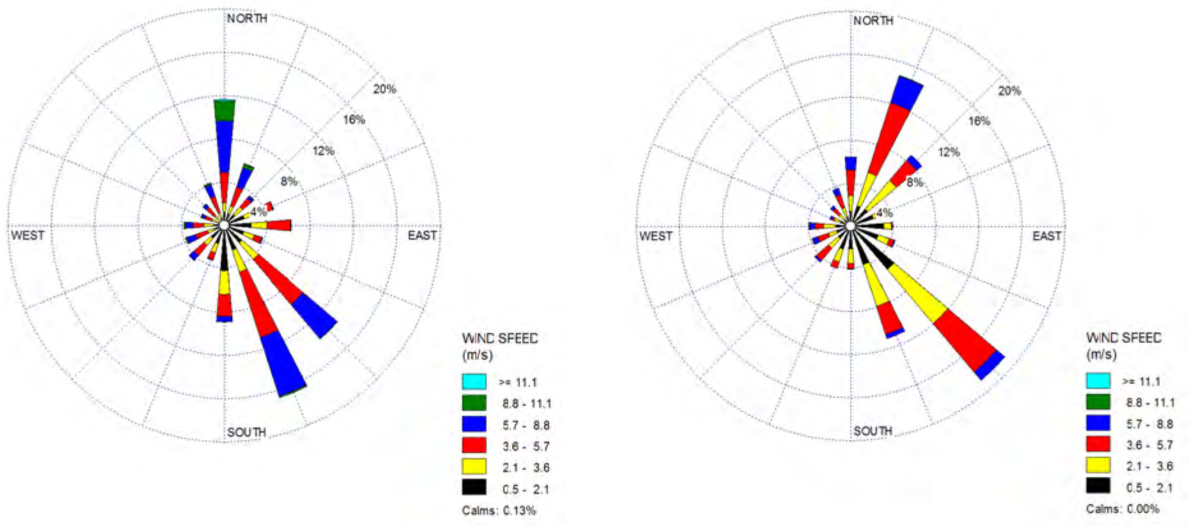
SKILL_R (sr) takes into account systematic and unsystematic errors in relation to the observed standard deviation. For good model performance, the value for Skill_E should be less than one, i.e.:

SKILL_R = (RMSE/ STDEV _OBS) < 1 shows skill

2 TAPM model performance evaluation

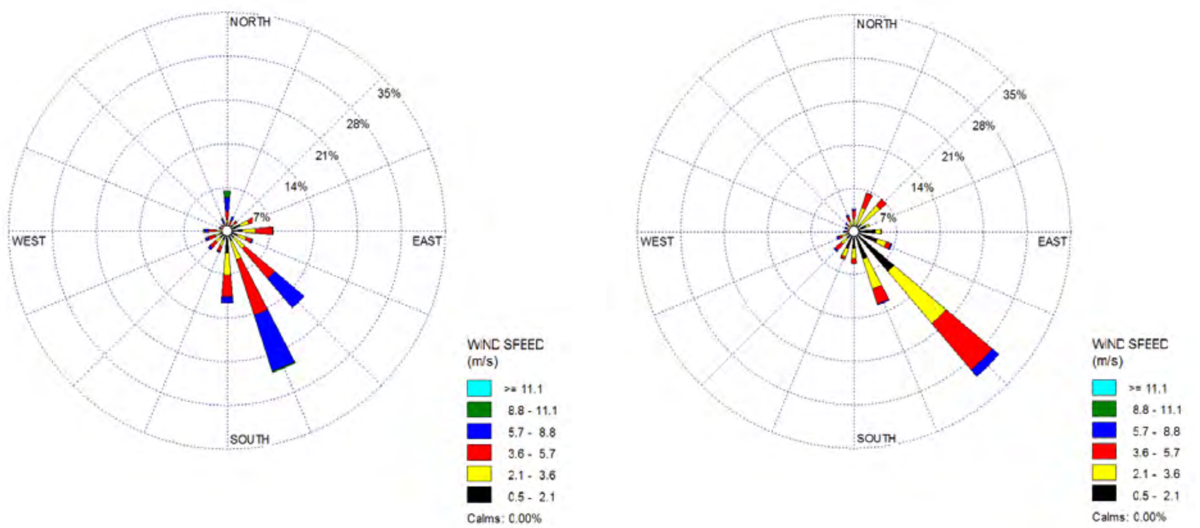
2.1 Analysis of distributions of meteorological variables

A comparison of TAPM predicted and observed meteorology at Narrabri Airport AWS is presented in this section. The wind rose diagrams for the annual and seasonal distributions of TAPM predicted and AWS observed winds are presented in Figure 1 to Figure 5.



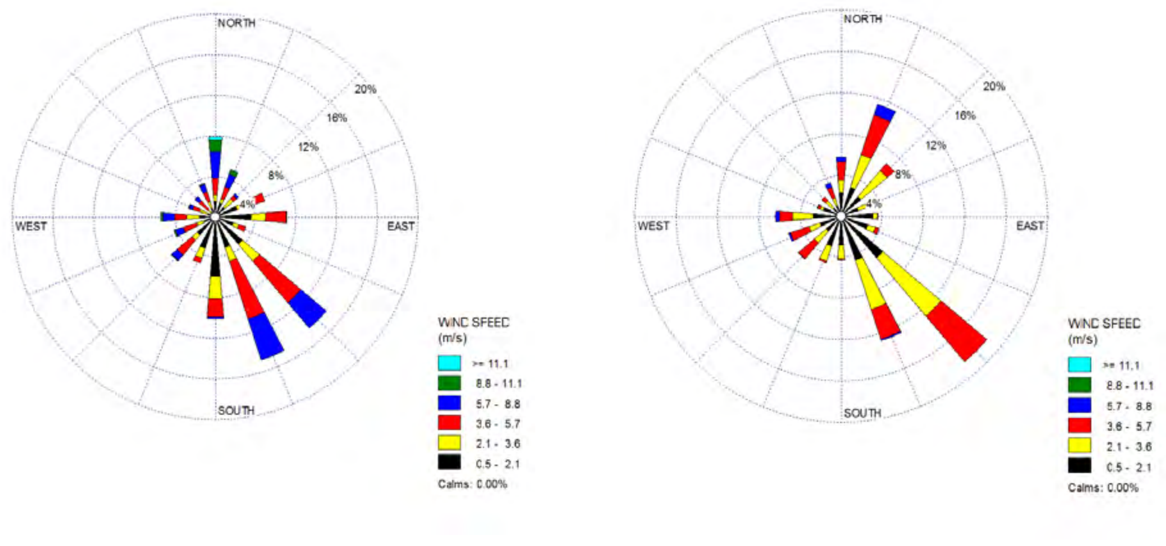
AWS observations TAPM modelled

Figure 1 Annual distributions of wind speed and direction, as a wind rose diagram, for the TAPM predicted and BOM AWS datasets at the Narrabri Airport AWS site



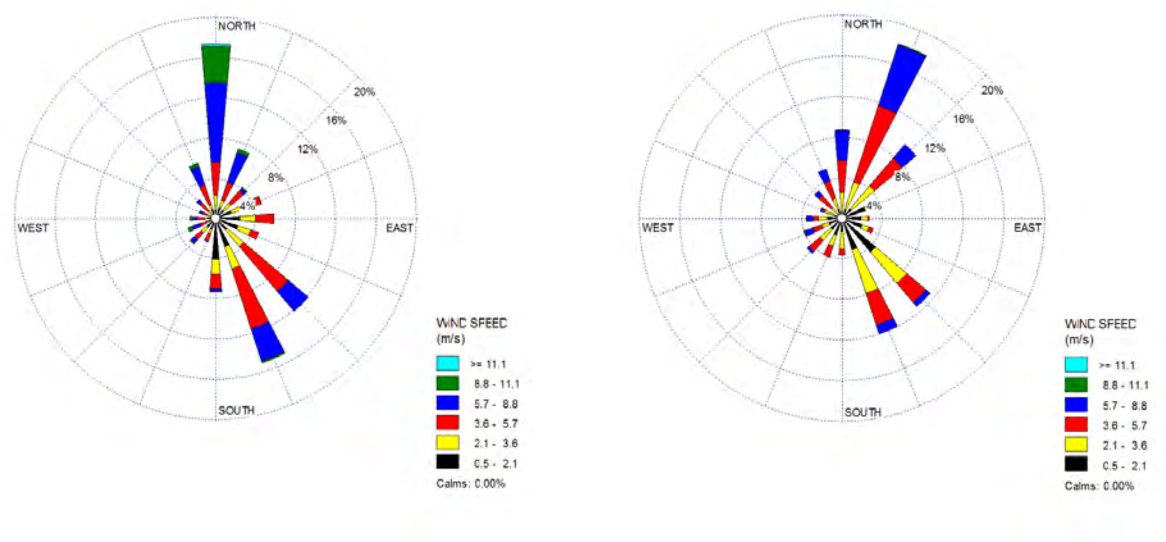
AWS observations TAPM modelled

Figure 2 Distributions of autumn wind speed and direction for the observed and modelled datasets



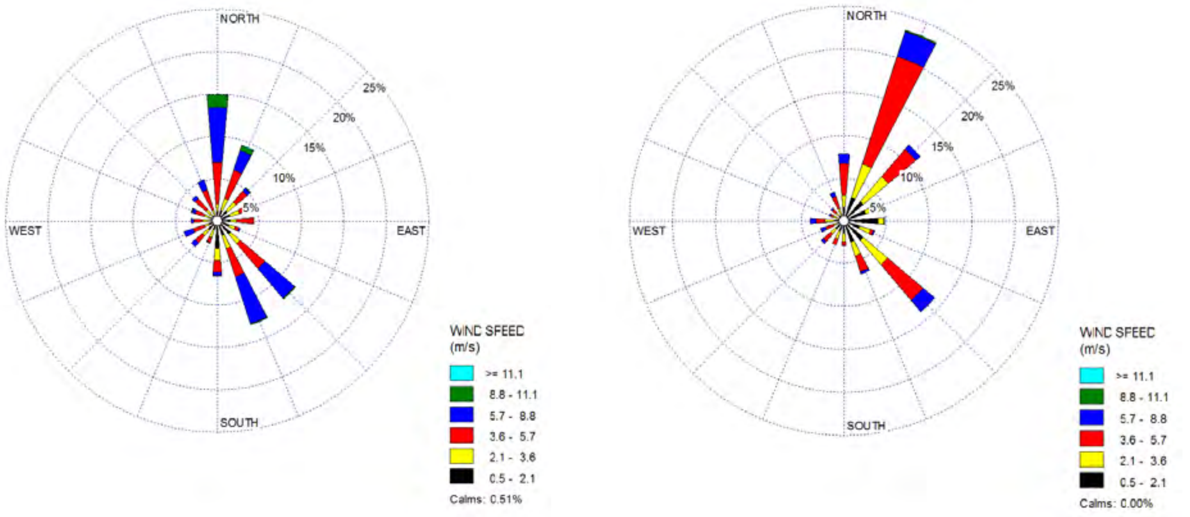
AWS observations TAPM modelled

Figure 3 Distributions of winter wind speed and direction for the observed and modelled datasets



AWS observations TAPM modelled

Figure 4 Distributions of spring wind speed and direction for the observed and modelled datasets



AWS observations TAPM modelled

Figure 5 Distributions of summer wind speed and direction for the observed and modelled datasets

A comparison of the distributions of wind speed, wind direction, vector U wind and vector V wind components and temperature are presented as probability density function plots in Figure 6 to Figure 10, respectively.

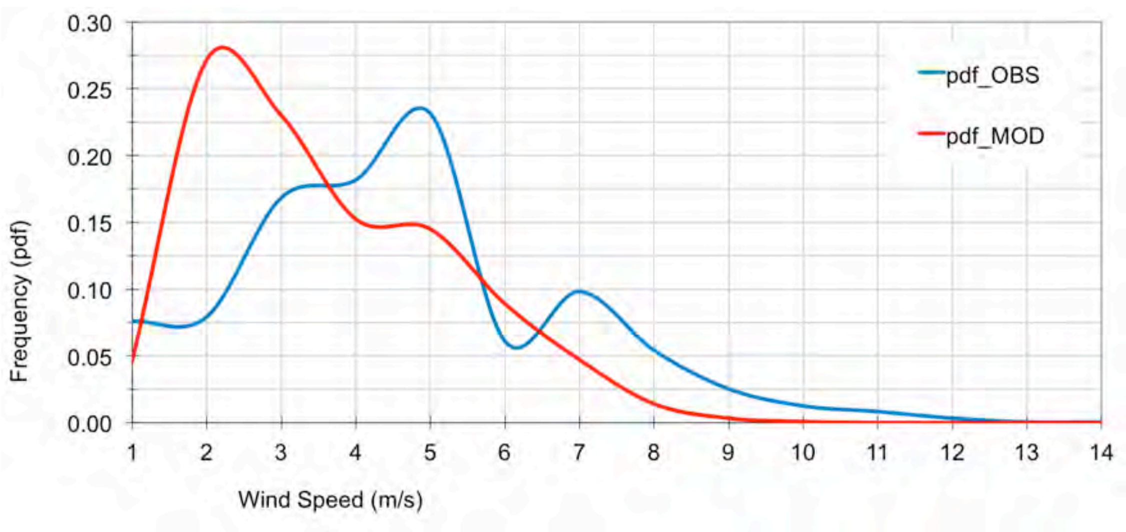


Figure 6 Frequency distributions of observed versus TAPM predicted (modelled) wind speed at the BOM AWS site

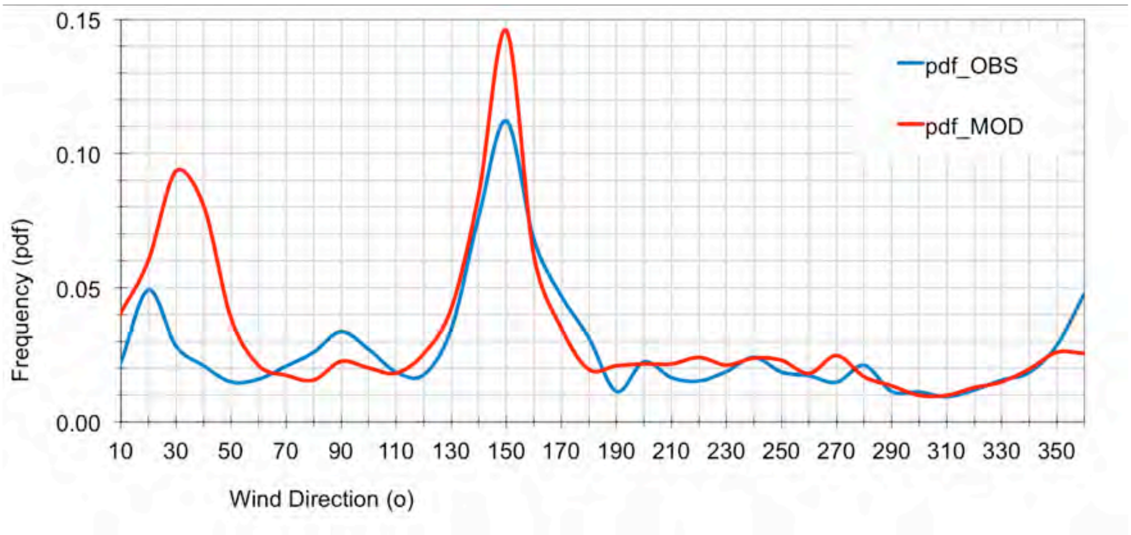


Figure 7 Frequency distributions of observed versus TAPM predicted (modelled) wind direction at the BOM AWS site

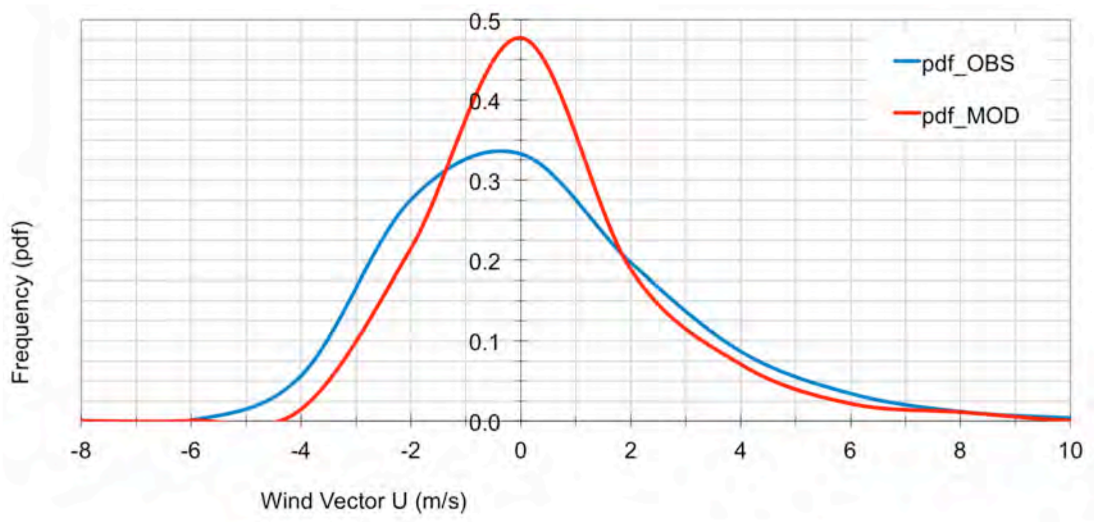


Figure 8 Frequency distributions of observed versus TAPM predicted (modelled) wind vector component U at the BOM AWS site

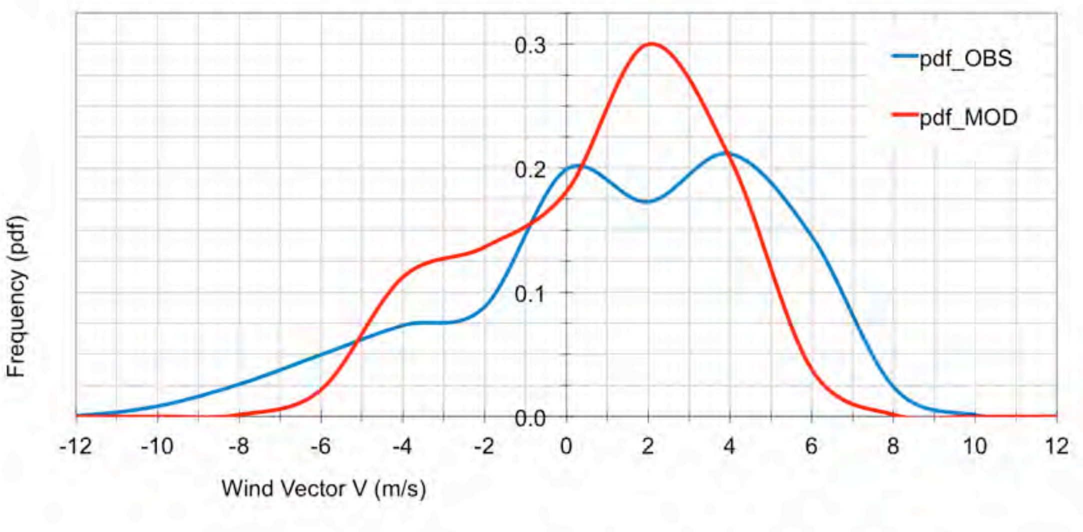


Figure 9 Frequency distributions of observed versus TAPM predicted (modelled) wind vector component V at the BOM AWS site

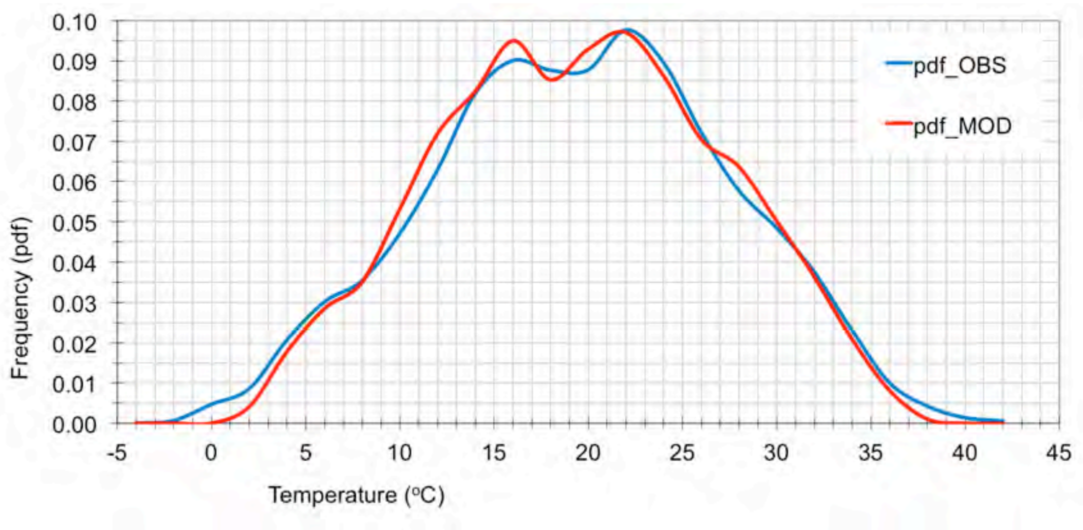


Figure 10 Frequency distributions of observed versus TAPM predicted (modelled) surface air temperatures at the BOM AWS site

The charts indicate the following:

- TAPM performs reasonably well in predicting the general shape of the distributions of wind direction and temperature, but performs poorly in simulating wind speed.
- TAPM over-predicts the frequency of light winds in the 0 – 3.5 m/s range, and under-predicts the frequency of moderate wind speeds in the 3.5 – 5.5 m/s range. This is a common finding with TAPM v4 since adjustments to the model algorithms were made after issues were raised regarding TAPM v3's under-estimation of light wind frequency. TAPM v3's under-prediction of light winds raised issues when modelling odour emissions that typically generate impacts under light wind, stable atmospheric conditions. To improve upon this finding, wind observations have been incorporated into the CALMET model (see section 3).
- TAPM performs well in predicting the shape of the distribution of wind direction.

- TAPM generally performs well in predicting hourly temperatures, except for temperatures below 0°C and above 38°C.
- TAPM performs reasonably well in predicting the shape of the wind vector U distribution, while exaggerating the peak of the wind vector V distribution.

2.2 Analysis of predicted meteorology in time and space

Descriptive statistics for the modelled and observed winds are presented in Table 1.

Table 1 Descriptive statistics for meteorological observations and TAPM model predictions

Descriptive Statistics	Wind speed		Wind direction		Temperature		U Vector wind		V Vector wind	
	AWS OBS	TAPM MOD	AWS OBS	TAPM MOD	AWS OBS	TAPM MOD	AWS OBS	TAPM MOD	AWS OBS	TAPM MOD
Average	4.0	3.2	165.0	142.8	18.6	19.0	-0.7	-0.6	0.3	-0.2
Standard deviation	2.3	1.7	97.8	97.3	7.9	7.5	2.5	2.0	3.8	2.9
Minimum	0.0	0.5	0.0	0.0	-3.6	1.0	-8.8	-6.5	-13.1	-8.9
Maximum	13.9	9.6	360.0	359.0	41.8	38.0	12.5	9.1	13.1	7.1

Correlation statistics for the performance of TAPM when compared to the observations at Narrabri Airport AWS are summarised in Table 2.

Table 2 Meteorological model correlation statistics for TAPM performance

Statistics	Wind speed	Wind direction	Temperature	U vector wind	V vector wind
RMSE	2.7	138.7	6.4	2.9	3.9
$RMSE_S$	2.2	98.7	3.1	2.2	2.8
$RMSE_U$	1.6	97.4	5.7	2.0	2.7
IOA	0.5	0.4	0.8	0.5	0.6
$Skill_e$	0.7	1.0	0.7	0.8	0.7
$Skill_v$	0.7	1.0	0.9	0.8	0.7
$Skill_r$	1.2	1.4	0.8	1.2	1.0
MAE	2.2	99.6	5.0	2.2	3.0

The correlation statistics indicate the following:

- The RMSE and MAE statistics indicate a slightly poor performance. However, as discussed in Appendix D Section 1.1, it is not expected that TAPM will predict the exact wind speed and direction in time and space.
- The IOA statistics indicate the model's performance is slightly poor but within an acceptable range.
- The $Skill_e$ and $Skill_v$ values show good performance, however the $Skill_r$ indicates poor performance for wind direction.

Overall, the evaluation indicates that TAPM has performed well in predicting temperature but less well in predicting the regional wind fields. The distribution of predicted wind direction is in good agreement with the observations, however the model does not predict the wind direction well in time and space. The model also performs poorly in predicting the distribution of wind speeds in the local area.

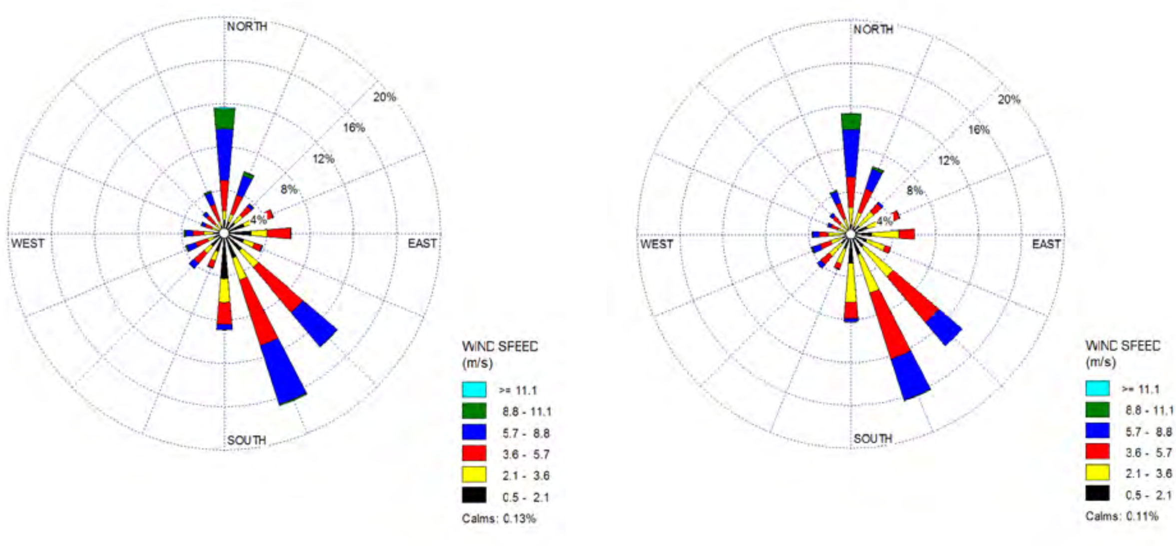
An important consideration is that the AWS sensors are situated at a specific location at Narrabri Airport, 10 metres above the ground, and that the observations are influenced by its surrounds. Consequently, it is inherently difficult for a prognostic mesoscale meteorological model to downscale to tens and hundreds of metres to predict specific hourly conditions with absolute accuracy and precision. The model's performance is relative and should be considered in light of the quality of the observed data and model inputs.

It is considered that TAPM's performance is acceptable for use in the dispersion modelling study and that further improvement of the local wind fields has been achieved by using the TAPM output as an input to the CALMET model and assimilating the Narrabri Airport data into the CALMET simulation. An evaluation of the CALMET model's performance is presented in the following section.

3 CALMET model performance evaluation

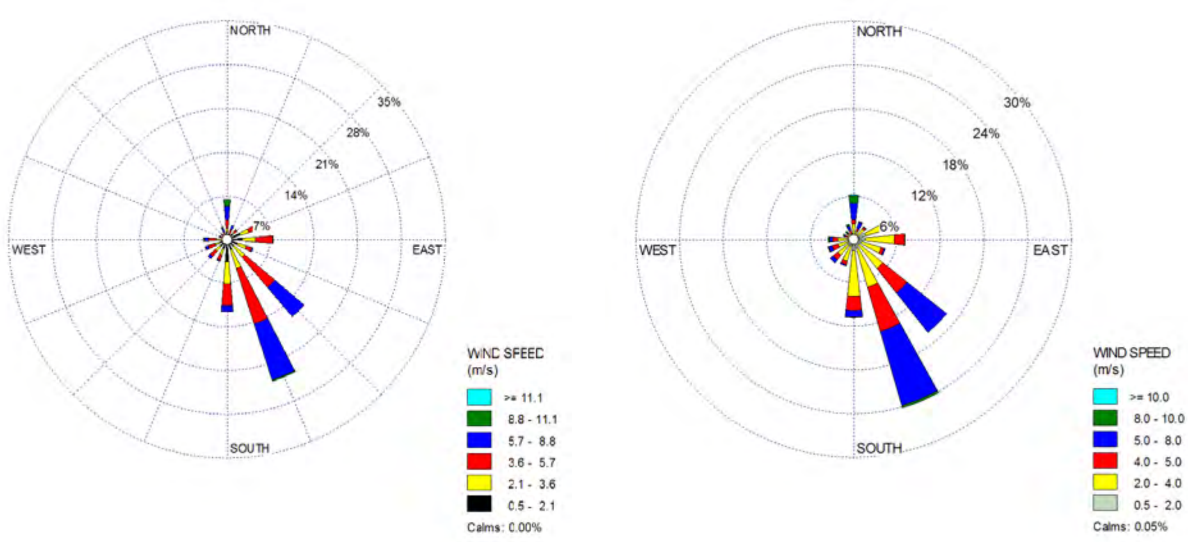
3.1 Analysis of distributions of meteorological variables

CALMET was run in Hybrid Mode with observed data from the BOM Narrabri Airport AWS incorporated into the model. A comparison of CALMET predicted and observed meteorology is presented in this section. The wind rose diagrams for the annual and seasonal distributions of CALMET predicted and AWS observed winds are presented in Figure 11 to Figure 15.



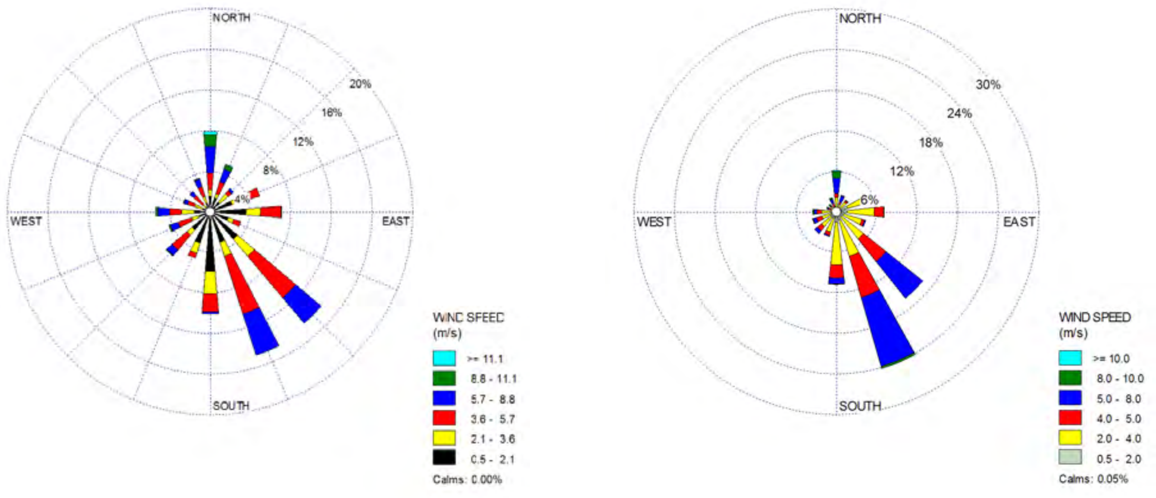
AWS Observations CALMET predicted

Figure 11 Annual distributions of wind speed and direction, as a wind rose diagram, for the CALMET predicted and BOM AWS datasets at the Narrabri Airport AWS site



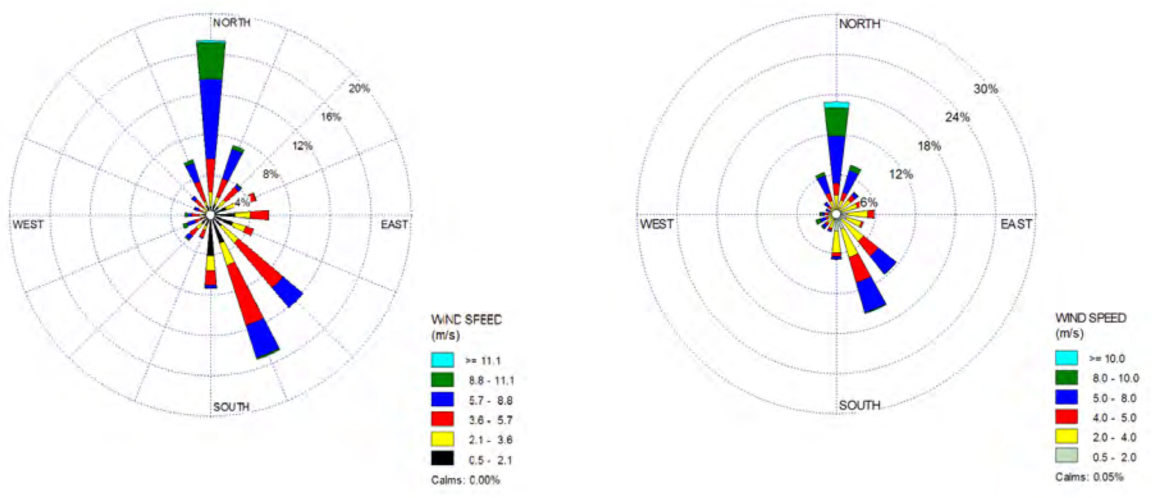
AWS observations CALMET modelled

Figure 12 Distributions of autumn wind speed and direction for the observed and modelled datasets



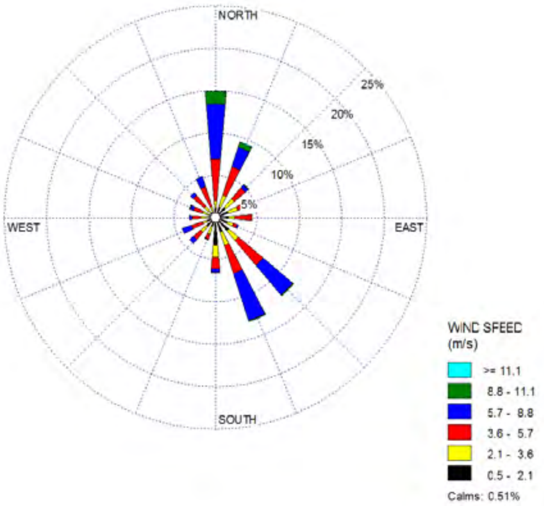
AWS observations CALMET modelled

Figure 13 Distributions of winter wind speed and direction for the observed and modelled datasets

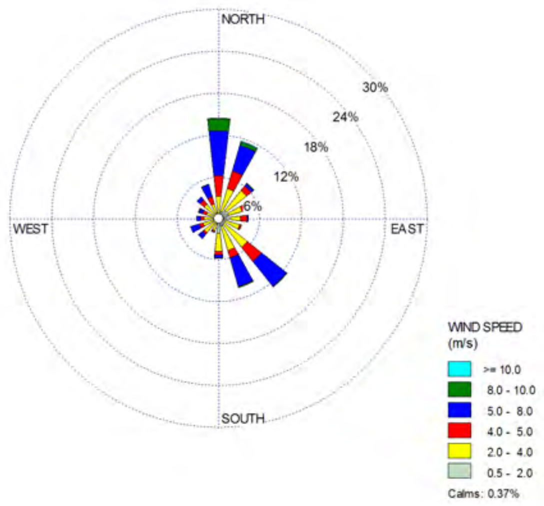


AWS observations CALMET modelled

Figure 14 Distributions of spring wind speed and direction for the observed and modelled datasets



AWS observations



CALMET modelled

Figure 15 Distributions of summer wind speed and direction for the observed and modelled datasets

A comparison of the distributions of wind speed, wind direction, vector U wind and vector V wind components and temperature are presented as probability density function plots in Figure 16 to Figure 20, respectively.

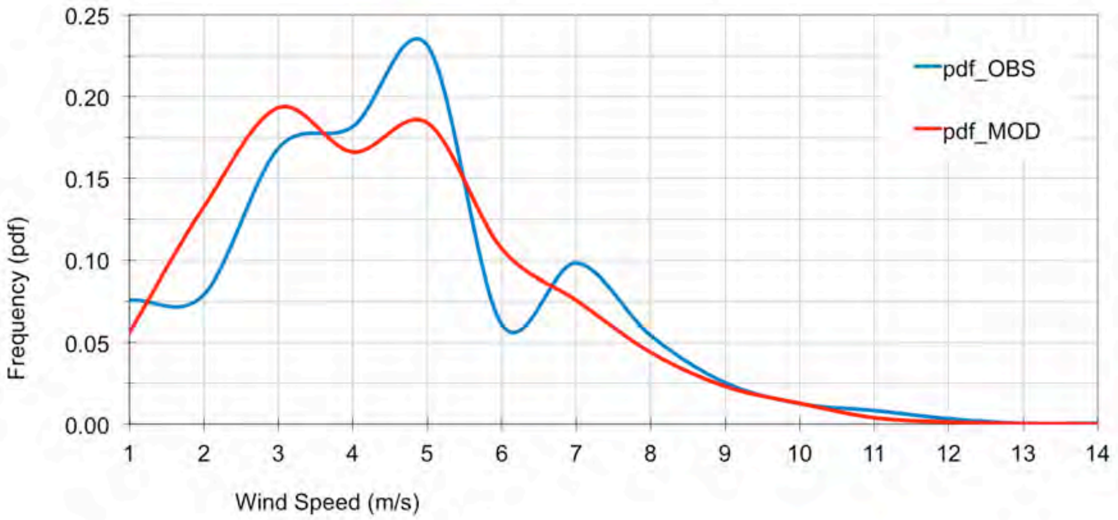


Figure 16 Frequency distributions of observed versus CALMET predicted (modelled) wind speed at the BOM AWS site

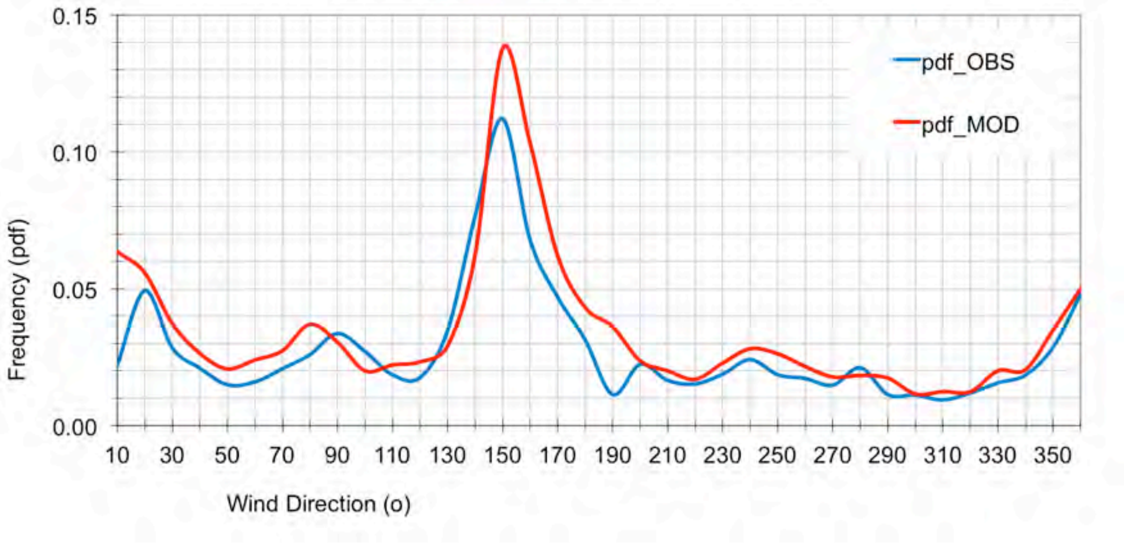


Figure 17 Frequency distributions of observed versus CALMET predicted (modelled) wind direction at the BOM AWS site

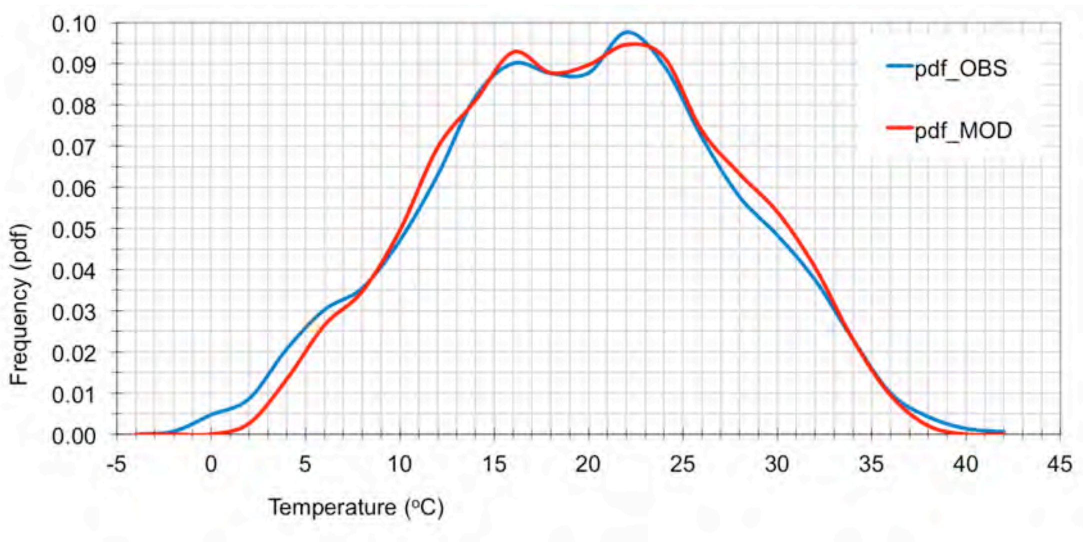


Figure 18 Frequency distributions of observed versus CALMET predicted (modelled) surface air temperatures at the BOM AWS site

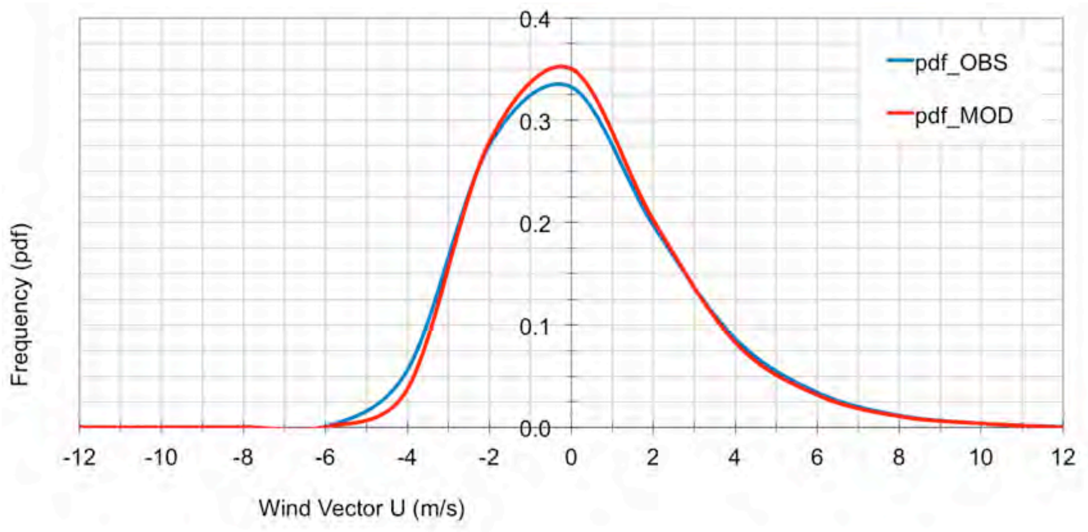


Figure 19 Frequency distributions of observed versus CALMET predicted (modelled) wind vector component U at the BOM AWS site

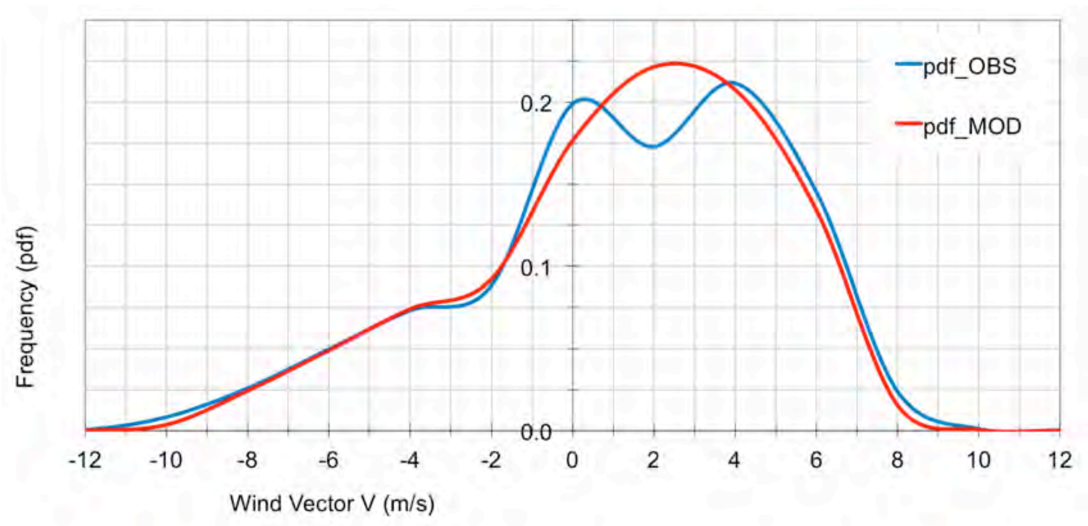


Figure 20 Frequency distributions of observed versus CALMET predicted (modelled) wind vector component V at the BOM AWS site

The charts indicate the following:

- The assimilation of wind speed and direction surface observations has significantly improved the distribution of predicted wind speed, and improved the distribution of predicted wind direction.
- The PDF plots and wind roses show improved correlation of the distributions of wind speed and direction. As expected, the skill of the model to predict wind speed has been improved with the assimilated winds.
- The shape of the distributions of the U and V vector components are in good agreement.

3.2 Analysis of predicted meteorology in time and space

Descriptive statistics for the modelled and observed winds are presented in Table 3.

Table 3 Descriptive statistics for meteorological observations and CALMET model predictions

Descriptive Statistics	Wind speed		Wind direction		Temperature		U vector wind		V vector wind	
	AWS OBS	CALMET MOD	AWS OBS	CALMET MOD	AWS OBS	CALMET MOD	AWS OBS	CALMET MOD	AWS OBS	CALMET MOD
Average	4.0	3.9	165.0	158.9	18.6	18.9	-0.7	-0.6	0.3	0.2
Standard deviation	2.3	2.1	97.8	97.8	7.9	7.5	2.5	2.4	3.8	3.7
Minimum	0.0	0.3	0.0	0.0	-3.6	0.8	-8.8	-8.1	-13.1	-13.0
Maximum	13.9	13.2	360.0	360.0	41.8	37.8	12.5	11.5	13.1	10.1

Correlation statistics for the performance of CALMET when compared to the observations at Narrabri Airport AWS are summarised in Table 4.

Table 4 Meteorological model correlation statistics for CALMET performance

Statistics	Wind speed	Wind direction	Temperature	U vector wind	V vector wind
RMSE	2.8	138.5	6.4	3.2	4.5
$RMSE_s$	1.9	98.0	3.1	2.2	2.7
$RMSE_u$	2.1	97.9	5.7	2.4	3.5
IOA	0.5	0.4	0.8	0.5	0.6
$Skill_e$	0.9	1.0	0.7	0.9	0.9
$Skill_v$	0.9	1.0	0.9	1.0	1.0
$Skill_r$	1.2	1.4	0.8	1.3	1.2
MAE	2.2	101.1	5.0	2.4	3.3

The correlation statistics indicate the following:

- The $RMSE_S$ and $RMSE_U$ statistics have improved with the incorporation of surface observations.
- The model's skill has improved for both wind speed and direction.
- The IOA and MAE statistics for wind speed and direction have not significantly changed with the incorporation of surface observations.

4 Conclusion

The evaluation of the model's performance has found that the combined two-stage TAPM-CALMET modelling approach with assimilated surface observations has performed within the expected range of statistical scores for use in a dispersion modelling study. Consequently, the meteorological file developed is considered to be suitable for use in the impact assessment.