Supplement of

Quantifying methane emissions from Queensland's coal seam gas producing Surat Basin using inventory data and a regional Bayesian inversion

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Contents

S1. Data filtering

S1.1 Filtering for nearby cattle

Our standard data processing, using the software package GCWerks (http://www.gcwerks.com/), involves manual checks on a number of instrument parameters, but also some automatic flagging procedures based on very conservative thresholds for removing spurious data. In particular, GCWerks removes outlying points in the high frequency data if they lie more than 10 standard deviations from the mean, as calculated over a two-minute moving average window. By judiciously modifying the default parameters in the GCWerks' statistical filter, we are able to remove the signal due to the local cattle, without modifying the underlying signal from more distant sources. We find the optimal filter parameters for filtering nearby cattle signal to be a standard deviation of 2.5, with a moving average over a ten-minute window.

To give an example, Figure S1 shows the measured time series of minutely mean CO_2, CH_4 and CO at Burncluith for 10 January 2017. Particularly from 0100–0900 UTC (1100–1900 AEST), there is a series of sharp spikes in the CH_4 record. At this time, there were light winds from an east-south-easterly direction, and the landholder confirmed that there were cows loitering to the east of the intake line. While the 'tight' or cattle filter removes most of these sharp peaks in the minutely data, it retains the underlying rise in CH_4 between 0400 and 0600 UTC which mirrors the rise in CO, suggestive of biomass burning signal being transported from further afield.

The same cattle filter was applied to the Ironbark data, for consistency, although cattle are fewer and further away at Ironbark and have much less impact on the methane measurements.

S1.2 Diurnal and low wind filtering

Nocturnal low wind conditions can be approximately defined as those with a wind speed at 10-m above ground of less than 2–3 m s^{-1}, which corresponds to a Richardson number (a stability parameter that is the ratio of buoyant suppression of turbulence to shear generation of turbulence in the lower atmosphere) greater than $0.2 - 0.3$ (Luhar et al., 2009). There are considerable occurrences of high methane concentrations at the two sites under such conditions. This is mostly because under these conditions the atmosphere near the ground is typically characterised by strong stable stratification with a very shallow inversion layer so that even small local sources near the ground can lead to very large enhancements in the local methane concentration due to very little vertical atmospheric mixing. Despite being of considerable practical interest, however, these are some of the most difficult conditions to simulate by a flow and dispersion model, particularly at a regional or mesoscale. Thus, one option to circumvent the issue of modelling generally not being able to properly simulate strong inversion conditions at night is to consider, for each site, daytime hours (1000–1700 h) irrespective of wind speed, and the remaining hours for which the observed wind speed is greater than 3 m s^{-1}. The daytime window typically corresponds to periods of strong mixing dominated by convective motions resulting from the solar heating of the ground. For data selection for the two sites, the respective measured wind speeds were used.

S1.3 Filtering for biomass burning events

Both methane and CO are emitted from biomass burning. CO is not present in other large methane sources of interest, including those compiled in the bottom-up emissions inventory. Methane emissions from power stations, domestic wood heating and vehicles on the other hand would contain CO, but the modelled CH_4 signals for these sources are predicted to be virtually undetectable at Burncluith. The majority (89%) of CSG methane source emissions in the bottom-up inventory are not from combustion. Importantly, emissions from the less well known migratory or seepage sources, which also do not originate from combustion, would not be screened out by a CO filter. Thus, comparisons of observed CH_4 with model simulations are more accurately made by excluding hourly periods with large CO enhancements above the background CO concentration.

A plot of the measured CO vs CH_4 concentrations at Burncluith after applying the above cattle and low wind filtering is shown in in Figure S2 (orange circles). Two distinct groupings are apparent; the data group with high magnitudes of CO concentration likely represents dominant contributions from combustion sources. Enhancements of CO above background at Burncluith are mostly observed during north-westerly and easterly winds, consistent with the locations of the occasional forest burn offs and the wood fire in the dwelling adjacent to the monitoring station, respectively. (The background CO concentration was calculated using the same methodology as the background CH_4 (Section 4.2). To filter out such events, we chose an hourly mean CO enhancement of 10 ppb (above the background) as a cut off, which is about twice the one standard-deviation uncertainty in the observed CO around the estimated background CO variation without considering the CO enhancement periods. The hourly mean data points after removing the data points with CO values greater than 10 ppb above background concentrations are shown as blue dots in Figure S2. This CO filter further removed about 22% of the filtered Burncluith data.

S2. Bottom-up methane emission inventory (full details in S6)

The following is a brief account of how the bottom-up methane emissions from the various sectors for the year 2015 were compiled. Full details are given in the attached report "Surat Basin Methane Inventory 2015 – Summary Report" by Katestone (2018).

S2.1 Grazing cattle

The information used to estimate methane emissions for grazing cattle included:

- Total cattle livestock and grazing area based on agricultural commodities for Australia for 2014-15 (ABS, 2015a) and Land Management and Farming in Australia for 2014-15 (ABS, 2015b).
- Digital Boundaries for National Resource Management (NRM Regions) for 2016 (DEE, 2016).
- Methane emission factor for grazing cattle based on direct measurements (Harper et al., 1999).

The number of grazing cattle were calculated in each NRM region and was distributed uniformly across the region. This was then multiplied by the emission factor to give the corresponding methane emissions. There were 1,086,059 grazing cattle in the study area.

S2.2 Feedlots

The following information was used to compute methane emissions for cattle in feedlots:

- National Pollutant Inventory (NPI) data for the 2014/15 reporting year with the ANZSIC (Australian and New Zealand Standard Industrial Classification) description "Beef Cattle Feedlots (Specialised)".
- Queensland Government datasets including Lot and plan boundaries (Property boundaries Queensland cadastral dataset) and Locations and standard cattle unit numbers contained in NRM regions (Department of Agriculture and Fisheries).
- Methane emission factor for "enteric fermentation" and "manure management" for non-dairy cattle from the Food and Agriculture Organization (FAO) of the United Nations (FAOSTAT, 2016). A total emission factor combines the above two methane sources at a feedlot.

There were 235 cattle feedlots in the study area. The number of cattle per feedlot was estimated. The methane emissions were calculated by multiplying the number of cattle per feedlot by the emission factor.

S2.3 Coal Seam Gas (CSG) activities

The locations of CSG wells and processing facilities were based on data available through DNRM and methane emissions data and calculations were provided by the operators.

The information used to calculate the CSG methane emissions included: locations of CSG wells and processing facilities, methane emissions data and reporting prepared for the National Greenhouse and Energy Reporting (NGER) program and directly from the operators, quantity of gas combusted and the volume of produced water.

The calculation methods are consistent with the NGER program where methane is classified as a greenhouse gas and is quantified and reported in terms of carbon dioxide equivalents.

Combustion: Emissions of methane due to incomplete combustion of CSG (including flaring) and diesel were calculated as the product of the quantity of fuel type, the energy content of fuel type, an appropriated emission factor and the GWP of methane.

Fugitive emissions (venting of CSG): Estimates of the quantities of gas vented are based on methods prescribed by the Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry (API Compendium) (API,

2009). Emissions were estimated based on the direct measurement of gas released, if this information was unavailable industry standard factors were applied (API, 2009).

Methane from produced water is a component of both CSG production and processing is an important source. It was included under venting and was calculated at 1.63×10^6 kg yr^{-1} (~ 10% of the total CSG emissions) using an emission factor of 0.036 tonnes CH_4 per 1000 m^3 of produced water based on API (2009) (Table 5-11, page 5-57).

Fugitive emissions (other than venting or flaring): These fugitive methane emissions include emissions from (NGER Determination 2008, Section 3.70 (Clean Energy Regulator, 2016)): a gas wellhead through to the inlet of a gas processing plant, a gas wellhead through to the tie-in points on gas transmission systems (if processing of natural gas is not required), gas processing plants, well servicing, gas gathering, gas processing and associated waste water disposal. The emissions are calculated as the product of the total quantity of natural gas, the appropriate emission factor and the GWP of methane.

S2.4 Coal mining

Methane emissions for four coal mines in the study were calculated from the following information (only the dominant coal extraction process was included):

- Run of Mine (ROM) (gross raw output) coal tonnages for 2014/15 (Department of Natural Resources and Mines (DNRM) - *Queensland coal production by individual mine*, May 2016).
- DNRM Mining lease surface areas.
- Fugitive methane emission factor for extraction of coal in Queensland of 0.02 tonnes CO_2-e per tonne of raw coal (DoE, 2016).
- Methane Global Warming Potential (GWP) of 25 (DoE, 2016).

The methane emissions for each mine were calculated by multiplying the amount of ROM coal by the appropriate emission factor. They were allocated uniformly across the mining lease areas associated with each mine as identified from the DNRM dataset.

S3. Estimating the background methane concentration

Data from the measured concentration time series were retained if they occurred between 1200 – 1500 h local time (typically the time of highest boundary layer height and maximum trace gas homogeneity during the diurnal cycle) and the hourly standard deviation of concentration was less than or equal to 1 ppb, indicating very well mixed conditions. This filtered dataset was then used to derive a smooth curve. Based on the method described by Thoning et al. (1989), the filtered dataset was fitted with a function consisting of a cubic polynomial and three harmonics. This fit is then subtracted from the filtered data and the residuals further filtered with a band-pass filter of 80 days. The original function fit is then added back to the filtered residuals

to give a smooth fit through the data. These operations are performed iteratively (with hours lying outside twice the standard deviation around the fit excluded) until the fit converges. An interpolation routine then produced the fitted background CH_4 concentrations at each of the hourly timestamps of the original measured data.

S4. Model performance for meteorology

145 Figure S3 presents wind roses for Burncluith and Ironbark constructed using the TAPM generated hourly vector winds and the observed hourly vector winds for all hours (i.e. without filtering, with sample size 12855 and 13198, respectively) for the period August 2015 to December 2016. The TAPM winds are from the inner-nest model output at a height of 10 m (i.e. the lowest model level). Only those modelled hours for which there are wind data are considered. The modelled winds are qualitatively similar to those observed, with the most frequent modelled wind direction also from the north-east quadrant, and

150 winds from the south-west quadrant modelled at a relatively smaller frequency in agreement with the observations. The modelled winds at Burncluith and Ironbark are more similar than those observed. At Burncluith the model underestimates the frequency of low wind speed events (< 2 m s^{-1}), which mostly occurs at night, and overestimates the frequency of higher wind speed events (> 4 m s^{-1}) from the north-east sector. The wind speed distribution at Ironbark is better modelled than that at Burncluith—one reason for this could be that Burncluith has several tall trees in the vicinity which may weaken the flow field

155 and whose influence is not properly accounted for in the model. There is also a difference in the height at which winds are given: the model height is 10 m whereas, it is 7.6 m at Burncluith and 5.8 m at Ironbark. Generally, in the surface layer, winds get stronger with height, and, therefore, one factor in the modelled winds being stronger than the observation could be the height difference.

Figure S4 is the same as Figure S3, except that only the filtered hours (i.e. the daytime hours 1000–1700 h irrespective of wind

160 speed and the remaining hours for which the observed wind speed is greater than 3 m s^{-1}) are used. The sample size after filtering is 5452 and 7841 for Burncluith and Ironbark, respectively. These two sets of plots are qualitatively similar, except that, as expected, the low wind underprediction by the model has reduced after filtering, particularly for Burncluith, and the frequency of flow from between 0°–45° has reduced for this site.

Values of some commonly used model performance statistics are given in Table S1 for the prediction of wind speed (WS, m s^{-1}

165), the west-east component of the wind (U, m s^{-1}), the south-north component of the wind (V, m s^{-1}), temperature (T, °C) and relative humidity (R_H, %). The statistics make use of the hourly model predictions (M) at 10 m and the observed (O) data from the two monitoring stations, and they are the arithmetic means $\bar{O}$ and $\bar{M}$, Root Mean Square Error (RMSE), Index of Agreement ($\text{IOA} = 1 - [\overline{(M - O)^2}/\overline{(|M - \bar{O}| + |O - \bar{O}|)^2}]$, where 0 = no agreement and 1 = perfect agreement), and correlation coefficient (r). The IOA, unlike the correlation coefficient, is sensitive to differences between the observed and model means

170 as well as to certain changes in proportionality (Willmott, 1981).

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The IOA and *r* values in Table S1 suggest that with the filtering the mean wind speed (*WS*) is predicted slightly worse, but the wind components *U* and *V* are predicted better, which implies that there is an improvement in the estimation of wind direction with filtering.

Table S1: Model performance statistics for meteorology.

Data	Site (sample size *N*)	Parameter	$\bar{O}$	$\bar{M}$	RMSE	IOA	*r*
All	Ironbark (*N* = 13198)	*WS*	3.18	3.15	1.26	0.82	0.69
		U	-0.73	-1.01	1.43	0.90	0.82
		V	-0.67	-0.78	1.55	0.89	0.80
		T	20.23	19.44	2.53	0.97	0.94
		R_H	55.11	65.23	18.66	0.83	0.76
	Burncluith (*N* = 12855)	*WS*	2.21	2.84	1.27	0.76	0.66
		U	-0.40	-0.80	1.26	0.90	0.83
		V	-0.08	-0.68	1.46	0.84	0.77
		T	19.80	19.39	2.63	0.96	0.93
		R_H	64.61	68.88	14.82	0.89	0.80
Filtered	Ironbark (*N* = 7841)	*WS*	4.16	3.76	1.37	0.75	0.58
		U	-0.83	-1.09	1.57	0.91	0.84
		V	-1.02	-1.08	1.68	0.91	0.84
		T	22.86	21.43	2.78	0.95	0.93
		R_H	48.94	60.49	18.96	0.81	0.76
	Burncluith (*N* = 5452)	*WS*	3.26	3.61	1.30	0.70	0.52
		U	-0.40	-0.86	1.46	0.92	0.87
		V	0.27	-0.52	1.62	0.88	0.82
		T	23.66	22.04	2.89	0.94	0.92
		R_H	50.73	57.81	15.72	0.84	0.74

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As judged from the IOA values, the overall TAPM performance for meteorology for the Surat Basin is satisfactory and comparable to those in other studies (e.g., Luhar and Hurley, 2003; Hurle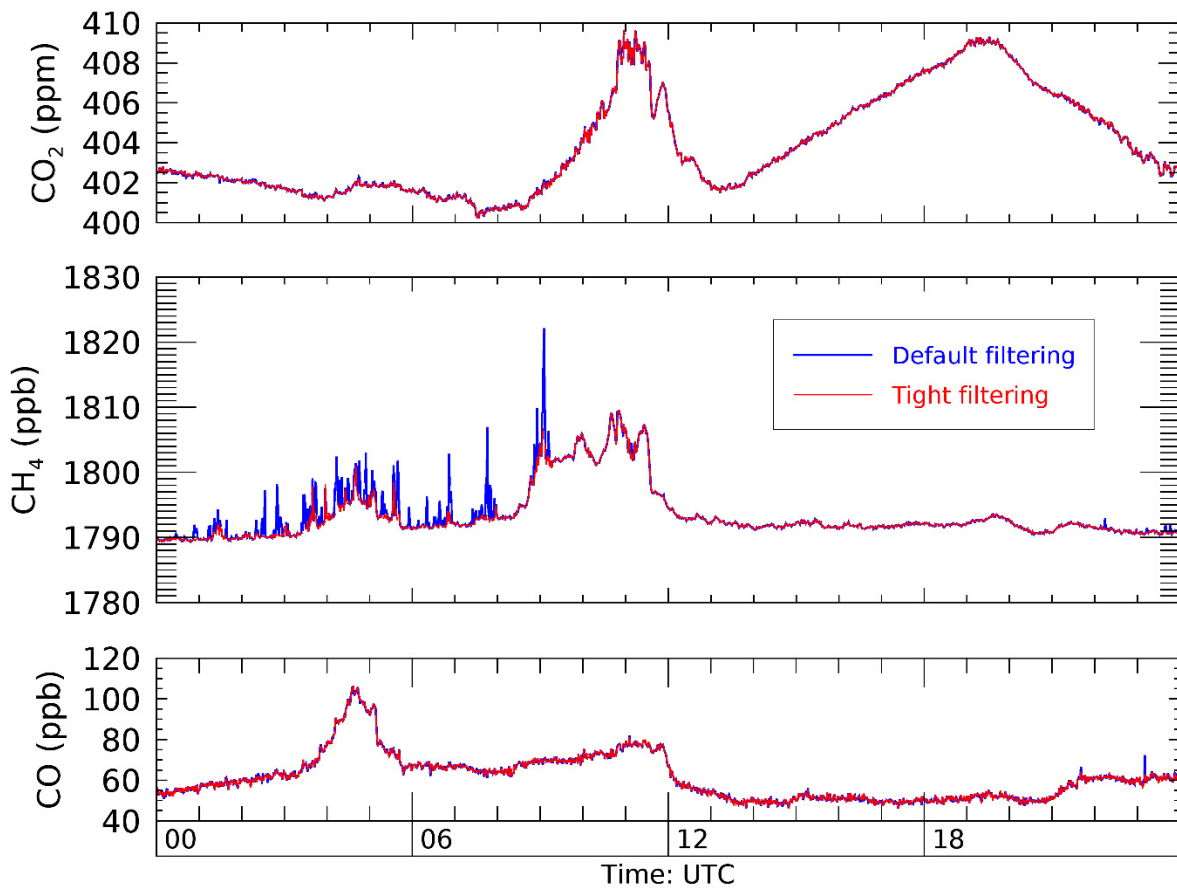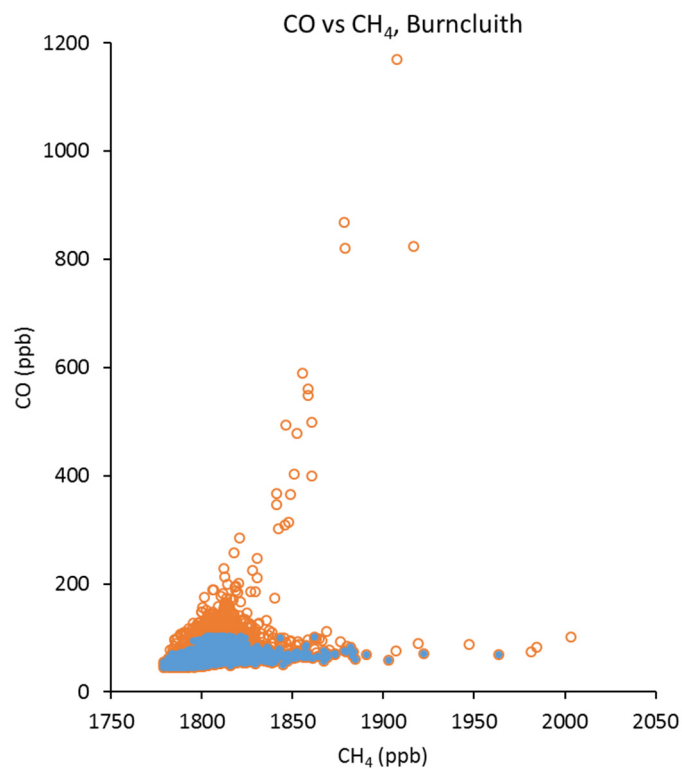y et al., 2005) (also see papers in TAPM citation database https://scholar.google.com.au/scholar?oi=bibs&hl=en&cites=13876071272134760358).

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Figure S1. Burncluith minutely-mean data for 10 January 2017. Blue curve represents the default filtering, red curve the cow filtering ("tight"). Where the two curves cannot be seen separately, they overlap.

Figure S2. Hourly mean concentrations of CO versus CH_4 measured at Burncluith selected for 1000-1700 for all wind speeds and for 1800-0900 for wind speed greater than 3 m s^{-1} (orange circles). The data group with high magnitudes of CO concentration likely represents dominant contributions from combustion sources. The data marked with blue dots are the measurements when hourly mean CO concentrations are within 10 ppb of the background CO concentration at the time of measurement and are selected to represent contributions from non-combustion sources.
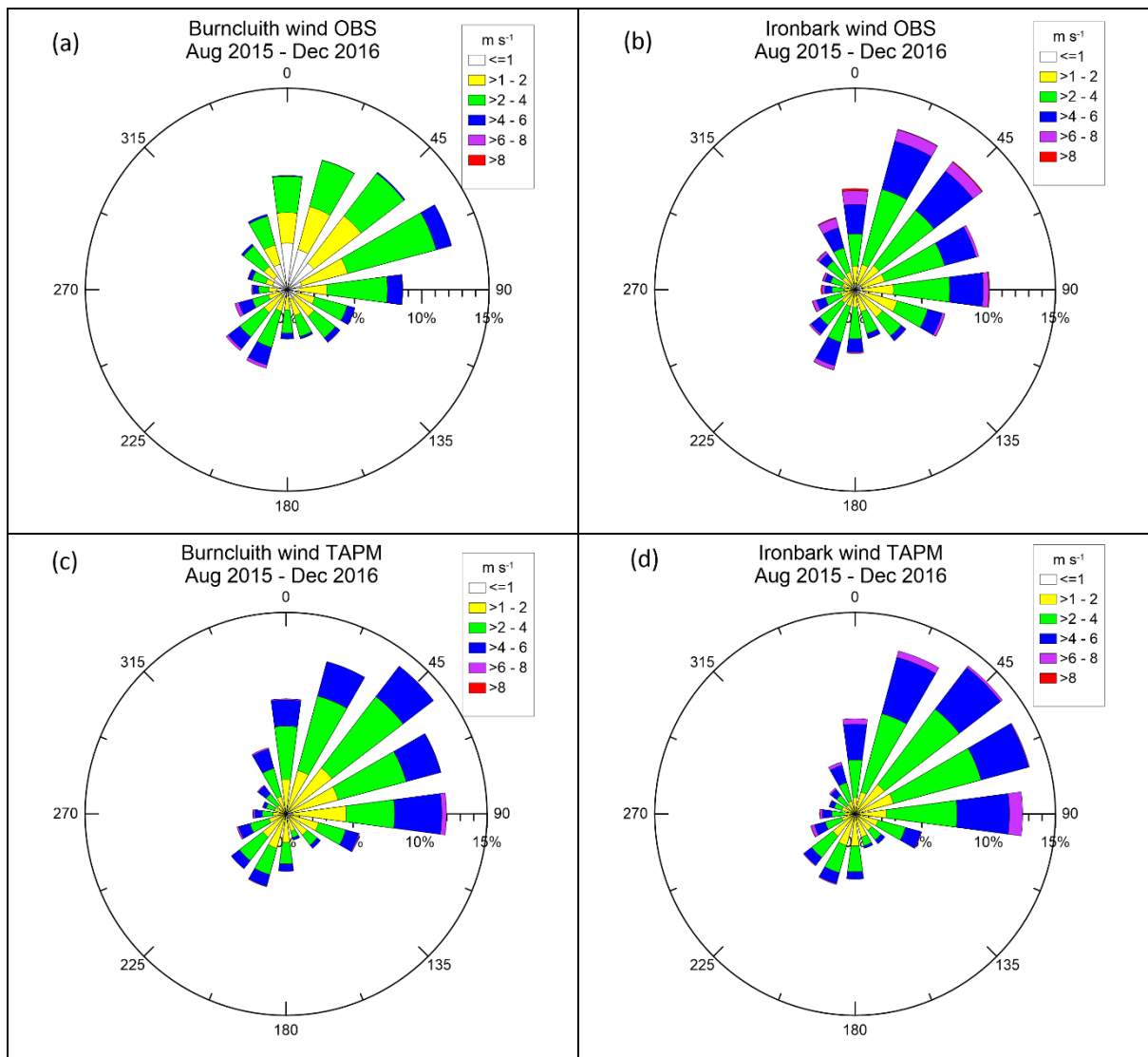
Figure S3. Observed (a, b) and modelled (c, d) wind roses for the Burncluith and Ironbark monitoring sites for the period August 2015 to December 2016 (all hours considered).
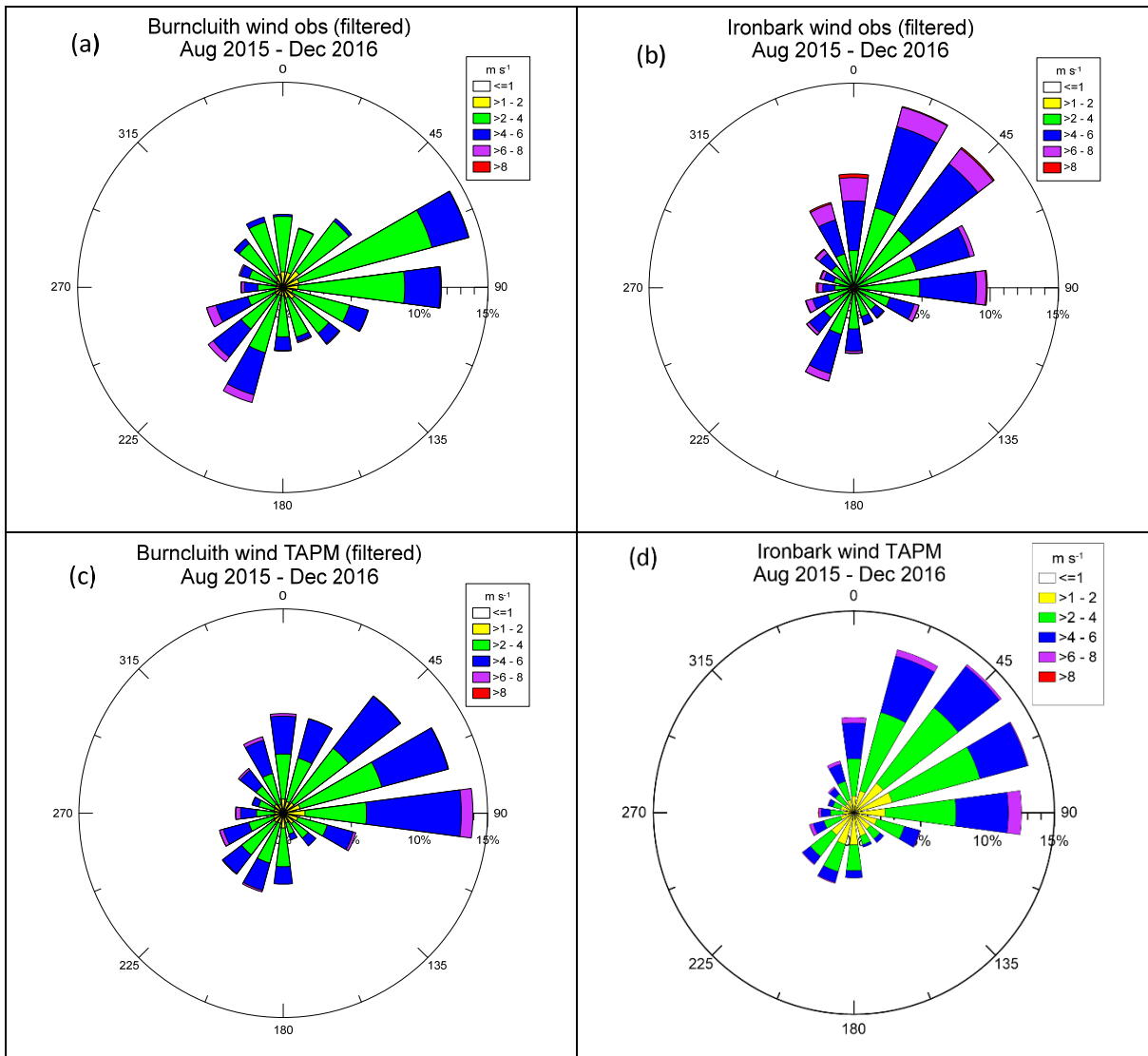
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Figure S4. Observed (a, b) and modelled (c, d) wind roses for the Burncluith and Ironbark monitoring sites for the period August 2015 to December 2016 (filtered hours considered).

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S5. Sensitivity of the inversion to an alternate background methane concentration

The background concentration calculation methodology used in the paper and described in Section S3 assumes that under vigorous atmospheric mixing conditions in the daytime, the measured concentrations within study domain represent methane levels both within and outside the domain boundaries, so that the measured concentrations can be taken to represent the background (i.e. the concentration outside the study domain boundaries) under such conditions. In our study, because the background concentration is calculated from the measurements within the source region under study, it may represent an upper limit on the magnitude of the background. Below, as a sensitivity test, we try an alternate methane background time series in our inversion.

The Cape Grim Baseline Air Pollution Station, located on the north-west tip of Tasmania (40.7ºS, 144.7ºE), is a baseline air pollution station (https://research.csiro.au/acc/capabilities/cape-grim-baseline-air-pollution-station/; https://capegrim.csiro.au) that measures atmospheric composition, including continuous, in-situ measurements of methane (Figure S5). It is part of the World Meteorological Organization-Global Atmosphere Watch (WMO-GAW) network (https://community.wmo.int/gaw-stations-network-and-other-measurements; data from https://gaw.kishou.go.jp). The measurements from the Station are filtered for the marine baseline air in southern mid latitudes, with the baseline (or clean air) sector as defined in Figure S5. The baseline methane thus represents concentration levels without the direct influence of the continental sources.
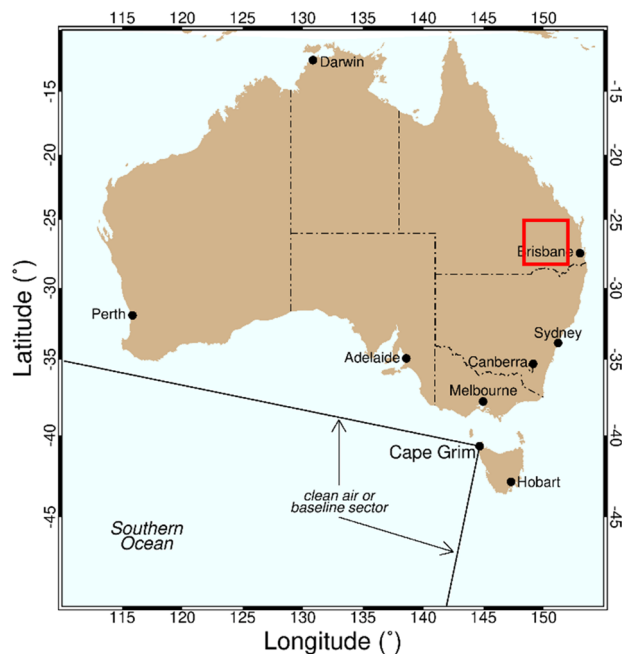

Figure S5. The Cape Grim Baseline Air Pollution Station, with the clean air sector used for baseline composition measurement (https://capegrim.csiro.au). The Surat Basin region as used in our study is shown as a red square.

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The hourly-averaged Cape Grim baseline methane for the study period is shown in Figure S6 (red line). Also shown is the background methane used in the present paper (green line – which is the average of the background times series calculated from the Ironbark and Burncluith data). On average, the Cape Grim marine baseline is 8.4 ppb (by volume) lower than the background we used in the model (green line). It is thus reasonable to assume an alternate background that lies between the Surat Basin background as used in our study and the Cape Grim marine baseline (i.e. between the two bounds). The 8.4 ppb gradient reflects the impact of methane emissions over the land surface in the fetch between the coast and the Surat measurement sites. So how much of this total gradient is due to the inland sources within the model domain (350 km × 350 km) and those beyond? The fetch of the latter from the coast varies with direction and is on average much greater than our regional domain. However, plumes from these sources would be much more diffused arriving in the study domain than sources within the study domain. Here we make a rather crude assumption that 2/3rd of the gradient (i.e. 5.6 ppb on average) is due to sources from the outer parts of the model domain (due to larger fetches and hence larger integrative surface source areas) and 1/3rd (i.e. 2.8 ppb on average) due to sources within the model domain (in other words, on average our background may have been overestimated by 2.8 ppb). Hence, our alternate hourly background ($c_{b,new}$) is as follows:

$$c_{b,new} = c_b - \frac{1}{3}(c_b - c_{CG}), \qquad\qquad (S1)$$

where c_b is the hourly background as used in our study and c_{CG} is the hourly Cape Grim marine baseline concentration.

Figure S6 shows the alternate background based on Eq. (S1) as a blue line. On average, the alternate background is 2.8 ppb lower than the original background and 5.6 ppb higher than the Cape Grim baseline. (Obviously, it is possible that, at a given time, the background concentration may vary spatially along the study domain boundaries, and as such it is not possible to investigate this with the modelling tools and measurements we have at present.)

To examine how the alternate background influences the inferred emissions, we performed an inversion using the alternate background methane with all other inversion settings the same as finalised Case 3c (i.e., a Gaussian prior with the bottom-up inventory emission as the mean (q_p) and standard deviation $\sigma_p = 3\%$ of the mean value (q_p) for each of the 11 × 11 sources).
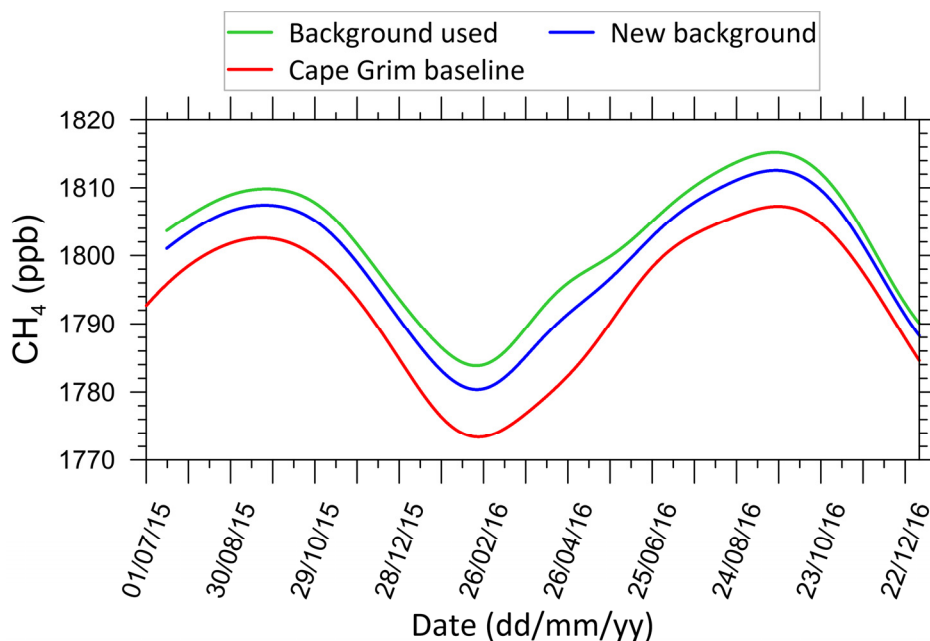
Figure S6. The average hourly background CH_4 concentration (ppbv) time series (green line) as used in the present paper. The hourly-averaged Cape Grim marine baseline methane is shown as a red line. The alternate background (blue line) is as calculated from the Cape Grim baseline methane (red line) and the background concentration (green line) using Eq. **(S1)**, and is used for an inversion sensitivity test here.

The inversion results in Table S2 show that compared to the inferred emissions obtained using the original background methane the alternate background gives total emissions that are 6.8% higher, while the increase is smaller at 3.9% in the CSG subdomain and larger at 8.5% in the non-CSG region. The overall increase is expected because the increase in the measured concentrations by 2.8 ppb as a result of the use of the alternate background needs to be accounted for by the inversion by enhancing the amount of inferred emissions.

We also find that the amount of increase in the inferred emissions with the alternate background is almost uniformly spread through the study domain relative to the total emission, and that there are no significant spatial distributional shifts in the inferred emissions with the two background choices. This means that if these emissions were to be used in a forward model simulation, they would lift the modelled concentrations throughout the region by a very similar amount (likely by 2.8 ppb).

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Table S2: Inferred emissions ($\times 10^6$ kg yr^{-1}) obtained using the original methane background variation used in the paper (Case 3c, with the bottom-up inventory as a Gaussian prior with $\sigma_p = 3\%$ q_p) and those obtained using the alternate methane background variation calculated in this section using Eq. (S1). The values in the parentheses are % change over the original inferred emissions.

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Methane background	Total	CSG subdomain	Non-CSG subdomain
Original background (as used in the paper)	165.8	63.6	102.2
Alternate background	177.0 (+6.8%)	66.1 (+3.9%)	110.9 (+8.5%)

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Glossary

Term	Definition
kg	kilograms
kg/year	kilograms per year
kL	kilolitre
km	kilometre
km/h	kilometre per hour
m	metre
m^2	square metres
MWh	megawatt hour
SCU	standard cattle unit
tCO$_{2-e}$	tonnes carbon dioxide equivalent
yr	year

Nomenclature	Definition
CH$_4$	methane
CO$_2$	carbon dioxide

Abbreviations	Definition
AADT	Annual Average Daily Traffic
ABS	Australian Bureau of Statistics
ADR	Australian Design Rules
AEMO	Australian Energy Market Operator
ANZSIC	Australian and New Zealand Standard Industrial Classification
ASGS	Australian Statistical Geography Standard
CSG	Coal Seam Gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAF	Department of Agriculture and Fisheries
NRM	Department of Natural Resources and Mines
DTMR	Department of Transport and Main Roads
EF	Emission Factor
ER	Emission Rate
LDV	Light Duty Vehicles
NPI	National Pollutant Inventory
NSW	New South Wales
NSW EPA	NSW Environment Protection Authority
NSW EPA GMR	NSW Environment Protection Authority Greater Metropolitan Region
PD	Property Development
VKT	Vehicle Kilometres Travelled

1. INTRODUCTION

The Surat Basin is a geological region in central Queensland that has seen large scale development of coal seam gas (CSG) extraction and processing operations in the past five years. The main driver of CSG development in the Surat Basin is the recent technology advancement in unconventional gas (CSG) extraction techniques and specifically advanced drilling capabilities. This technology advancement has made unconventional gas extraction projects commercially viable and, coupled with the extensive CSG resources in Surat Basin, has led to large scale development.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) commissioned Katestone Environmental Pty Ltd (Katestone) to develop an inventory of activities that generate emissions of methane within the Surat Basin and quantify their associated annual emission rates (Surat Basin Methane Inventory).

The Surat Basin Methane Inventory was provided to CSIRO as a series of datafiles. This report provides a summary of the activities that generate methane emissions and describes the methodologies that were used to generate the Surat Basin Methane Inventory.

1.1   Project background

The datafiles provided to CSIRO for the Surat Basin Methane Inventory include the following industry sectors and activities:

- Large industry (power stations, coal mines, coal seam gas processing and production)
- Agriculture (feedlots, grazing cattle, piggeries and poultry farms)
- Domestic wood heating
- Motor vehicles
- Miscellaneous sources (landfills, sewage treatment plants, river seeps and geological seeps).

1.2   Study area

The study area for the Surat Basin Methane Inventory was defined by CSIRO. It extends from Toowoomba in the southeast to Emerald in the northwest. The study area is 344 km by 345 km and is shown in Figure 1. The study area was divided into a network of evenly-spaced grid cells each 1 km by 1 km.

1.3   Scope of works

The scope of works includes the following elements:

- Identification and mapping of sources in the Surat Basin with emissions of methane for the year 2015
- Quantification of annual methane emission rates from each identified source for 2015
- Provision of a methane emissions dataset for each source type in a format suitable for use by CSIRO
- Provision of a summary report detailing all the methods and sources used to create the inventory.

1.4 Exclusions and missing data

The scope of works does not include methane emissions from the following activities:

- Land clearing

- Biomass burning

- Wetlands

- Registered ground water wells

- Fuel usage and material handling associated with mining activities. Methane emissions from these aspects of mining operations are expected to be minimal and significantly less than the aspects of mining that have been quantified, namely: open cut coal mining and coal off gassing.
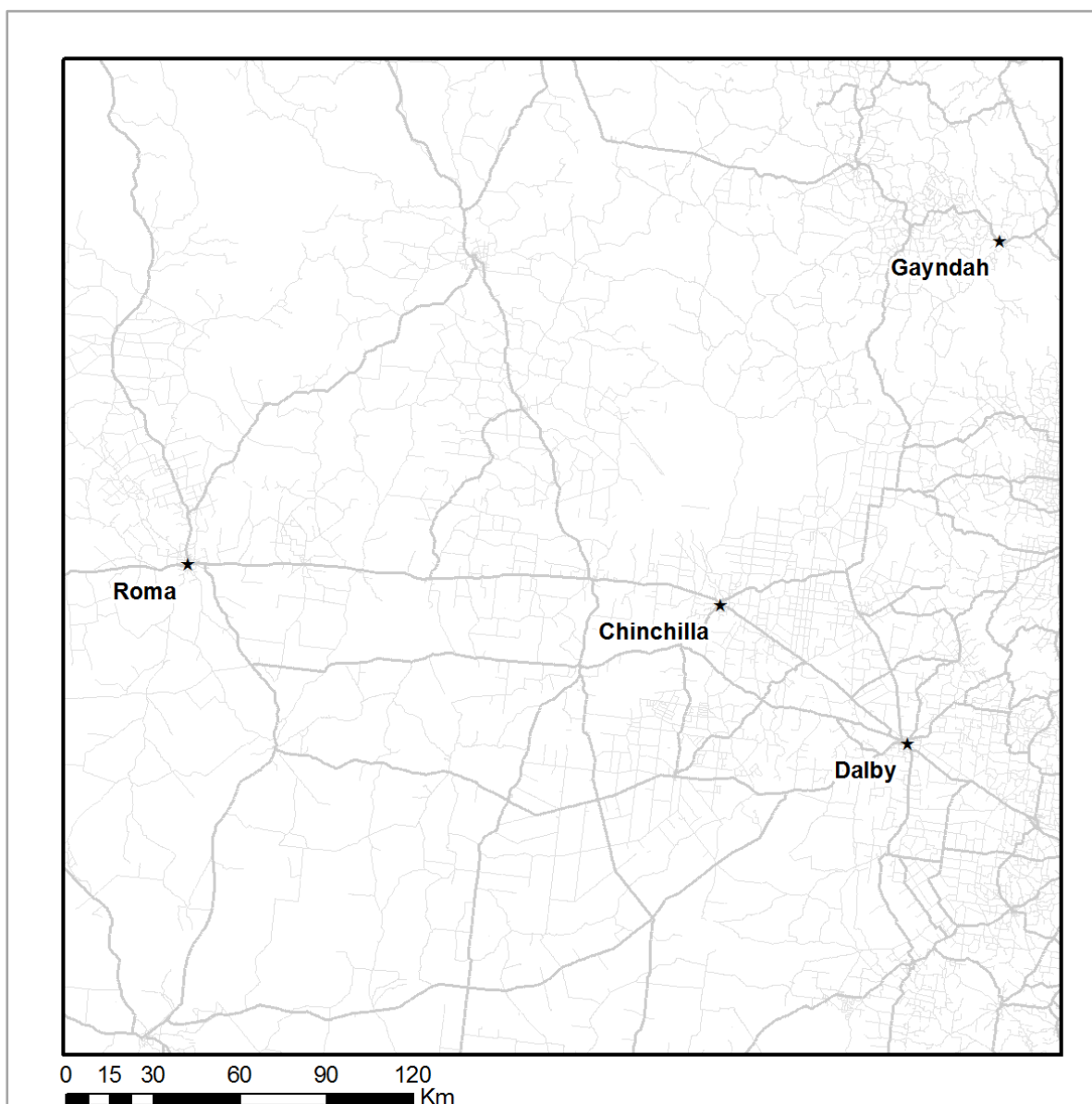
Figure 1   **Surat Basin Methane Inventory Study Area**

2. SUMMARY OF THE SURAT BASIN METHANE INVENTORY

A summary of total methane emissions from the industry sectors and sources included in the Surat Basin Inventory is presented in Table 1 and shown in Figure 2. Emission rates of methane aggregated by each 1 km by 1 km grid cell across the study area is presented in Figure 3. A detailed breakdown of the Surat Basin Methane Inventory by industry sector or source, including a description of the methane emissions calculation methodology, is provided in the following sections.

Table 1   Surat Basin Methane Inventory (kg/year) by industry sector or source

Industry sector or source		Methane emissions (kg/year)
Agriculture	Feedlot	42,270,444
	Grazing cattle	92,991,979
	Poultry	96,699
	Piggeries	2,358,892
Coal seam gas	Processing	14,610,306
	Production	1,918,532
Domestic wood heating		280,324
Landfill		1,905,644
Mining	Coal extraction	14,424,564
Motor vehicles		24,071
Power stations		640,070
Seeps	Ground seeps	127,714
	River seeps	375,909
Wastewater treatment		1,137,905
Total		**173,163,053**
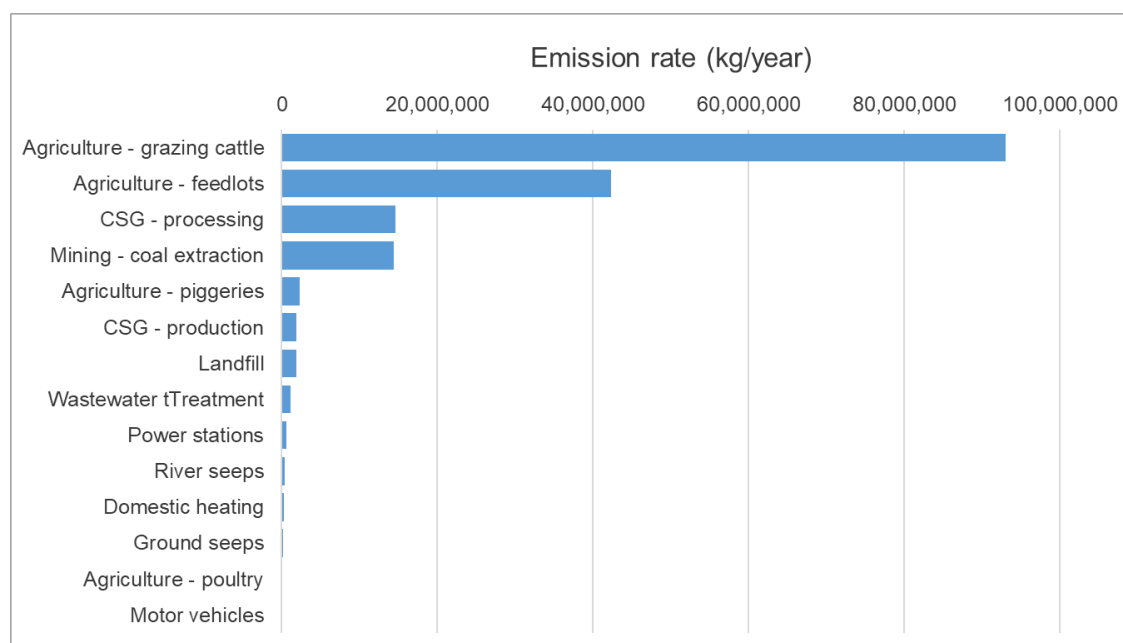
Figure 2   Surat Basin Methane Inventory by industry sector or source (kg/year)

Methane Emissions (kg/year/km²)

336 - 500	5,001 - 10,000	100,001 - 200,000
501 - 1,000	10,001 - 20,000	200,001 - 500,000
1,001 - 2,000	20,001 - 50,000	500,001 - 1,000,000
2,001 - 5,000	50,001 - 100,000	1,000,001 - 2,000,000
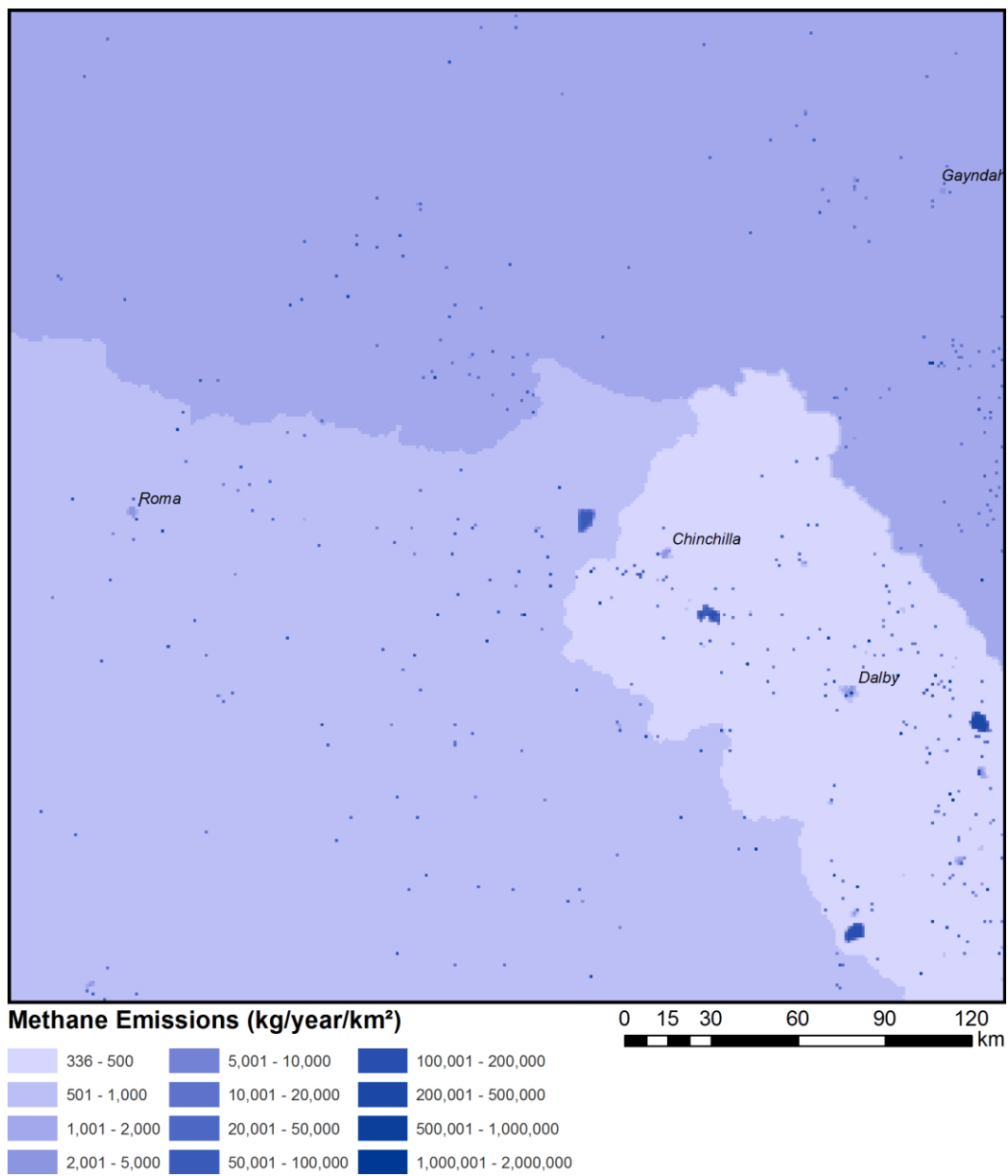
Figure 3   **Spatial distribution of the Surat Basin Methane Inventory**

3. AGRICULTURE

3.1 Overview

This chapter details the agricultural activities included in the Surat Basin Methane Inventory and summarises their associated emission rates of methane. The methods used to calculate methane emissions, the data sources and assumptions are provided.

3.2 Emission sources

There are 235 beef cattle feedlots, 1,086,059 grazing cattle, 114 piggeries and 18 poultry farms in the study area for which methane emissions have been estimated for 2015.

The locations of the agricultural facilities (feedlots, poultry farms and piggeries) included in the Surat Basin Methane Inventory are shown in Figure 4. The National Resource Management (NRM) region boundaries within the study area are also shown in Figure 4 (blue lines).
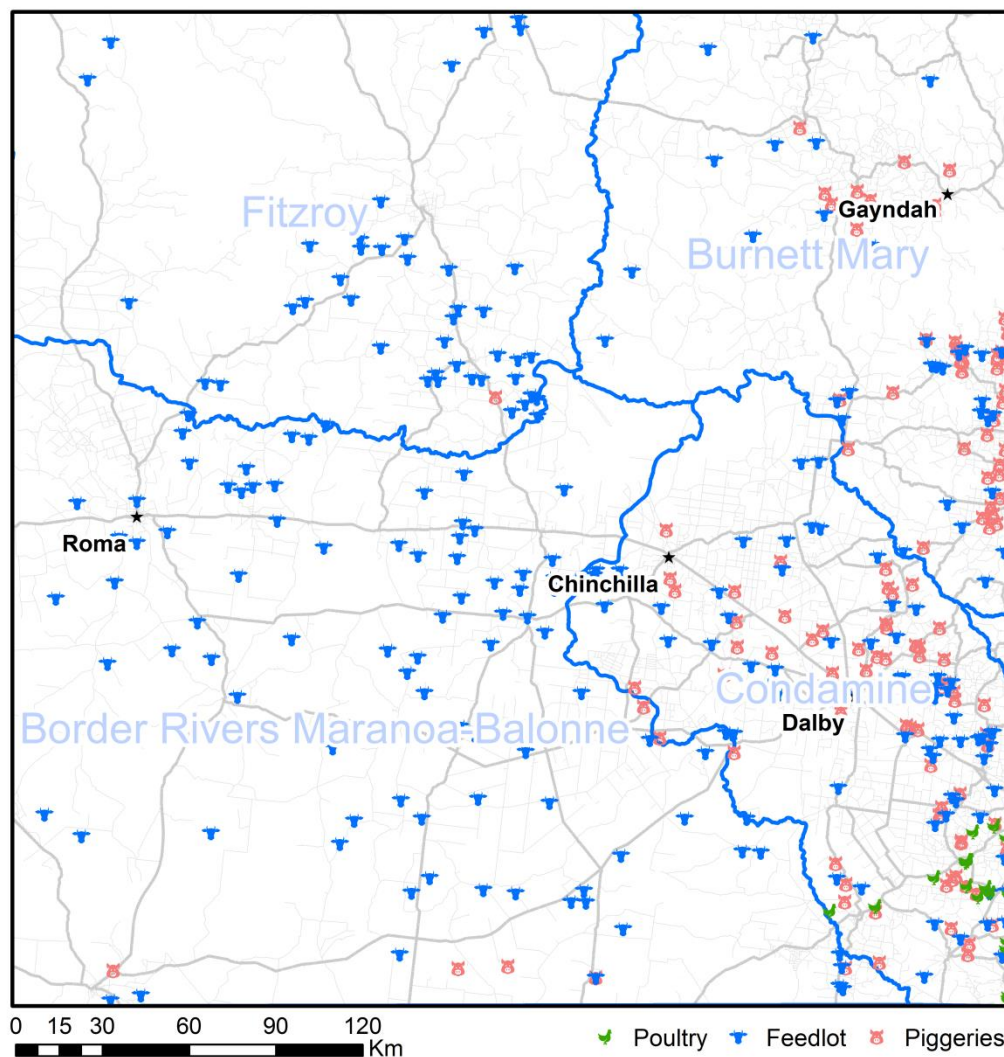
Figure 4   Agricultural facilities included in the Surat Basin Methane Inventory

3.3 Methodology

3.3.1 Information

3.3.1.1 Feedlots

The following information was used to calculate methane emissions from cattle feedlots:

- National Pollutant Inventory (NPI) data for the 2014/15 reporting year for facilities in the study area with the ANZSIC description "Beef Cattle Feedlots (Specialised)".

- Queensland Government datasets including:

    o Lot and plan boundaries contained in the *Property boundaries Queensland* cadastral dataset

    o Locations and standard cattle unit (SCU) numbers contained in NRM regions (Department of Agriculture and Fisheries (DAF)).

- Methane emission factor for enteric fermentation and manure management for non-dairy cattle from the Food and Agriculture Organization (FAO) of the United Nations (FAOSTAT, 2016). A total emission factor of 62 kg CH_4/SCU was used, which combines the two key methane sources at a feedlot (Table 2).

Table 2   Methane emission factors for non-dairy cattle (FAOSTAT, 2016)

Emissions Source	Methane emission factor (kg CH_4/SCU)
Enteric Fermentation	60
Manure Management	2

3.3.1.2 Grazing cattle

The following information was used to calculate methane emissions for grazing cattle:

- Total cattle livestock information and total area used mainly for grazing based on agricultural commodities for Australia for 2014-15 (ABS, 2015a) and Land Management and Farming in Australia for 2014-15 (ABS, 2015b).

- Digital Boundaries for NRM Regions for 2016 (DEE, 2016) in the study area.

- Methane emission factor for grazing cattle of 0.23 kg CH_4/animal/day based on direct measurements (Harper et al., 1999).

3.3.1.3 Poultry farms

The following information was used to calculate methane emissions from poultry farms:

- NPI for the 2014/15 reporting year for facilities in the study area with the ANZSIC description "Poultry farming (Eggs)" and "Poultry Farming (Meat)." There were three records returned for the filter "Poultry farming (Eggs)." There were no records returned for "Poultry Farming (Meat)."

- NRM's and DAF's (Department of Agriculture and Fisheries) datasets including:
  - Lot and plan boundaries contained in the *Property boundaries Queensland* cadastral dataset
  - Locations and bird numbers contained in the *Agricultural land audit - current poultry farms - Queensland* dataset.

- Approvals documentation publicly available via council's PD (Property Development) online services.

- Google Earth imagery to determine approximate floor areas of some poultry farm sheds.

- Distribution of broiler chickens and layer chickens for Australia (Table 3) from the FAO (FAOSTAT, 2016).

- Methane emission factor for manure management (Table 4) for broiler chickens and layer chickens from the FAO (FAOSTAT, 2016). Emission factor for unknown poultry farm types derived from combined emissions for broiler and layer chickens, using a weighted average based on population distribution.

- Stocking densities for different farm types (Table 5) based on industry literature (Sustainable Table, 2015; Queensland Government, 2013) and industry experience.

Table 3   Distribution of birds by poultry farm type for Australia (FAOSTAT, 2016)

Parameter	Number of birds by Farm Type	
	Broiler	**Layer**
Count	83,052,847	14,447,153
Percentage	85.2%	14.8%

Table 4   Methane emission factors for various poultry farm types (FAOSTAT, 2016)

Emission source	Methane emission factor by farm type (kg CH$_4$/bird)		
	Broiler	**Layer**	**Default – Unknown Type**
Manure Management	0.02	0.03	0.0215[1]

Table notes:
[1] Emission factor for unknown poultry farm types based on scaling based on distribution of bird types in Australia

Table 5   Poultry farm stocking densities

Farm type	Stocking density (birds/m²)	Information Source
Meat chicken	18	Assumed, based on highest stocking density for Post 1 January 2001 cages for laying or breeding fowls from the Model Code of Practice for the Welfare of Animals, Domestic Poultry 4th Edition (CSIRO, 2002)
Breeder	14	Assumed, based on highest stocking density for Australian Egg Corporation Assured standard (11-14) (Sustainable Table, 2015)
Layer	14	Highest stocking density for Australian Egg Corporation Assured standard (11-14) (Sustainable Table, 2015)
Barn layer	9	Maximum stocking density for RSPCA Approved Farming standard (Sustainable Table, 2015)

3.3.1.4 Piggeries

The following information was used to calculate methane emissions from piggeries:

- Emissions of ammonia reported to the NPI for the 2014/15 reporting year for facilities in the study area with the ANZSIC description "Pig Farming".

- The NPI reporting threshold of 10,000 kg/year of ammonia emissions for facilities that do not report to the NPI.

- NRM's and DAF's datasets including:

  o Lot and plan boundaries contained in the *Property boundaries Queensland* cadastral dataset

  o Locations of piggeries contained in the *Agricultural land audit - current piggeries - Queensland* dataset.

- Distribution of breeding swine and market swine for Australia (Table 6) from the FAO (FAOSTAT, 2016).

- Methane emission factor for enteric fermentation and manure management (Table 7) for breeding swine and market swine from the FAO (FAOSTAT, 2016). A total emission factor of 15.6 kg CH_4/SPU (standard pig unit) (default type) was used, which combines the two key methane sources at a piggery.

Table 6   Distribution of pig types for Australia (FAOSTAT, 2016)

Parameter	Number of pigs by pig type	
	Breeding	Market
Count	230,800	2,077,200
Percentage	10%	90%

Table 7   Emission factors used to calculate emissions from piggeries

Farm type	Methane emission factor (kg CH₄/head)		
	Breeding	**Market**	**Default – Unknown Type**
Enteric Fermentation	1.5	1.5	1.5
Manure Management	24	13	14.1

3.3.2 Data checks

The calculation of the methane emissions for agriculture involved obtaining information from a range of sources (as described in Section 3.3.1). To ensure that activities were not double counted, a number of checks were conducted.

3.3.2.1 Feedlots

Several feedlots were contained in both the NPI and DAF datasets. To avoid double counting of feedlot emissions, the following checks were conducted:

- Lot and plan numbers were identified for all feedlots in both datasets.
- For each feedlot in the NPI dataset, the nearest feedlot in the DAF's dataset was identified.
- Any feedlots with matching plan numbers were considered to be the same. The coordinates of the feedlots identified to be within both datasets varied by no more than 70 m.

3.3.2.2 Poultry farms

Locations of poultry farms contained in the NPI and DAF datasets were overlaid on aerial imagery to identify farms that were contained in both datasets. The checks found that the three poultry farms that reported to the NPI were also found in the DAF dataset.

3.3.2.3 Piggeries

Some piggeries, but not all, were contained in both the NPI and DAF datasets. To avoid double counting, the following steps were taken:

- Lot and plan numbers were identified for all piggeries in both datasets.
- For each piggery in the NPI dataset, the nearest piggery in the DAF dataset was identified.
- Any piggeries with matching lot or plan numbers in both datasets were considered to be the same.

3.3.3 Calculation methodology

3.3.3.1 Feedlots

There were 217 cattle feedlots identified in DAF dataset and 19 cattle feedlots that reported to the NPI during the 2014/15 period within the study area, resulting in a total number of 236 cattle feedlots.

For the 19 cattle feedlots that reported to the NPI, the number of cattle was estimated based on the reported ammonia emissions for 2014/15 and the emission factor for ammonia of 67.3 kg NH_3/SCU (Katestone, 2016).

The 217 cattle feedlots identified in the DAF dataset included information on the operating capacity (maximum SCU) for each feedlot. Methane emissions from a cattle feedlot are directly dependent on the number of cattle. Therefore, the emission factor of 62 kg CH_4/SCU was multiplied by the operating capacity (SCU) to estimate total emissions for each facility. In equation form methane emissions due to feedlot cattle were calculated as:

$$CH_4\_ER = FeedlotCattle \times CH_4\_EF$$

where:

CH$_4$_ER   Methane emissions (kg/year)

FeedlotCattle   Feedlot capacity in SCU (registered operating capacity)

CH$_4$_EF   Methane emission factor of 62 kg/SCU/year

3.3.3.2 Grazing cattle

The total number of grazing cattle in each NRM region are available within the NRM dataset. The percentage of each NRM region that intersects the study area was calculated using GIS and the equivalent number of grazing cattle for each NRM region in the study area was calculated as:

$$Cattle_{NRM\_Dom} = Cattle_{NRM} \times \frac{Area_{NRM\_Dom}}{Area_{NRM}}$$

where:

Cattle$_{NRM\_Dom}$ Number of cattle livestock within the NRM region within the study area

Cattle$_{NRM}$ Number of cattle livestock within the entire NRM region

Area$_{NRM\_Dom}$ Area of NRM region within the study domain

Area$_{NRM}$ Area of the entire NRM region

The number of grazing cattle within the study area were calculated as the difference between the total cattle livestock in the NRM region and the total number of feedlot livestock. There is no detailed information on the type of livestock, therefore each head of cattle is assumed to be equivalent to 1 SCU.

In equation form:

$$GrazCattle_{NRM\_Dom} = Cattle_{NRM\_Dom} - FeedlotCattle_{NRM\_Dom}$$

where:

GrazCattle$_{NRM\_Dom}$ Number of grazing cattle livestock within the NRM region within the study area

Cattle$_{NRM\_Dom}$ Number of cattle livestock within the NRM region within the study area

FeedlotCattle$_{NRM\_Dom}$ Feedlot cattle livestock within the NRM region within the study area

Methane emissions due to grazing cattle were calculated as:

$$CH_4\_ER = GrazCattle_{NRM\_Dom} \times CH_4\_EF$$

where:

CH_4_ER	Methane emissions (kg/year)
$GrazCattle_{NRA\_Dom}$	Number of grazing cattle livestock within the NRM region within the study area
CH_4_EF	Methane emission factor of 83.95 kg/SCU/year (equivalent to 0.23 kg/SCU/day).

3.3.3.3 Poultry farms

The DAF dataset identified 12 poultry farms within the study area.

The comparison of the NPI database and DAF dataset indicated that all poultry farms that reported to the NPI were found in the DAF dataset.

The capacity of each poultry farm was determined from publicly available approval documents, where available. Where no publicly available data could be found, capacity was estimated from the area of poultry sheds evident in aerial imagery and stocking densities presented in Table 5.

The DAF dataset reported poultry farm capacity as a range. In these cases, a mid-point was selected. For example, for poultry farms with a reported capacity of 1,000 – 200,000, emissions were calculated using a capacity of 100,000.

The type of poultry farm was determined from approval documents or publicly available information, where available. Where no information could be found, the default emission factors were used.

For poultry farms of unknown type, a stocking density for breeder farms of 14 birds/m2 was used as required to calculate poultry farm capacity.

Methane emissions due to poultry were calculated as:

$$CH_4\_ER = Poultry \times CH_4\_EF$$

where:

CH_4_ER	Methane emissions (kg/year)
Poultry	Poultry population
CH_4_EF	Methane emission factor (kg/bird/year) for bird type summarised in Table 4.

3.3.3.4 Piggeries

The DAF dataset included 114 piggeries within the study area. Six of these facilities reported to the NPI during the 2014/15 period.

For facilities that reported to the NPI, piggery capacity was estimated based on the reported ammonia emissions for 2014/15 and the ammonia emission factor of 6.8 kg NH_3/SPU (Katestone, 2016). Where piggeries did not report to the NPI, the capacity was estimated as the number of pigs that would produce ammonia emissions equal to 70% of the reporting threshold of 10,000 kg NH_3/year.

There is no detailed information on specific farm types. Therefore, the default factor of 15.6 kg CH_4/SPU, estimated using pig population distribution (Table 6) and emission factors for enteric formation and manure management (Table 7), was used.

Methane emissions due to piggeries were calculated as:

$$CH_4\_ER = Pigs \times CH_4\_EF$$

where:

CH$_4$_ER   Methane emissions (kg/year)

Pigs   Piggery capacity

CH$_4$_EF   Methane emission factor (kg/bird/year) of 15.6 kg/SPU

3.4 Emission rates

Total methane emissions from agriculture (feedlots, grazing cattle, poultry farms and piggeries) included in the Surat Basin Methane Inventory are summarised in Table 8.

Table 8   Total methane emissions (kg/year) due to agriculture

Source Type	Methane emissions (kg/year)
Feedlots	42,270,444
Grazing Cattle	92,991,979
Poultry farms	96,699
Piggeries	2,358,892

4. COAL MINING

4.1 Overview

This chapter details the coal mines included in the Surat Basin Methane Inventory and summarises their associated emissions of methane. The methods used to calculate emissions, data sources and assumptions are provided.

4.2 Emission sources

Four coal mines within the study area were identified as in operation during 2015. Table 9 details Run-of-mine (ROM) tonnages for each mine for 2014/15 (DNRM, 2016) and Figure 5 shows the mine locations.

Table 9   ROM coal tonnages for Surat Basin mines

Coal Mine	ROM Coal (Gross Raw Feed) Million tonnes (Mt)
Cameby Downs Coal Mine	1.75
Kogan Creek Mine	2.66
New Acland Open Cut Coal Mine	10.14
Commodore Coal Mine	3.48

Mining activities that may result in methane emission include:

- Extraction of coal
- Coal exploration
- Material handling
- Combustion of fuel.

There is no emission factor for methane emissions associated with coal exploration. Therefore, emissions of methane from this activity could not be quantified and have been excluded for the inventory. Notwithstanding this, methane emissions associated with coal exploration are likely to be relatively small.

There is also no publicly available information regarding material handling and fuel usage at the coal mines identified in the study area. Emissions of methane from these activities are expected to be relatively small compared to extraction of coal, consequently, emissions of methane from these sources have been excluded from the inventory.
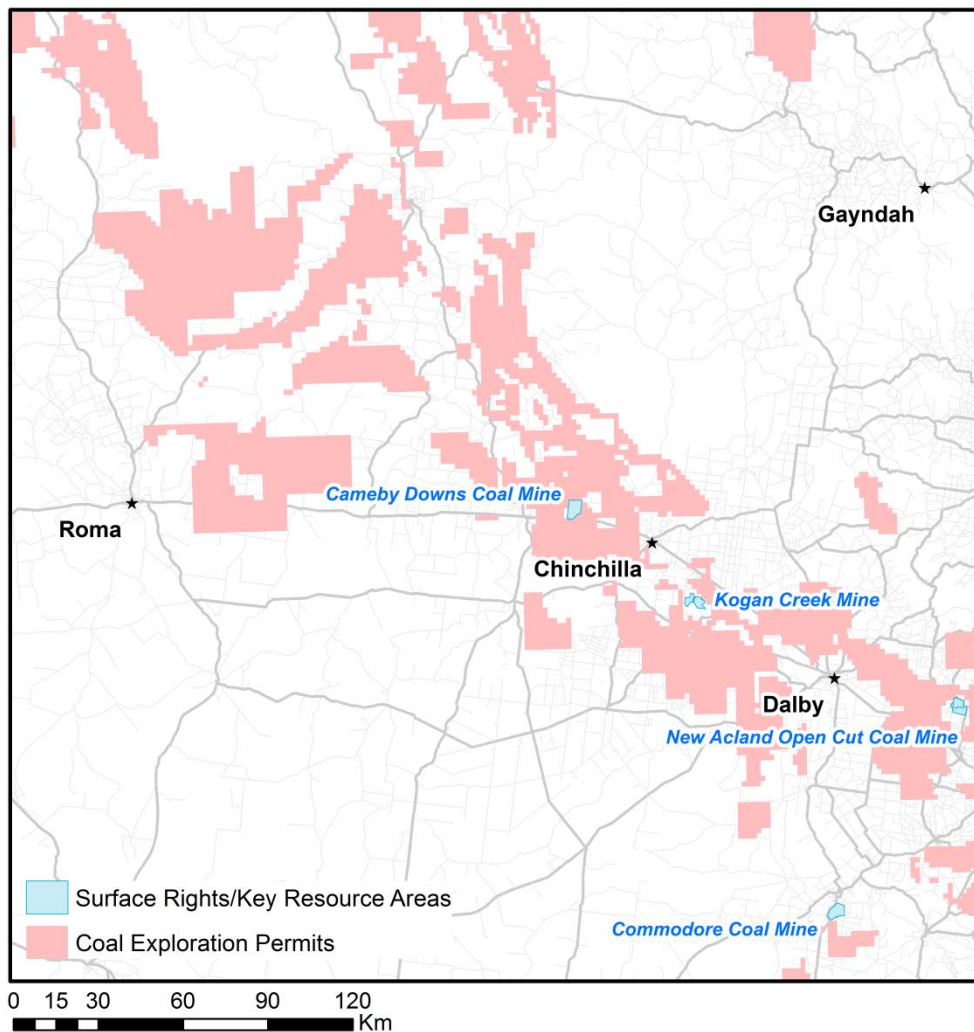
Figure 5   Coal mines included in the Surat Basin Methane Inventory

4.3   Methodology

4.3.1 Information

The following information was used to estimate methane emissions from coal mining:

- Run of mine (ROM) (gross raw output) coal tonnages for 2014/15 (Department of Natural Resources and Mines (DNRM) - *Queensland coal production by individual mine*, May 2016).

- DNRM Mining lease surface areas.

- Fugitive methane emission factor for extraction of coal in Queensland of 0.020 tonnes CO_2-e / tonne raw coal (DoE, 2016).

- Methane GWP of 25 (DoE, 2016).

4.3.2 Calculation methodology

4.3.2.1 Coal extraction

Methane emissions from extraction of coal were calculated as:

$$CH_4\_ER = Coal \times CH_4\_EF$$

where:

CH$_4$_ER   Methane emissions (kg/year)

Coal   Amount of run-of-mine coal (kg/year)

CH$_4$_EF   Methane emission factor of 0.8 kg/tonne coal/year (equivalent to 0.020 tonnes CO_2-e/tonne coal)

Methane emissions were allocated uniformly across the mining lease areas associated with each mine as identified from the DNRM dataset.

4.4 Emission rates

Methane emissions from coal mining activities included in the Surat Basin Methane Inventory are summarised in Table 10.

Table 10　　　　**Total methane emissions (kg/year) due to coal mining**

Source Type	Cameby Downs Coal Mine	Kogan Creek Coal Mine	New Acland Open Cut Coal Mine	Commodore Coal Mine
Coal extraction	1,397,990	2,128,364	8,115,158	2,783,052

5. COAL SEAM GAS ACTIVITIES

5.1 Overview

This chapter details the coal seam gas (CSG) activities that were considered by the Surat Basin Methane Inventory. The methods used to calculate emissions, data sources and assumptions are provided.

5.2 Emission sources

CSG is primarily composed of methane. CSG production and processing can lead to the release of methane into the atmosphere. Methane emission from CSG operations can occur for a number of reasons, with some sources emitting continuously while others are more intermittent in nature. A summary of the emission sources considered in this inventory is provided in Table 11.

Table 11   Summary of methane emission sources from CSG operations

		Emission source	Intermittent	Continuous
Production emissions	Wellhead emissions	Wellhead control equipment		X
		Separators		X
		Maintenance	X	
		Leaks	X	
	Combustion emissions	Well head pumps		X
		Flaring	X	
		Diesel used in vehicles	X	
		Backup generators	X	
	Pipeline emissions	Pipeline control equipment		X
		High point vents on produced water pipelines	X	
Processing emissions	Processing facility emissions	Compressor venting		X
		Control equipment		X
		Gas conditioning units including dehydrators		X
	Combustion emissions	Plant compressors		X
		Flaring	X	
		Diesel used in vehicles	X	
		Backup generators	X	
	Produced water	Collection and storage of produced water	X	

The CSG operators active in the study area are as follows:

- Origin
- QGC
- Arrow
- Santos
- APT Petroleum Pipelines (Kogan North Processing Facility).

Table 12 provides a summary of the operations.

Table 12   Summary of gas field operations

Number of Operators	Number of Gas Fields	Number of Wells^	Number of Processing Facilities
Five	16	4628	16
Table note: ^Number of wells estimated based on Queensland Government CSG production data			

Methane emissions due to two of the five operators have not been included in the inventory due to insufficient detail being available at the time of this report. Based on published Queensland government CSG production data, it has been determined that these operators account for approximately 1.5% of emissions associated with CSG activities. This is small compared to the overall uncertainty associated with the estimated methane emissions from CSG operations (see Section 13). As a result, omission of these small operators from the inventory is unlikely to affect the reliability of the CSG methane inventory.

Figure 6 provides a summary of the location and scale of operations considered by the study.

● Processing Facilities
· Wells
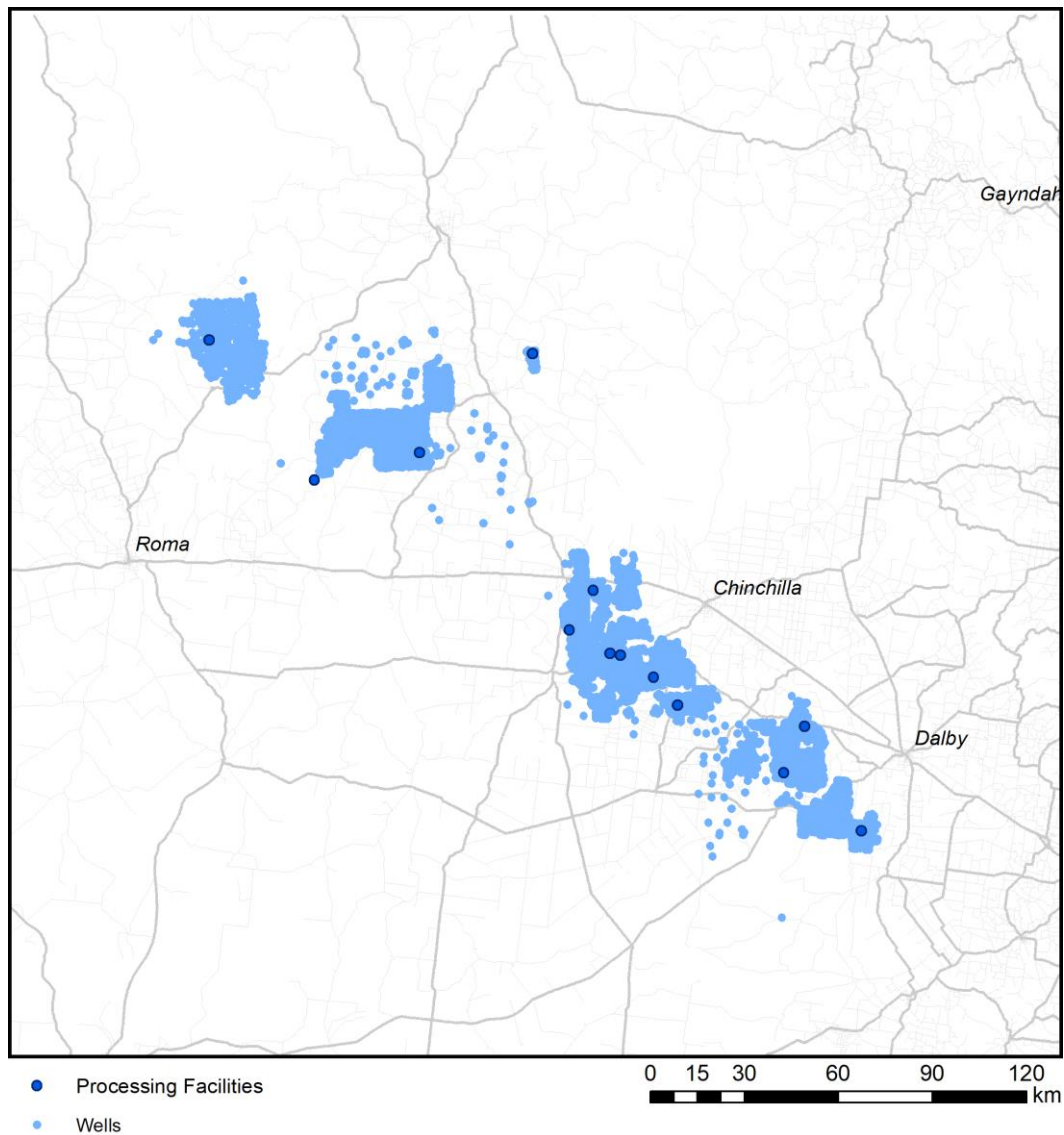
Figure 6   CSG operations in the Surat Basin

5.3 Methodology

The methane emissions resulting from CSG activities in the Surat Basin have been estimated in consultation with the relevant operators.

5.3.1 Information

Information sources used in the assessment include:

- Location of CSG well and processing facilities based on data available through DNRM.
- Methane emissions data and calculations provided by operators.

Where possible, all information provided by operators has been subject to a comprehensive review process. This has included consideration of the calculation methods and emission factors as well as the magnitude and intensity of methane emissions associated with production and processing activities.

5.3.2 Calculation methodology

The calculation methods used to estimate methane emissions from CSG activities are consistent with the NGER program. Methane is classified as a GHG under the NGER program and is quantified and reported in terms of carbon dioxide equivalents (CO_2-e). CO_2-e is calculated by multiplying the mass rate of methane by its Global Warming Potential (GWP), which for methane (GWP_{CH4}) is 25. It provides an indication of the contribution of methane to global warming relative to CO_2 (where CO_2 GWP=1). In simple terms the quantity of methane emissions can be calculated by dividing the quantity of methane emissions estimated in CO_2-e by the GWP for methane:

tonnes **CH₄ =** tonnes **CO₂-e** / **25**

The general equations used to estimate methane emissions from CSG activities are described in the following sections.

5.3.2.1 Combustion

Emissions due to combustion of CSG (including flaring) and diesel were calculated based on the following equation:

$$E_{CH_4} = Q_i \times EC_i \times EF_{CH_4}/GWP_{CH_4}$$

Where:

E_{CH_4}	Emissions of methane in kilograms due to the combustion of fuel type (*i*).
Q_i	Quantity of fuel type (*i*) combusted measured in cubic metres (CSG combustion), tonnes (CSG flaring), kilolitres (diesel) or gigajoules (energy content is not applied in this instance).
EC_i	Energy content of fuel type (*i*) measures in gigajoules per cubic metre (CSG) or gigajoules per kiloliter (diesel).
EF_{CH_4}	Emission factor for methane (CH₄) measured in kilograms CO_2-e/gigajoule (CSG combustion and diesel), tonnes CO_2-e/tonnes of gas flared (CSG flaring).
GWP_{CH_4}	Global Warming Potential (GWP) of methane, equals 25.

Table 13   Emission factors and energy content for methane emissions from combustion and flaring of CSG

Emission source	Energy content	Units	Emission factor***	Units
Coal seam methane (combustion)*	37.7×10^{-3}	GJ/m^3	0.2	kgCO$_2$e/GJ
Unprocessed natural gas (flaring)**	-	-	0.1	tCO$_2$e/t gas flared
Diesel*	38.6	GJ/kL	0.1	kgCO2e/GJ
Table note: *Source: *National Greenhouse and Energy Reporting (Measurement) Determination 2008, Schedule 1* **Source: *National Greenhouse and Energy Reporting (Measurement) Determination 2008, Section 3.85* ***Emission factors listed are for a Method 1 estimation of emissions				

5.3.2.2 Fugitive emissions - Venting of CSG

Estimates of the quantities of gas vented are based on methods prescribed by the Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry (API Compendium) (API, 2009). Emissions estimated based on the direct measurement of gas released is the preferred and sometimes only available method; however, if this information is unavailable industry standard factors can be applied. Table 14 provides a list of the relevant sections of the API Compendium.

Table 14   Summary of API Compendium venting emissions calculation methodologies

Emissions process	API Compendium section
Gas treatment processes	Section 5.1
Cold process vents	Section 5.3
Other venting sources—gas driven pneumatic devices	Section 5.6.1
Other venting sources—gas driven chemical injection pumps	Section 5.6.2
Other venting sources—coal seam exploratory drilling, well testing and mud degassing	Section 5.6.3 and 5.6.6
Non-routine activities—production related non-routine emissions	Section 5.7.1 or 5.7.2
Non-routine activities—gas processing related non-routine emissions	Section 5.7.1 or 5.7.3

5.3.2.3 Fugitive emissions – other than venting or flaring

Fugitive methane emissions, other than emissions that are vented of flared (also referred to as leaks), include emissions from (NGER Determination 2008, Section 3.70):

- *a gas wellhead through to the inlet of gas processing plants; and*

- *a gas wellhead through to the tie-in points on gas transmission systems, if processing of natural gas is not required; and*

- *gas processing plants; and*

- *well servicing; and*

- *gas gathering; and*

- *gas processing and associated waste water disposal.*

Fugitive methane emissions other than emission that are vented or flared have been calculated based on the following equation:

$$E_{CH_4} = Q \times EF_{CH_4}/GWP_{CH_4}$$

E_{CH_4} — Emissions of methane other than emissions that are vented or flared from production and processing of natural gas in kilograms.

Q — the total quantity of natural gas that passes through the natural gas.

production and processing measured in tonnes.

EF_{CH_4} — 1.2 x 10^{-3}, which is the emission factor for methane from general leaks in the natural gas production and processing, measured in CO_2-e tonnes per tonne of natural gas that passes through the natural gas production and processing.

GWP_{CH_4} — Global Warming Potential (GWP) of methane, equals 25.

5.4   Emission Rates

Methane emissions associated with CSG activities have been estimated based on the data provided together with supplementary calculations using the methodology described above. Table 15 provides a summary of methane emissions from CSG activities in the Surat Basin.

Table 15   Total methane emissions (kg/year) due to CSG activities

Activity	Methane emissions (kg/year)
Gas consumed for combustion	197,603
Diesel combustion	4,384
Flaring	1,309,137
Venting	14,499,257
Fugitive emissions	518,456
TOTAL	**16,528,838**

6. LANDFILLS

6.1   Overview

This chapter details the landfills that were included in the Surat Basin Methane Inventory and summarises their estimated methane emissions. The methods used to calculate emissions, data sources and assumptions are provided.

6.2   Emission sources

There are 41 landfills in the Surat Basin Methane Inventory study area for which methane emissions have been calculated, as shown in Figure 7.
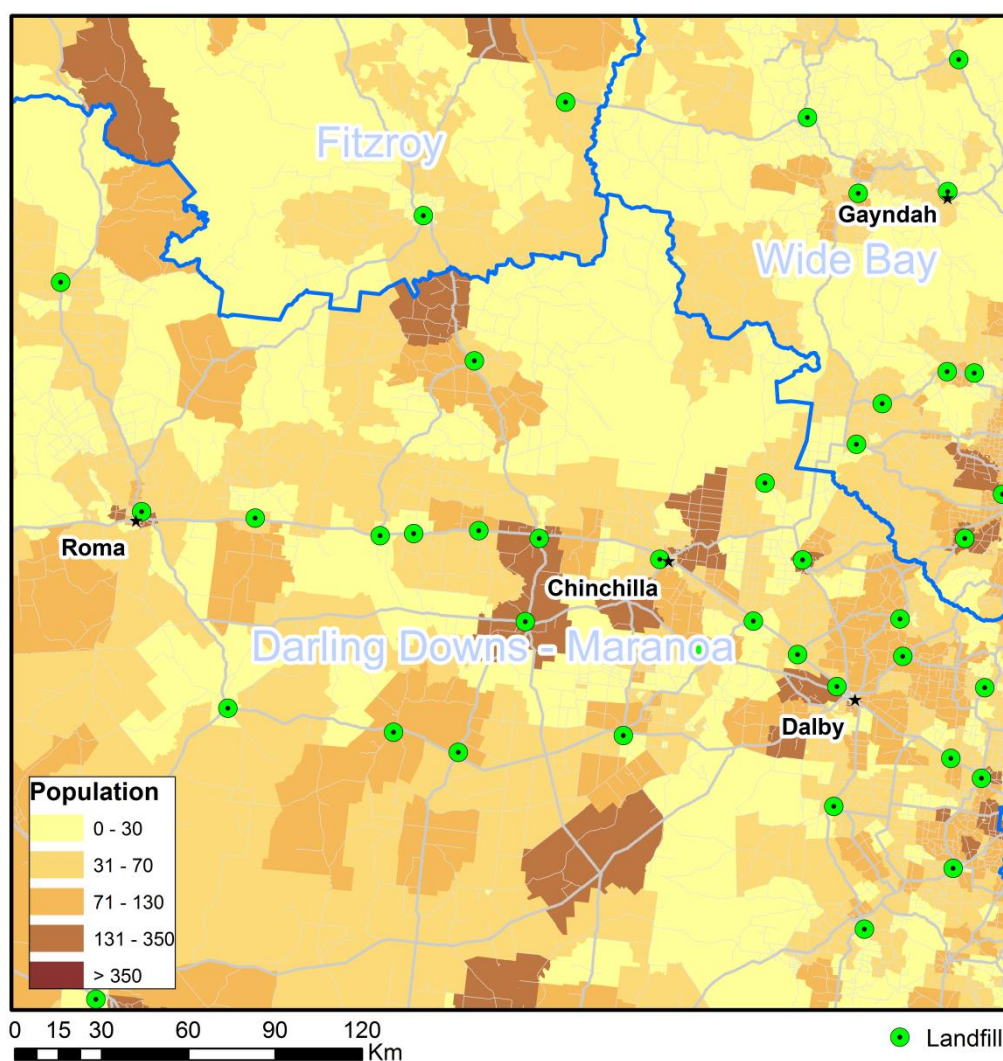
Figure 7   Location of landfills in the study area

6.3 Methodology

6.3.1 Information

The following information was used to generate the methane emissions for landfills in the study area:

- Locations of landfills was based on contact details and site information for public waste and recycling facilities in Queensland (EHP, 2016)

- Population data for 2011 (ASGS, 2011) from residential mesh blocks, approximately 30-60 dwellings designed to be small enough to aggregate accurately to a wide range of spatial units

- Statistical Area Level 4 (SA4) ASGS digital boundaries (ASGS,2011)

- Queensland regional waste per person estimate (DERM, 2011)

- Methane fraction of landfill gas (50%) and emission factor for municipal solid disposed to landfill of 1.4 tonnes CO_2-e/tonne waste (DoE, 2016)

- Methane GWP of 25 (DoE, 2016).

6.3.2 Calculation methodology

Locations of each landfill in the study area were identified from the EHP (2016) dataset. Population data for the study area was sourced from ASGS (2011) for residential mesh blocks.

The total waste per mesh block was calculated using the estimated waste per person for Queensland, detailed in Table 16.

Table 16   Waste per person estimate for Queensland (DERM, 2011)

Region	Waste per person disposed to landfill (tonnes waste / person)
Darling Downs - Maranoa	1
Fitzroy	0.51
Wide Bay	0.28
Toowoomba[1]	1

Table note:
[1] The Toowoomba region is not defined in the DERM study. Estimated waste per person for this region based on the adjacent Darling Downs – Maranoa region.

In equation form:

$$Waste_{mb} = Pop_{mb} \times WasteFactor_{reg}$$

where:

Waste$_{mb}$ Total waste per mesh block (tonnes waste)

Pop$_{mb}$ Population per mesh block (count)

WasteFactor$_{reg}$ Waste Factor for the region

Distances between the mesh block and landfill facilities were calculated using GIS. Mesh blocks were then assigned to the nearest landfill facility. Total waste processed at each facility was then calculated.

In equation form:

$$Waste_{fac} = \sum_{mb=1}^{n} Waste_{mb}$$

where:

Waste$_{fac}$ Total waste per facility (tonnes waste)

Waste$_{mb}$ Total waste per mesh block (tonnes waste)

n   Number of mesh blocks assigned to facility

The population and total waste calculated for each region are summarised in Table 17.

Table 17   **Population and total waste calculated for each region**

Region	Population	Waste (tonnes)
Darling Downs - Maranoa	63,891	63,891
Fitzroy	1,504	767
Wide Bay	11,656	3,264
Toowoomba	137	137
Total	**77,188**	**68,059**

6.4   Emission rates

Methane emissions due to landfills included the Surat Basin Methane Inventory are summarised in Table 18.

Table 18   **Total methane emissions (kg/year) due to landfills**

Landfill Area	Methane emissions (kg/year)
Darling Downs - Maranoa	1,788,948
Fitzroy	21,477
Wide Bay	91,383
Toowoomba	3,836
Total	**1,905,644**

7. POWER STATIONS

7.1 Overview

This chapter details the power stations that were included in the Surat Basin Methane Inventory. The methods used to calculate emissions, data sources and assumptions are provided.

7.2 Emission sources

There are eight power stations in the study area for which methane emissions have been calculated. The power stations detailed in Table 19 and Figure 8 are:

- Braemar 1 Power Station
- Braemar 2 Power Station
- Condamine Power Station
- Daandine Power Station
- Darling Downs Power Station
- Roma Power Station
- Kogan Power Station
- Millmerran Power Station.

Methane emissions from the above power stations are related to the combustion of coal or natural gas.

Table 19   Power stations in Surat Basin Methane Inventory

Power Station	Easting (WGS-84, m)	Northing (WGS-84, m)	Latitude	Longitude	Type
Braemar 1	292,235	6,999,150	-27.1145	150.9041	Gas, open cycle turbines
Braemar 2	292,352	6,999,341	-27.1128	150.9053	Gas, open cycle turbines
Condamine	228,319	7,047,429	-26.6680	150.2703	Gas, combined cycle turbines
Daandine	295,724	7,002,098	-27.0884	150.9397	Gas, reciprocating engines
Darling Downs	291,352	6,999,208	-27.1138	150.8952	Gas, combined cycle turbines
Roma	85,549	7,053,625	-26.5775	148.8404	Gas, open cycle turbines
Kogan	276,249	7,020,300	-26.9212	150.7467	Coal
Millmerran	330,698	6,905,504	-27.9648	151.2788	Coal
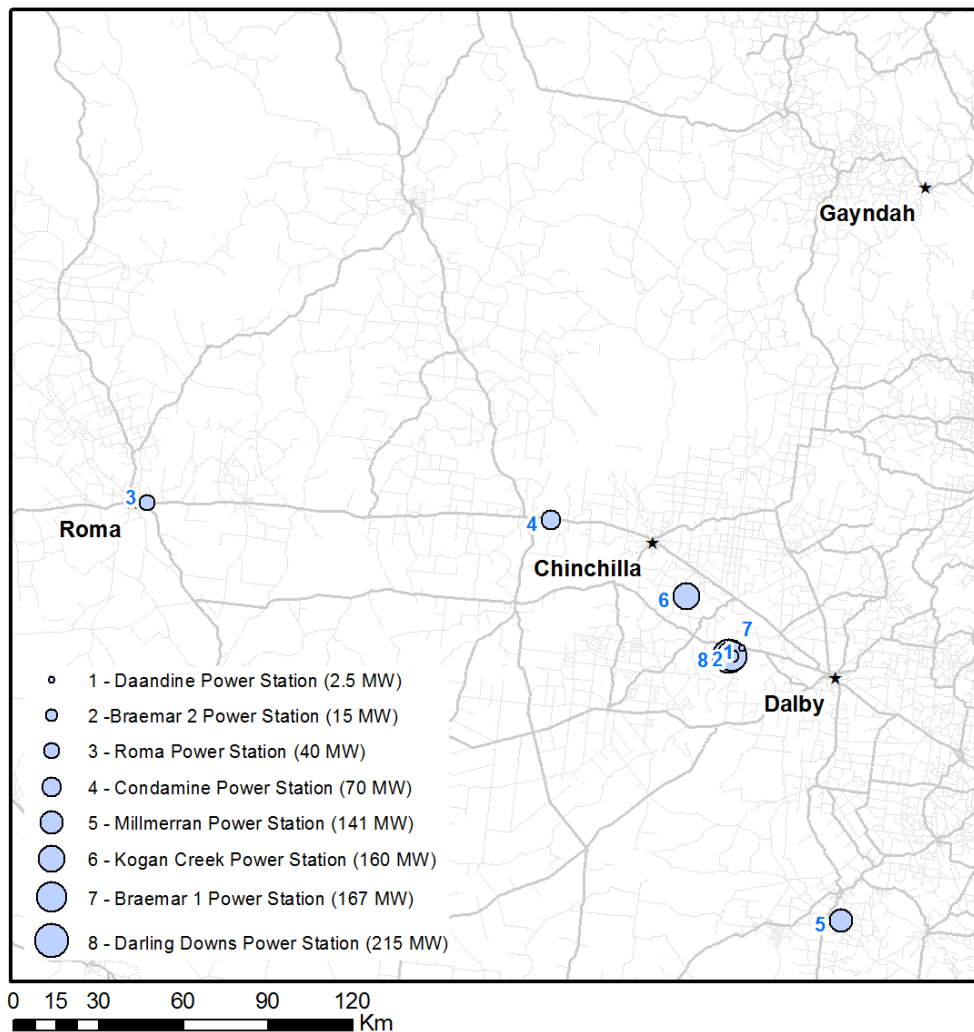
Figure 8   Power stations included in the Surat Basin Methane Inventory

7.3   Methodology

7.3.1   Information

The following information was used to generate the power stations methane emissions:

- Actual electricity generation for each power station from the Australian Energy Market Operator (AEMO) for 2015 at 5-minute intervals

- Emission intensity information from the Clean Energy Regulator for 2015/2016 National Greenhouse and Energy Reporting year

- National Greenhouse Accounts Factors (DoE, 2016)

    o   Emission and energy content factors - gaseous fuels

    o   Emission and energy content factors – solid fuels and certain coal-based products

- Methane GWP of 25 (DoE, 2016).

- Stack characteristics sourced from *Australia Pacific LNG Project Volume 5: Attachments Attachment 28: Air Quality Impact Assessment – Gas Fields* (Katestone, 2010b).

Emission intensity for each power station changes with load. However, this detailed information was not available. Therefore, it was assumed that the emission intensity remained constant throughout the year.

7.3.2 Calculation methodology

Methane emissions from the power stations were calculated as follows:

$$CH_4\_ER = MWh \times EI \times CH_4\_EF$$

where:

CH4_ER   Methane emission rate in g/s

MWh   Megawatt hours per 5 minutes

EI   Emission intensity in tonnes / MWh

CH4_EF   Emission factor for methane derived from CO2-e emission factors and GWP for methane

Table 20 details total electricity generation and intensity data used for 2015.

Table 20   **Total electricity generation (MWh) for each power station for 2015**

Power Station	2015 MWh	Intensity data (t/MWh)[1]
Braemar 1	1,600,121	0.57
Braemar 2	1,944,877	0.59
Condamine	527,140	0.44
Daandine	236,520	0.52
Darling Downs	4,373,193	0.41
Roma	118,572	0.65
Kogan	5,764,719	0.83
Millmerran	6,983,105	0.81
Table note: 1 Emission intensity data is based on 2014/2015 NGER reporting period		

7.4 Emission rates

Methane emissions due to power stations included in the Surat Basin Methane Inventory are summarised in Table 21.

Table 21   **Total methane emissions (kg/year) due to power stations**

Power Station	Methane emissions (kg/year)
Braemar 1	141,324
Braemar 2	177,800
Condamine	18,004
Daandine	18,888
Darling Downs	139,182
Roma	5,983
Kogan	63,634
Millmerran	75,255

8. WASTEWATER TREATMENT FACILITIES

8.1   Overview

This chapter details the wastewater treatment facilities that were included in the Surat Basin Methane Inventory and summarises the estimated methane emissions. The methods used to calculate emissions, data sources and assumptions are provided.

8.2   Emission sources

There are 20 wastewater treatment facilities in the Surat Basin study area for which methane emissions have been calculated.

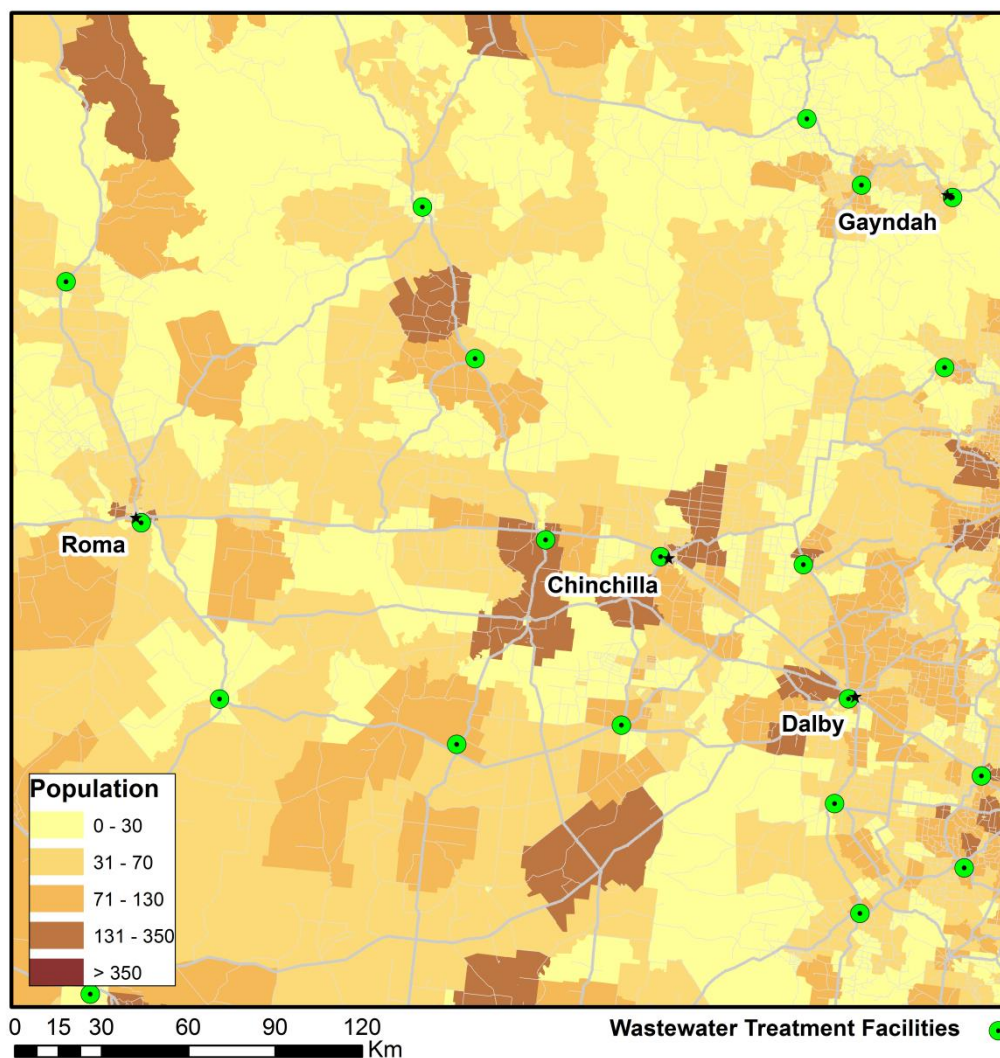The location of the wastewater treatment facilities in the study area are shown in Figure 9.

Figure 9   Wastewater treatment facilities in the study area

8.3   Methodology

8.3.1 Information

The following information was used to generate the wastewater treatment facility methane emissions:

- Locations of wastewater treatment facilities based on national database (Geoscience Australia, 2012)

- Population data for 2011 (ASGS, 2011) from residential mesh blocks, approximately 30-60 dwellings designed to be small enough to aggregate accurately to a wide range of spatial units

- Wastewater per person estimate of 0.0585 tonnes wastewater/person (DoE, 2016)

- Methane emission factor of 6.3 tonnes CO_2-e/tonne waste (DoE, 2016)

- Methane GWP of 25 (DoE, 2016).

8.3.2 Calculation methodology

The location of each wastewater treatment facility in the study area was identified from the Geoscience Australia (2012) dataset. Population data within the study area were sourced from ASGS (2011), consistent with population data used in the development of the landfill and motor vehicle methane inventory.

The total wastewater per mesh block was calculated using the estimated wastewater factor of 0.0585 tonnes wastewater/person (DoE, 2016).

In equation form:

$$Wastewater_{mb} = Pop_{mb} \times WasteFactor$$

where:

Wastewater$_{mb}$ Total wastewater per mesh block (tonnes waste)

Pop$_{mb}$ Population per mesh block (count)

WasteFactor   Waste Factor for the region (0.0585 tonnes wastewater/person (DoE, 2016))

Distances between the mesh block and wastewater treatment facilities were calculated using GIS. Mesh blocks were then assigned to the nearest facility. Total wastewater treated at each facility was then calculated.

In equation form:

$$Wastewater_{fac} = \sum_{mb=1}^{n} Wastewater_{mb}$$

where:

Wastewater$_{fac}$ Total wastewater per facility (tonnes waste)

Wastewater$_{mb}$ Total wastewater per mesh block (tonnes waste)

n   Number of mesh blocks assigned to facility

The population and total wastewater treated in the study area is summarised in Table 22.

Table 22   Population and total wastewater treated in the study area

Source	Population	Wastewater treated (tonnes)
Wastewater Treatment Facility	77,188	4,515

Further assumptions used in estimating emissions include:

- All wastewater assumed to be sludge treated at each facility
- Chemical oxygen demand (COD) of sludge removed from each facility assumed to be zero, resulting in the most conservative estimate of methane emissions
- Direct discharge to open waters does not occur
- No capture of methane.

8.4   Emission rates

Methane emissions from wastewater treatment facilities included in the Surat Basin Methane inventory are summarised in Table 23.

Table 23   Total methane emissions (kg/year) due to wastewater treatment facilities

Source	Methane emissions (kg/year)
Wastewater treatment facilities	1,137,905

9. RIVER SEEPS

9.1 Overview

This chapter summarises the methane emissions due to river seeps included in the Surat Basin Methane Inventory. The methods used to calculate emissions, data sources and assumptions are provided.

9.2 Information

The emissions of methane from river seeps in the study area is based on advice from Stuart Day from CSIRO who advised that a total methane flux of 1000L/min should be used for the four main seeps in the Condamine River.

The location of river seeps in the study area are shown in Figure 10 and correspond to locations provided by CSIRO in the file "Condamine River Seeps.kmz".
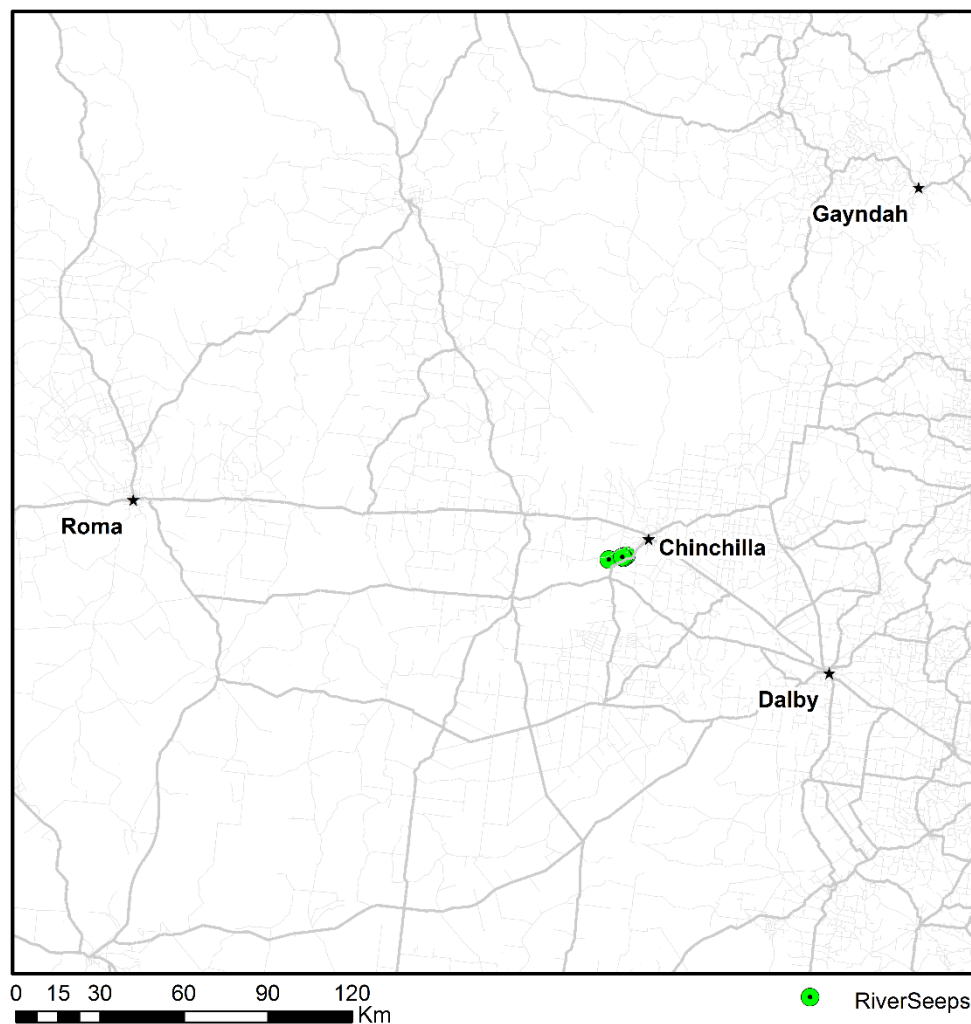
Figure 10   Location of river seeps included in the Surat Basin Methane Inventory

9.3   Calculation methodology

The emission rate of methane from river seeps was calculated using the following formula:

$$CH_4\_ER = \frac{methane\ flux\ x\ density}{n_{sites}\ x\ 60}$$

Where:

CH$_4$_ER   Emission rate of methane g/s

Methane flux   Methane flux in L/min (1000)

n$_{sites}$ Number of sites giving methane flux (4 sites)

density   Density of methane (0.716 g/L)

9.4   Emission rates

Methane emissions due to river seeps included in the Surat Basin Methane Inventory are summarised in Table 24.

Table 24   Total methane emissions (kg/year) due to river seeps

Source	Methane emissions (kg/year)
River seeps	375,909

10. GROUND SEEPS

10.1 Overview

This chapter summarises the methane emissions due to ground seeps included in the Surat Basin Methane Inventory. The methods used to calculate emissions, data sources and assumptions are provided.

10.2 Information

The emissions of methane from ground seeps in the study area is based on work conducted by CSIRO and reported in the report Characterisation of Regional Fluxes of Methane in the Surat Basin, Queensland, Phase 2: A Pilot Study of Methodology to Detect and Quantify Methane Sources (CSIRO, 2015).

The locations of ground seeps in the study area are shown in Figure 11 and correspond to locations provided in CSIRO (2015).

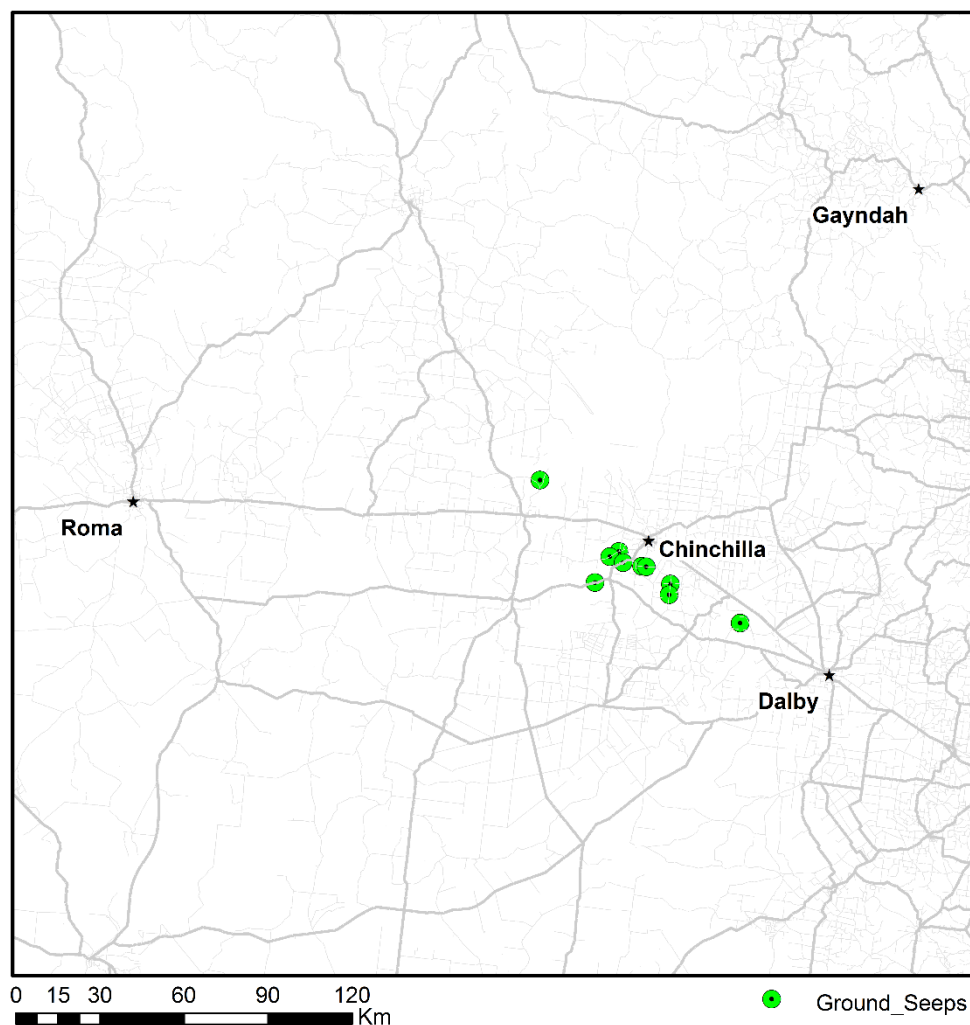**Figure 11   Location of ground seeps in the study area**

Table 3.5 of CSIRO (2015) summarised the measured methane emission rate for 10 sites using a combination of measurement methods (traverse and flux chamber). The measured emission rates are reproduced in Table 25. The maximum emission at each site has been used in the Surat Basin Methane Inventory.

Table 25   Summary of emission flux results for ground seeps (Table 3.5 CSIRO, 2015)

Site	Emission rate (kg/day)	
	Traverse	Flux Chamber
Site 1 Jan 2013	48.8	46.6
Site 1 Sept 2013	79.8	na
Site 2	na	102
Site 3	103	61.3
Site 4	na	7.1
Site 5	na	3.7
Site 6	na	51.5
Site 7	na	1.7
Site 8	na	1.0
Site 9	na	0.2
Site 10	0.1	na

10.3   Emission rates

Methane emissions due to ground seeps included in the Surat Basin Methane Inventory are summarised in Table 26.

Table 26   Total methane emissions (kg/year) due to ground seeps

Source	Methane emissions (kg/year)
Ground seeps	127,714

11. DOMESTIC WOOD HEATING

11.1 Overview

This chapter details the domestic wood heating sources included in the Surat Basin Methane Inventory. The methods used to calculate emissions, data sources and assumptions are provided.

11.2 Emission sources

The types of domestic wood heaters included in the Surat Basin Methane Inventory were based on the NSW EPA GMR Inventory 2008 (NSW EPA, 2012a) and include the following:

- Slow combustion heaters with compliance plates
- Slow combustion heaters without compliance plates
- Open fireplaces
- Potbelly stoves.

11.3 Methodology

11.3.1 Information

The following information was used to generate the domestic wood heating methane emissions:

- NSW EPA GMR Inventory 2008 (NSW EPA, 2012a):
    - Emission factors for domestic wood heating
    - Diurnal, weekly and monthly profiles for domestic wood heating.
- Number of dwellings by mesh block based on the 2011 census (ASGS, 2011), presented in Figure 12.
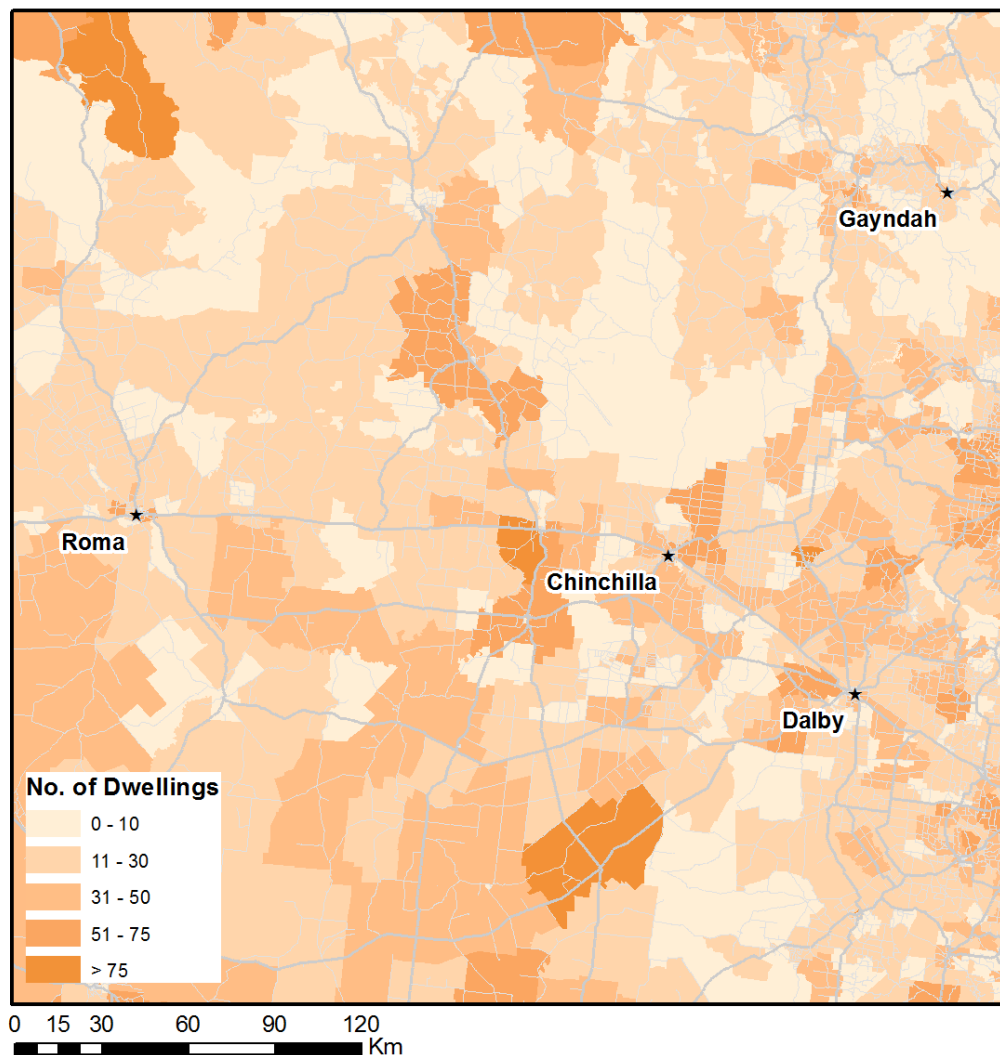
Figure 12   Number of dwellings in the study area (assigned by mesh block)

11.3.2 Calculation methodology

The following approach was taken to assign domestic wood heating methane emissions spatially:

- The average ownership of solid fuel heaters and the average consumption of fuel per heater were taken from the NSW EPA GMR Inventory 2008 and used to determine a consumption factor for each heater type per dwelling

- The consumption factor was then applied to estimate the total annual consumption of fuel within each ABS mesh block

- The estimated consumption rates were assigned to individual grids within the study area.

Diurnal, weekly and monthly profiles were constructed from information presented in the NSW EPA GMR Inventory 2008.

All dwellings in the study area were assumed to fall into the 'Separate house' category.

The methane emission factors for the different types of wood heaters are based on the NSW EPA GMR Inventory 2008 as presented in Table 27.

Table 27   Methane emission factors for solid fuel from the NSW EPA GMR Inventory 2008

Wood Heater Type	Methane emission factor (kg CH$_4$/tonne of fuel)
Slow combustion heater with compliance plate	14.2
Slow combustion heater without compliance plate	32
Open fireplace	7.2
Potbelly stove	32

11.4 Emission rates

Methane emissions due to wood-fired heaters included in the Surat Basin Methane Inventory are summarised in Table 28.

Table 28   Total methane emissions (kg/year) due to domestic wood heating

Domestic Wood Heater Type	Methane emissions (kg/year)
Slow combustion heater with compliance plate	109,171
Slow combustion heater without compliance plate	108,321
Open fireplace	34,889
Potbelly stove	27,943

12. MOTOR VEHICLES

12.1 Overview

This chapter details the methane emissions from motor vehicles included in the Surat Basin Methane Inventory. The methods used to calculate emissions, data sources and assumptions are provided.

12.2 Emission sources

Roads within the study area that were included in the Surat Basin Methane Inventory are shown in Figure 13. The following scenarios were used to develop methane emissions from motor vehicles in the study area:
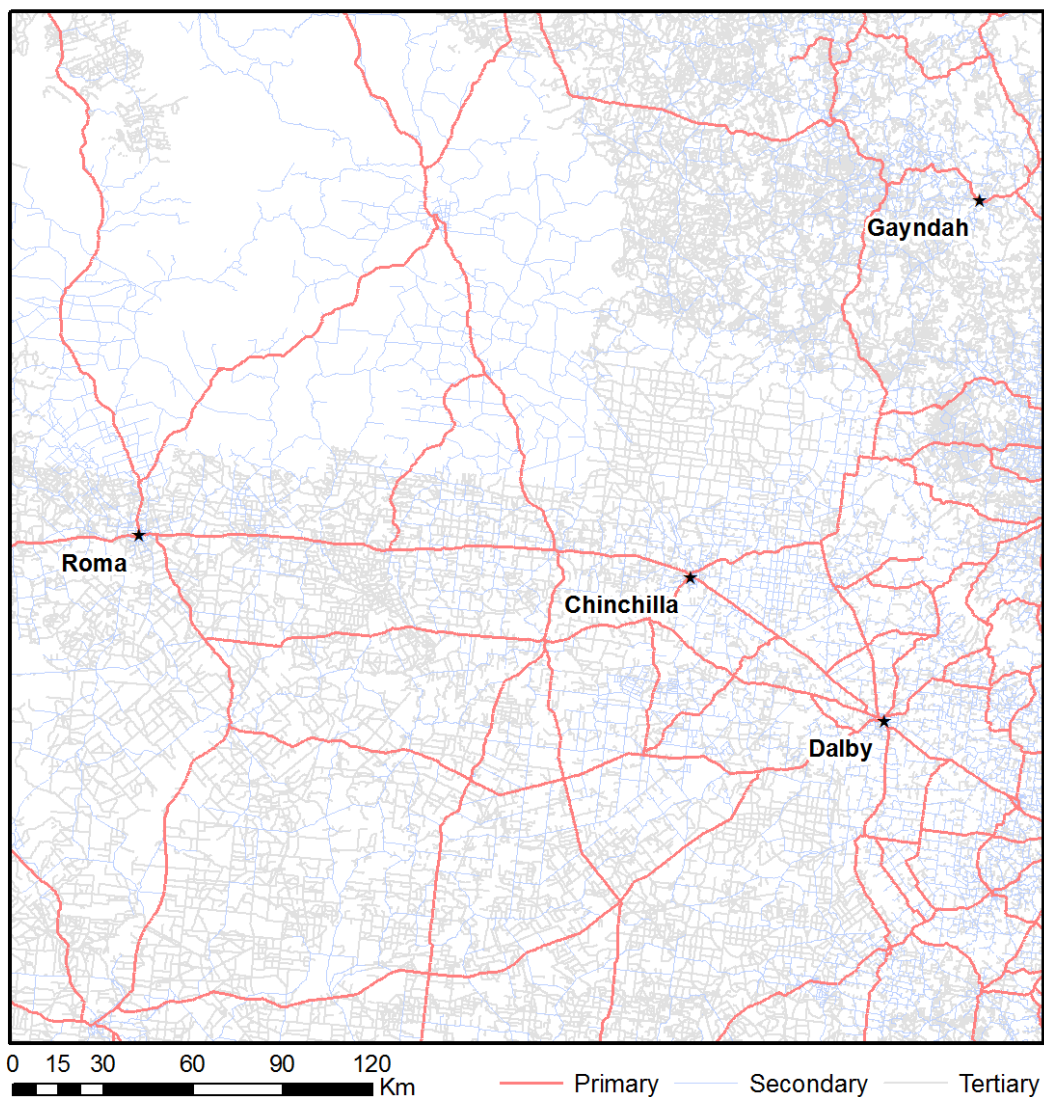
- Hot running base emissions
- Speed correction.

Figure 13   Roads within the study area

12.3 Methodology

12.3.1 Information

The following information was used to generate the motor vehicle inventory:

- NRM, 2010. Attributes and Locations of Queensland Roads
  - DTMR's (Department of Transport and Main Roads) dataset for Annual Average Daily Traffic (AADT) for most of the primary roads (Figure 14).

- Australian Bureau of Statistics:
  - Population and land use data (ASGS, 2011) from residential mesh blocks (Figure 15)
  - Vehicle fleet by age and fuel type from the Motor Vehicle Census (ABS, 2015c).

- NSW EPA GMR Inventory 2008 (NSW EPA, 2012b):
  - Hourly Vehicle Kilometer Travelled (VKT) distribution for average weekday/weekend by vehicle type
  - Hourly average speeds by road type
  - Fleet composite splitting factors by vehicle type and road type
  - Twenty-four-hour VKT weighted average speeds
  - Estimated number of axles for heavy duty fleet
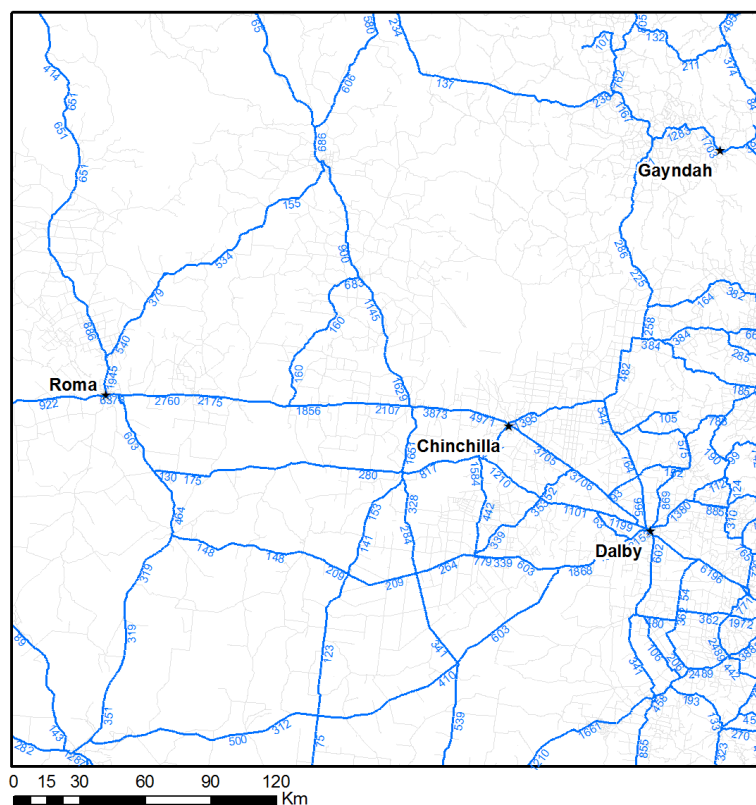 - Base exhaust hot running emissions by vehicle and fuel type.

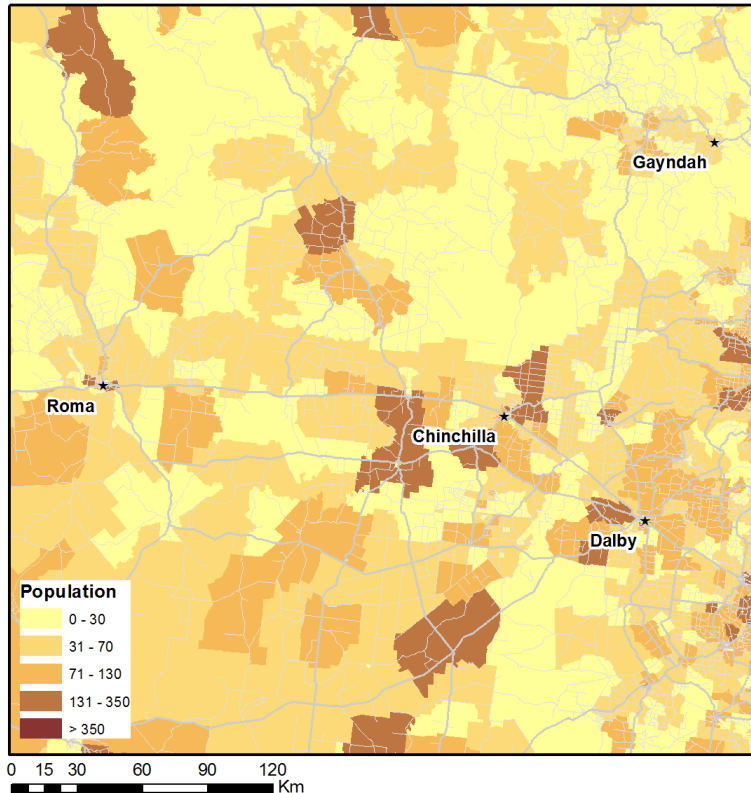**Figure 14   Annual average daily traffic data for primary roads**

Figure 15 Population data (mesh blocks) in the study area

12.3.1.1 Emission factors

Base hot running exhaust emissions are dependent on vehicle type, age of vehicle and fuel used. Organic compound emission factors for petrol and diesel vehicles, were based on emission factors used in the NSW EPA GMR Inventory 2008 (NSW EPA, 2012b).

12.3.2 Data checks

The following data checks were conducted on the motor vehicle information:

- Continuity of AADT data in segments
- Estimates of AADT were compared with estimated grid emissions
- Missing data were interpolated from existing data
- Overlay of detailed road data with imagery
- Visual comparison and inspection of AADT road geospatial information and detailed road information.

12.3.3 Calculation methodology

Methane emissions attributed to motor vehicles were calculated using the base equation:

$$CH4\_ER = \frac{VKT \times CH4\_EF}{1000}$$

where:

CH₄_ER   Emission rate of methane in kg/year

VKT   Vehicle kilometres travelled per year

CH₄_EF   Emission factor methane in g/VKT.

Methane emission factors were determined for each vehicle type (light vehicles, heavy vehicles, diesel light duty vehicles). Total methane emissions were calculated as the aggregate emission factors for all vehicles in the fleet, proportional to the composition. In equation form, the methane emission factor for a vehicle type was calculated as:

$$EF_{substance,veh\_type} = \sum_{yr\_manufacture=1991}^{2014} \%yr\_manufacture \times EF_{substance,yr\_manufacture}$$

where:

substance   substance

veh_type   vehicle type (light vehicles, heavy vehicles, diesel light duty vehicles)

$EF_{substance,veh\_type}$ aggregate emission factor for *substance* for vehicle type(g/VKT)

$\%yr\_manufacture$ % of vehicle type per year of manufacture

$EF_{substance,yr\_manufacture}$ emission factor for *substance* for vehicle manufactured during *yr_manufacture* (g/VKT).

Methane emissions were derived using the speciation of organic compounds in vehicle exhausts by fuel type. Aggregate methane emission factors for each vehicle type are summarised in Table 29. Diesel light duty vehicles are a subset of diesel light vehicles on all road types except for off-road.

Table 29   Aggregate methane emission factors (g/VKT) by vehicle type and road type

Road Type	Petrol		Diesel		
	Light Vehicles	Heavy Vehicles	Light Vehicles	Heavy Vehicles	Light Duty Vehicles
Commercial Highway	1.45E-03	2.93E-02	7.76E-03	4.45E-02	
Commercial Arterial	2.04E-03	4.26E-02	1.18E-02	6.60E-02	
Arterial	1.90E-03	4.02E-02	1.11E-02	6.22E-02	
Local/Residential	2.91E-03	5.84E-02	1.61E-02	9.14E-02	
Tertiary roads	-	-	-	-	1.75E-02

12.4 Emission rates

Methane emissions due to motor vehicles included in the Surat Basin Methane Inventory are summarised in Table 30.

Table 30   Total methane emissions (kg/year) due to motor vehicles

Road Type	Methane emissions (kg/year)		
	Light Vehicles	Heavy Vehicles	Diesel LDV
Commercial Highway	1,918	13,139	-
Commercial Arterial	1,324	6,829	-
Arterial	83	51	-
Local/Residential	28	17	-
Offroad	-	-	681
Total	**3,354**	**20,036**	**681**

13. UNCERTAINTY

Table 31 provides an indication of the uncertainty associated with the emission source categories defined for the Surat Basin Methane Inventory.

Table 31 Methane Emissions CSG Activities - Uncertainty Estimate

Emission category	Emission source description	Estimated Uncertainty
Agriculture	Feedlots	Moderate (estimate ±10-50%)
	Grazing cattle	High (estimate ±50-100%)
	Poultry farms	Moderate (estimate ±10-50%)
	Piggeries	Moderate (estimate ±10-50%)
Coal mining	Coal extraction	Moderate (estimate ±10-50%)
Landfills	Landfill gas	High (estimate ±50-100%)
Wastewater Treatment Facilities	Off gas	Moderate (estimate ±10-50%)
Power Stations	Combustion emissions	Low (estimate ±0-10%)
River seeps	Fugitive emissions	High (estimate ±50-100%)
Domestic wood heading	Combustion emissions	High (estimate ±50-100%)
Ground seeps	Fugitive emissions	High (estimate ±50-100%)
Motor vehicles	Exhaust emissions	High (estimate ±50-100%)
CSG Activities	Gas consumed for combustion	Low (estimate +/-5%)
	Diesel combustion	Low (estimate +/-10%)
	Flaring	Low (estimate +/-10%)
	Venting	High (estimate +/-50-100%)
	Fugitive emissions	High (estimate +/-50-100%)

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