Australian Government

BIOREGIONAL ASSESSMENTS

PROVIDING SCIENTIFIC WATER RESOURCE INFORMATION ASSOCIATED WITH COAL SEAM GAS AND LARGE COAL MINES

Groundwater numerical modelling for the Maranoa-Balonne-Condamine subregion

Product 2.6.2 for the Maranoa-Balonne-Condamine subregion from the Northern Inland Catchments Bioregional Assessment

30 May 2016

A scientific collaboration between the Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia

The Bioregional Assessment Programme

The Bioregional Assessment Programme is a transparent and accessible programme of baseline assessments that increase the available science for decision making associated with coal seam gas and large coal mines. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential impacts of coal seam gas and large coal mining development on water resources. This Programme draws on the best available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at a regional scale.

The Programme is funded by the Australian Government Department of the Environment and Energy. The Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia are collaborating to undertake bioregional assessments. For more information, visit http://www.bioregionalassessments.gov.au.

Department of the Environment and Energy

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Cover photograph

Condamine river weir on Darling Downs in Queensland, 2005

Credit: Arthur Mostead © Commonwealth of Australia (Murray–Darling Basin Authority)

Australian Government
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Bureau of Meteorology
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Executive summary

Coal and coal seam gas (CSG) development can potentially affect water-dependent assets (either negatively or positively) through a direct impact on groundwater hydrology. This product presents the modelled hydrological changes in response to likely coal resource development in the Maranoa-Balonne-Condamine subregion after December 2012. First, the methods are summarised and existing models are reviewed, followed by details regarding the development and calibration of the model. The product concludes with probabilistic predictions of hydrological change, including uncertainty analysis and a discussion of model limitations, opportunities and conclusions.

Groundwater modelling for the Maranoa-Balonne-Condamine subregion follows the companion submethodology M07 (as listed in Table 1) for groundwater modelling. Specifically, the groundwater model produces spatially explicit model outputs that are used as inputs to other bioregional assessment (BA) models, including surface water models, uncertainty analysis and receptor impact modelling.

The Queensland Office of Groundwater Impact Assessment (OGIA) regional groundwater model is used to estimate hydrological changes arising from coal resource development for two possible futures – the baseline and the coal resource development pathway (CRDP). The OGIA model was developed with the single purpose 'to provide a suitable tool for assessing the impacts of CSG development on water levels in the aquifers present within the Surat cumulative management area'. It is 'therefore on its own not necessarily suitable for predicting responses to arbitrary changes in hydrological conditions, developing sustainable water resource management policies, assessing impacts on groundwater-dependent ecosystems or quantifying surface water – groundwater interactions'. However, it has the best available representation of CSG development in the Surat cumulative management area and is considered fit for purpose for groundwater modelling in BAs, with the exception of criteria related to the representation of water fluxes in surficial aquifers.

The entire Maranoa-Balonne-Condamine subregion falls within the boundary of the geological Surat Basin, which forms part of the wider Great Artesian Basin (GAB). The regional aquifers are important groundwater supplies for agriculture, industries and towns in the subregion. Coal mining and CSG development in the subregion targets the Walloon Coal Measures of the Surat Basin. Groundwater recharge occurs via infiltration and leakage from streams or overlying aquifers in the aquifer outcrop areas in the north, north-west, north-east and east along the Great Dividing Range. Groundwater flow is predominantly from the recharge areas to the south, south-west and west. Natural discharge from the geological Surat Basin occurs via vertical leakage through aquitards, springs, rivers and subsurface flow into adjoining areas.

Groundwater modelling results from the OGIA model estimates hydrological changes arising from coal resource development by comparing the difference in predicted water levels between two possible futures, which provides an estimate of water level impacts that are attributable to the additional coal resource development (ACRD). Five baseline open-cut coal mines, Cameby Downs, Commodore, Kogan Creek, New Acland Coal Mine Stage 2 and Wilkie Creek, are modelled in the Maranoa-Balonne-Condamine subregion. Two proposed open-cut coal mines, New Acland Coal Mine Stage 3 and The Range, are considered sufficiently advanced that under current knowledge and conditions they will most likely proceed. Five baseline CSG projects are modelled in the Maranoa-Balonne-Condamine subregion. This includes three large-scale gas field developments supporting the three liquefied natural gas (LNG) projects on Curtis Island near Gladstone, Australia Pacific LNG Project, the Queensland Curtis LNG Project, and the Santos Gladstone LNG and GLNG Gas Field Development projects. The staged expansion of production for the Surat Gas Project, and the smaller scale Ironbark Project, are considered to be part of the baseline for this Assessment to ensure consistency with OGIA reporting.

Model predictions of baseline groundwater drawdown associated with coal resource development are presented as maps of the 95th percentile of baseline groundwater drawdown. Maximum baseline groundwater drawdown associated with CSG production (in excess of 700 m drawdown in the productive Walloon Coal Measures model layer) is predicted near the towns of Chinchilla and Roma. Hydrological changes in excess of 0.2 m baseline groundwater drawdown in the vicinity of the five coal mines are generally within 5 to 10 km (maximum 15 to 20 km in the Walloon Coal Measures model layer) of the modelled pits. Baseline groundwater drawdown associated with CSG production in the vicinity of the five coal mines is generally less than 10 m (maximum 20–40 m in the Walloon Coal Measures model layer).

Model predictions of additional groundwater drawdown under the CRDP future are presented as maps of the probability of exceeding additional groundwater drawdown thresholds for each model layer and histograms of maximum additional drawdown (*dmax*) and time to maximum drawdown (*tmax*) at the economic bores within the two water balance areas. Hydrological changes in excess of 0.2 m additional groundwater drawdown in the vicinity of the proposed coal mines is generally within 20 to 40 km (maximum 50 to 60 km in the Walloon Coal Measures and Hutton / Marburg Sandstone model layers) of the proposed pits. Additional groundwater drawdown in excess of 5 m ($p=0.05$) is generally less than 10 km (maximum 15 km in the Walloon Coal Measures model layer) of the proposed pits. There is a greater than 5 percent probability of exceeding 5 m additional groundwater drawdown for 86 of the approximately 19,000 bores in the Maranoa-Balonne-Condamine subregion.

The water balance assessment presents a quantitative water balance for the Maranoa-Balonne-Condamine subregion for both the baseline and CRDP futures in order to quantify the effects of depressurisation of the coal seams for CSG production and mine pit dewatering. The water balance is compared with estimates of fluxes described in the regional-scale conceptual model and localised groundwater models to provide confidence in model predictions. Modelled CSG water production in The Range water balance area falls from 17% to 0% of modelled losses following modelled cessation of CSG production in 2065. Coal mine dewatering accounts for 2% of modelled losses in the first 30-year period and zero after modelled mine closure in 2041. In the New Acland Coal Mine water balance area, CSG water production falls from 3% to 0% of modelled losses over successive 30-year periods following modelled cessation of CSG production in 2065. Modelled coal mine dewatering during mine operation (2012 to 2029, 0.85 GL/year) is consistent with values reported in the New Acland Coal Mine Stage 3 environmental impact assessment documents (maximum of 1.4 GL/year).

The OGIA model uses calibration-constrained uncertainty analysis, which is also known as Null-space Monte Carlo Analysis. This approach provides an efficient method to explore the non-uniqueness of model parameters and resulting model prediction uncertainty. The formal uncertainty analysis considered hydraulic conductivity, recharge and storage values, but did not consider model conceptualisation or the parameters used to specify drain and river boundary conditions. The 200 calibration-constrained parameter sets are defined spatially using pilot points in each model layer, which gives spatial coherence to the model parameter values that is consistent with the model conceptualisation and uses regularisation to solve the problem mathematically.

The representations of surface water – groundwater interactions, mine pit dewatering, CSG activities and horizontal and vertical discretisation in the regional model are identified as having the greatest potential effect on model predictions in the qualitative uncertainty analysis. The revised OGIA model developed for the Surat Underground Water Impact Report (UWIR) and released for public comment in early 2016 has addressed many of the model data and resource availability and technical issues. The consistency between OGIA 2012 and revised OGIA 2016 model predictions of hydrological change lends confidence to the BA model predictions. The main opportunities to reduce predictive uncertainty in the regional model are related to the representation of hydrological changes in surficial aquifers that affect surface water – groundwater interactions and groundwater-dependent ecosystems.

The results of this groundwater numerical modelling will be used to inform the impact and risk analysis (product 3-4). Probabilistic estimates of hydrological changes arising from coal resource development will be used to assess direct impacts on groundwater-dependent assets, such as groundwater-dependent ecosystems and economic bores. The focus of the regional model on the deep regional aquifers targeted by CSG development, means that the conceptual model of causal pathways that describes the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water and water-dependent assets will inform the assessment of indirect impacts in the impact and risk analysis (product 3-4).

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- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment and Energy), this group comprises officials from the NSW, Queensland, South Australian and Victorian governments
- Independent reviewers: Warwick McDonald (CSIRO), Dirk Mallants (CSIRO).

This document largely describes a model developed and run by Office of Groundwater Impact Assessment (OGIA). The additional CRDP coal mines have also been added using information provided by OGIA.

Introduction

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) was established to provide advice to the federal Minister for the Environment on potential water-related impacts of coal seam gas (CSG) and large coal mining developments (IESC, 2015).

Bioregional assessments (BAs) are one of the key mechanisms to assist the IESC in developing this advice so that it is based on best available science and independent expert knowledge. Importantly, technical products from BAs are also expected to be made available to the public, providing the opportunity for all other interested parties, including government regulators, industry, community and the general public, to draw from a single set of accessible information. A BA is a scientific analysis, providing a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential impacts of CSG and coal mining development on water resources.

The IESC has been involved in the development of *Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (the BA methodology; Barrett et al., 2013) and has endorsed it. The BA methodology specifies how BAs should be undertaken. Broadly, a BA comprises five components of activity, as illustrated in Figure 1. Each BA will be different, due in part to regional differences, but also in response to the availability of data, information and fit-for-purpose models. Where differences occur, these are recorded, judgments exercised on what can be achieved, and an explicit record is made of the confidence in the scientific advice produced from the BA.

The Bioregional Assessment Programme

The Bioregional Assessment Programme is a collaboration between the Department of the Environment and Energy, the Bureau of Meteorology, CSIRO and Geoscience Australia. Other technical expertise, such as from state governments or universities, is also drawn on as required. For example, natural resource management groups and catchment management authorities identify assets that the community values by providing the list of water-dependent assets, a key input.

The Technical Programme, part of the Bioregional Assessment Programme, will undertake BAs for the following bioregions and subregions (see http://www.bioregionalassessments.gov.au/assessments for a map and further information):

- the Galilee, Cooper, Pedirka and Arckaringa subregions, within the Lake Eyre Basin bioregion
- the Maranoa-Balonne-Condamine, Gwydir, Namoi and Central West subregions, within the Northern Inland Catchments bioregion
- the Clarence-Moreton bioregion
- the Hunter and Gloucester subregions, within the Northern Sydney Basin bioregion

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

Technical products (described in a later section) will progressively be delivered throughout the Programme.

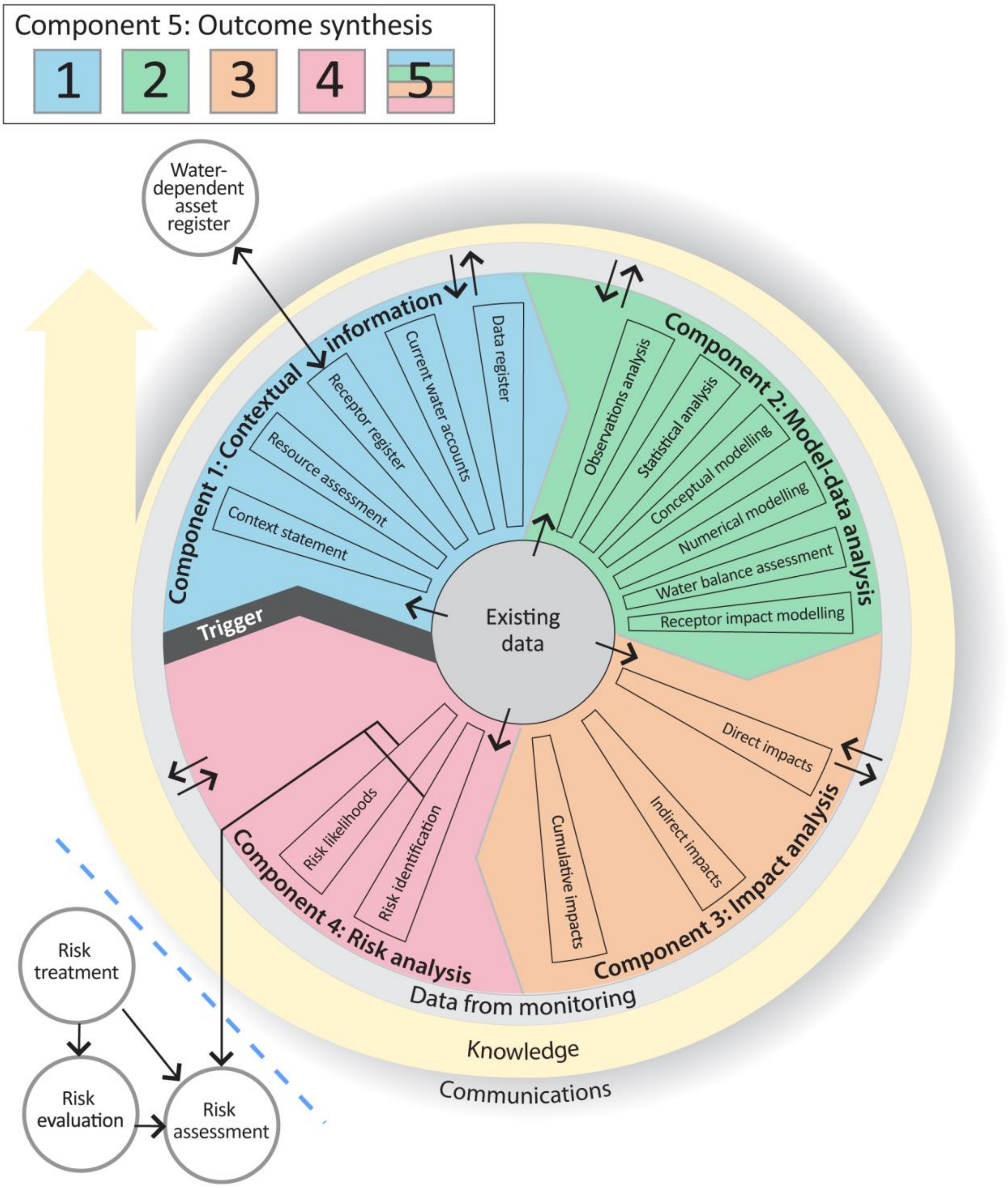

Figure 1 Schematic diagram of the bioregional assessment methodology

The methodology comprises five components, each delivering information into the bioregional assessment and building on prior components, thereby contributing to the accumulation of scientific knowledge. The small grey circles indicate activities external to the bioregional assessment. Risk identification and risk likelihoods are conducted within a bioregional assessment (as part of Component 4) and may contribute activities undertaken externally, such as risk evaluation, risk assessment and risk treatment. Source: Figure 1 in Barrett et al. (2013), © Commonwealth of Australia

Methodologies

The overall scientific and intellectual basis of the BAs is provided in the BA methodology (Barrett et al., 2013). Additional guidance is required, however, about how to apply the BA methodology to a range of subregions and bioregions. To this end, the teams undertaking the BAs have developed and documented detailed scientific submethodologies (Table 1) to, in the first instance, support the consistency of their work across the BAs and, secondly, to open the approach to scrutiny, criticism and improvement through review and publication. In some instances, methodologies applied in a particular BA may differ from what is documented in the submethodologies – in this case an explanation will be supplied in the technical products of that BA. Ultimately the Programme anticipates publishing a consolidated 'operational BA methodology' with fully worked examples based on the experience and lessons learned through applying the methods to 13 bioregions and subregions.

The relationship of the submethodologies to BA components and technical products is illustrated in Figure 2. While much scientific attention is given to assembling and transforming information, particularly through the development of the numerical, conceptual and receptor impact models, integration of the overall assessment is critical to achieving the aim of the BAs. To this end, each submethodology explains how it is related to other submethodologies and what inputs and outputs are required. They also define the technical products and provide guidance on the content to be included. When this full suite of submethodologies is implemented, a BA will result in a substantial body of collated and integrated information for a subregion or bioregion, including new information about the potential impacts of coal resource development on water and water-dependent assets.

Table 1 Methodologies

Each submethodology is available online at http://data.bioregionalassessments.gov.au/submethodology/XXX, where 'XXX' is replaced by the code in the first column. For example, the BA methodology is available at http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology and submethodology M02 is available at http://data.bioregionalassessments.gov.au/submethodology/M02. Submethodologies might be added in the future.

Code	Proposed title	Summary of content
bioregional-assessment-methodology	*Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources*	A high-level description of the scientific and intellectual basis for a consistent approach to all bioregional assessments
M02	*Compiling water-dependent assets*	Describes the approach for determining water-dependent assets
M03	*Assigning receptors to water-dependent assets*	Describes the approach for determining receptors associated with water-dependent assets
M04	*Developing a coal resource development pathway*	Specifies the information that needs to be collected and reported about known coal and coal seam gas resources as well as current and potential resource developments
M05	*Developing the conceptual model of causal pathways*	Describes the development of the conceptual model of causal pathways, which summarises how the 'system' operates and articulates the potential links between coal resource development and changes to surface water or groundwater
M06	*Surface water modelling*	Describes the approach taken for surface water modelling
M07	*Groundwater modelling*	Describes the approach taken for groundwater modelling
M08	*Receptor impact modelling*	Describes how to develop receptor impact models for assessing potential impact to assets due to hydrological changes that might arise from coal resource development
M09	*Propagating uncertainty through models*	Describes the approach to sensitivity analysis and quantification of uncertainty in the modelled hydrological changes that might occur in response to coal resource development
M10	*Impacts and risks*	Describes the logical basis for analysing impact and risk
M11	*Systematic analysis of water-related hazards associated with coal resource development*	Describes the process to identify potential water-related hazards from coal resource development

Technical products

The outputs of the BAs include a suite of technical products presenting information about the ecology, hydrology, hydrogeology and geology of a bioregion and the potential impacts of CSG and coal mining developments on water resources, both above and below ground. Importantly, these technical products are available to the public, providing the opportunity for all interested parties, including community, industry and government regulators, to draw from a single set of accessible information when considering CSG and large coal mining developments in a particular area.

The information included in the technical products is specified in the BA methodology. Figure 2 shows the relationship of the technical products to BA components and submethodologies. Table 2 lists the content provided in the technical products, with cross-references to the part of the BA methodology that specifies it. The red outlines in both Figure 2 and Table 2 indicate the information included in this technical product.

Technical products are delivered as reports (PDFs). Additional material is also provided, as specified by the BA methodology:

- unencumbered data syntheses and databases
- unencumbered tools, model code, procedures, routines and algorithms
- unencumbered forcing, boundary condition, parameter and initial condition datasets
- lineage of datasets (the origin of datasets and how they are changed as the BA progresses)
- gaps in data and modelling capability.

In this context, unencumbered material is material that can be published according to conditions in the licences or any applicable legislation. All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.

Technical products, and the additional material, are available online at http://www.bioregionalassessments.gov.au.

The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.

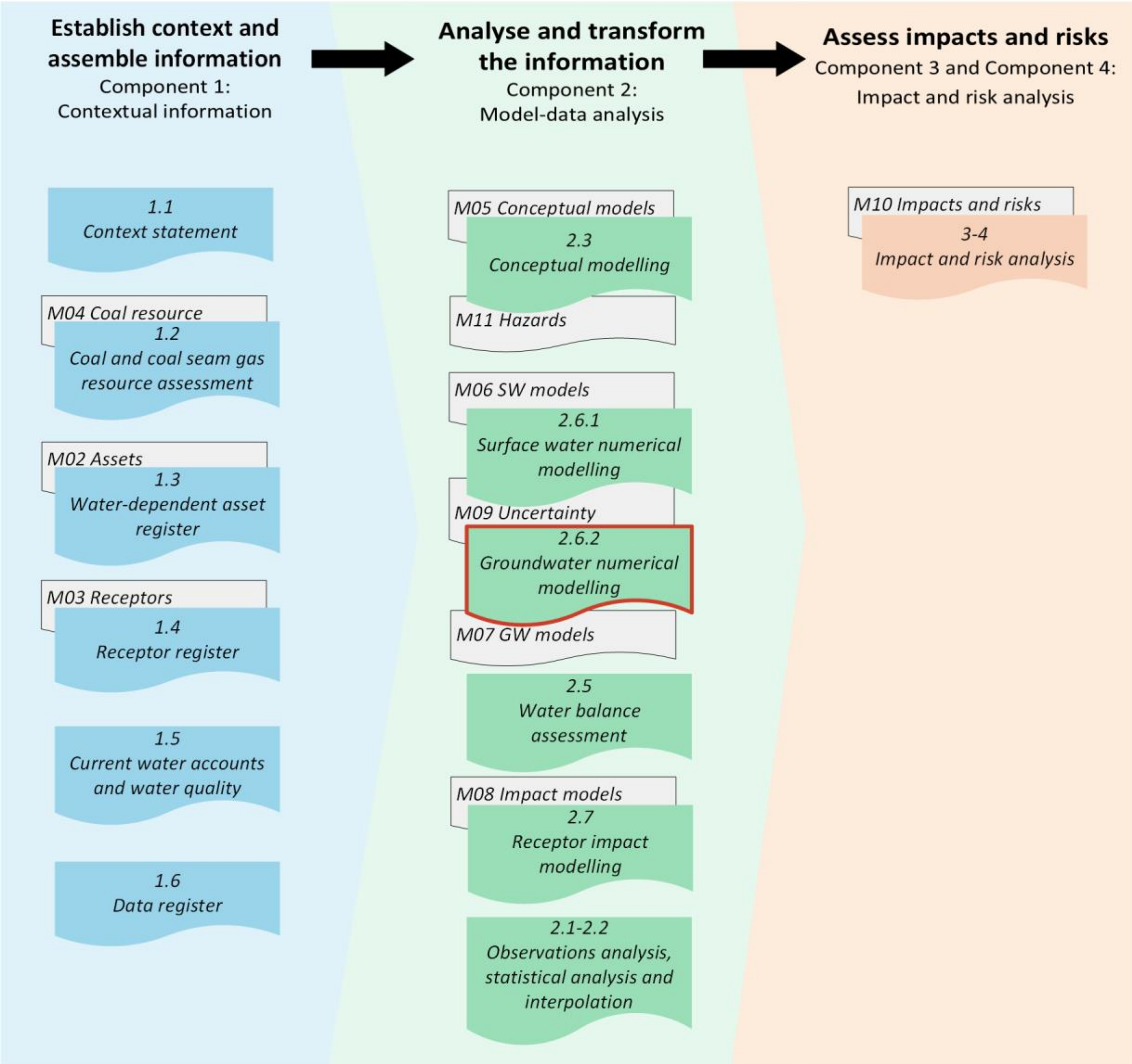

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

In each component (Figure 1) of a bioregional assessment, a number of technical products (coloured boxes, see also Table 2) are potentially created, depending on the availability of data and models. The light grey boxes indicate submethodologies (Table 1) that specify the approach used for each technical product. The red outline indicates this technical product. The BA methodology (Barrett et al., 2013) specifies the overall approach.

Table 2 Technical products delivered for the Maranoa-Balonne-Condamine subregion

For each subregion in the Northern Inland Catchments Bioregional Assessment, technical products are delivered online at http://www.bioregionalassessments.gov.au, as indicated in the 'Type' column[a]. Other products – such as datasets, metadata, data visualisation and factsheets – are provided online. There is no product 1.4. Originally this product was going to describe the receptor register and application of landscape classes as per Section 3.5 of the BA methodology, but this information is now included in product 2.3 (conceptual modelling) and used in products 2.6.1 (surface water modelling) and 2.6.2 (groundwater modelling). There is no product 2.4; originally this product was going to include two- and three-dimensional representations as per Section 4.2 of the BA methodology, but these are instead included in products such as product 2.3 (conceptual modelling) and product 2.6.2 (groundwater numerical modelling).

Component	Product code	Title	Section in the BA methodology[b]	Type[a]
Component 1: Contextual information for the Maranoa-Balonne-Condamine subregion	1.1	Context statement	2.5.1.1, 3.2	PDF, HTML
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3	PDF, HTML
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4	PDF, HTML, register
	1.5	Current water accounts and water quality	2.5.1.5	PDF, HTML
	1.6	Data register	2.5.1.6	Register
Component 2: Model-data analysis for the Maranoa-Balonne-Condamine subregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2	Not produced
	2.3	Conceptual modelling	2.5.2.3, 4.3	PDF, HTML
	2.5	Water balance assessment	2.5.2.4	Not produced
	2.6.1	Surface water numerical modelling	4.4	Not produced
	2.6.2	Groundwater numerical modelling	4.4	PDF, HTML
	2.7	Receptor impact modelling	2.5.2.6, 4.5	Not produced
Component 3 and Component 4: Impact and risk analysis for the Maranoa-Balonne-Condamine subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Maranoa-Balonne-Condamine subregion	5	Outcome synthesis	2.5.5	PDF, HTML

[a]The types of products are as follows:
- 'PDF' indicates a PDF document that is developed by the Northern Inland Catchments Bioregional Assessment using the structure, standards and format specified by the Programme.
- 'HTML' indicates the same content as in the PDF document, but delivered as webpages.
- 'Register' indicates controlled lists that are delivered using a variety of formats as appropriate.
- 'Not produced' indicates that the product was not developed. A webpage explains why and points to relevant submethodologies (Table 1).

[b]*Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (Barrett et al., 2013)

About this technical product

The following notes are relevant only for this technical product.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Northern Inland Catchments bioregion and two standard parallels of –18.0° and –36.0°.
- Contact bioregionalassessments@bom.gov.au to access metadata (including copyright, attribution and licensing information) for all datasets cited or used to make figures in this product. At a later date, this information, as well as all unencumbered datasets, will be published online.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived datasets, the created date is used.

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Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 29 September 2016, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 29 September 2016, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

2.6.2 Groundwater numerical modelling

Coal and coal seam gas (CSG) development can potentially affect water-dependent assets (either negatively or positively) through impacts on groundwater hydrology. This product presents the modelling of groundwater hydrology within the Maranoa-Balonne-Condamine subregion.

First, the methods are summarised and existing models reviewed, followed by details regarding the development and parameterisation of the model. The product concludes with probabilistic predictions of hydrological change, including uncertainty analysis and a discussion of model limitations, opportunities and conclusions.

Results are reported for the two potential futures considered in a bioregional assessment:

- *baseline coal resource development (baseline)*: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012
- *coal resource development pathway (CRDP)*: a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a bioregional assessment. This change is due to the additional coal resource development – all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012.

This product reports results for only those developments in the baseline and CRDP that can be modelled. Results generated at model nodes are interpolated to estimate potential hydrological changes for groundwater. Product 3-4 (impact and risk analysis) then reports impacts on landscape classes and water-dependent assets arising from these hydrological changes.

2.6.2.1 Methods

Summary

Coal resource development in the Maranoa-Balonne-Condamine subregion has the potential to directly affect groundwater conditions and indirectly affect deep soil drainage, surface water – groundwater interactions, streams and surface water catchments. Potential hydrological effects of coal resource development on the surface water system are changes to surface water quality, direction, flow and volume. Hydrological changes to the groundwater system can also affect groundwater quality, aquifer properties, groundwater composition, flow (reduction), level and pressure.

The Queensland Office of Groundwater Impact Assessment (OGIA) regional groundwater model is considered a fit-for-purpose regional-scale groundwater model for the Bioregional Assessment (BA) Programme. The OGIA model is re-run annually based on the latest available industry development plans and has been revised for the BA to also simulate water-related impacts of coal mine developments in the Maranoa-Balonne-Condamine subregion. Integration of the groundwater model with a surface water numerical model and receptor impact modelling is not possible at this time in the Maranoa-Balonne-Condamine subregion for two reasons. Firstly, there is limited availability of long-term, consistent water quality and water quantity data measurements. Secondly, the OGIA model is focused on the deep regional aquifers targeted by coal seam gas (CSG) development, which means that it may not on its own be suitable for assessing hydrological changes in surficial aquifers. For these reasons, the Assessment team have not developed a coupled surface water and groundwater model, but have leveraged existing state-based resources and knowledge for this Assessment.

2.6.2.1.1 Background and context

The numerical groundwater modelling has a very specific objective: to probabilistically evaluate potential hydrological change in the coal resource development pathway (CRDP) relative to the baseline at specified locations in the landscape to inform the impact and risk analysis reported in product 3-4 (impact and risk analysis).

In confined groundwater systems, and to an extent in unconfined systems, the response in groundwater level or flux is linear with respect to the change in stress – that is, a doubling of the pumping rate will result in a doubling of drawdown (Reilly et al., 1987; Rassam et al., 2004). If a system behaves linearly, it means that changes are additive, which is known as the principle of superposition (Reilly et al., 1987). The biggest implication of this is that the change to the system due to a change in stress is largely independent of current or initial conditions. The most well-known example is the interpretation of a pumping test; the drawdown is only a function of the hydraulic properties of the aquifer, not of the initial conditions.

While the validity of the principle of superposition will be evaluated, it does enable the modelling to focus on the change in hydrogeological stress and the hydraulic properties, rather than on reproducing historical conditions or predicting future-state variables of the system, such as groundwater levels or fluxes.

The probabilistic aspect of the analysis implies that modelling does not provide a single best estimate of the change, but rather an ensemble of estimates. This ensemble enables statements such as:

- 'In 95% of the simulations, the change at location x,y does not exceed z.'
- 'The probability of exceeding a drawdown of 5 m at location x,y is p%.'

To generate these ensembles of predictions, a large number of model parameter sets will be evaluated for the numerical modelling. The range of parameters reflects both the natural variability of the system and the uncertainty in the understanding of the system as of July 2015. During the uncertainty analysis, these parameter combinations are filtered in such a way that only those that are consistent with the available observations and the understanding of the system are used to generate the ensemble of predictions. The details are documented in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016).

It is not possible to capture all uncertainty of the understanding of the system in the parameterisation of the numerical models, so it is inevitable that there will be a number of assumptions and model choices necessary to create the models. These assumptions are introduced and briefly discussed in Section 2.6.2.3 about model development. The qualitative uncertainty analysis in Section 2.6.2.8.1 further provides a systematic and comprehensive discussion of these assumptions. This discussion focuses on the rationale behind the assumptions and the effect on the predictions.

The latter is crucial in justifying assumptions. In the numerical modelling the precautionary principle is adopted: impacts are overestimated rather than underestimated. As long as it can be shown that an assumption overestimates – not underestimates – impacts, the assumption is considered valid for the specific purpose of this modelling.

However, an overly conservative estimate of impact is not desirable either. If there are sound reasons to believe that predicted impacts are deemed unrealistically high (e.g. in comparison to earlier modelling efforts in the bioregion) or in excess of legally defined thresholds (such as the specified drawdown thresholds in the NSW aquifer interference policy), the assumptions may need to be revisited.

Another advantage of this stochastic modelling approach is that it enables a comprehensive sensitivity analysis to identify the model parameters or aspects of the system that are most influential on the predictions – and others that have little or no effect on the predictions. This information can guide future data collection and model development or inform the regulatory process.

This product starts with an overview of the methods as applied to the Maranoa-Balonne-Condamine subregion (Section 2.6.2.1.2), focusing on the numerical modelling requirements for BA and the groundwater modelling approach used for this Assessment, followed by a review of the existing groundwater models (Section 2.6.2.2). Section 2.6.2.3 to Section 2.6.2.7 describe the development of the model, its parameterisation, the available observations, required predictions and sensitivity of the model parameters to observations and predictions. Next is the uncertainty analysis (Section 2.6.2.8), which contains the justification of assumptions and the resulting ensembles of predicted impacts. The product concludes by describing the limitations and conclusions (Section 2.6.2.9).

2.6.2.1.2 Groundwater numerical modelling

The conceptual model for the Maranoa-Balonne-Condamine subregion (in companion product 2.3 (Holland et al., 2016)) indicates that coal resource development has the potential to directly affect the regional groundwater and surface water systems. Hydrological changes to the groundwater system can propagate through the alluvium and other aquifers to indirectly affect groundwater-dependent ecosystems and surface water – groundwater interactions in the aquifer outcrop and subcrop areas. Hydrological changes to the surface water system can affect deep soil drainage and surface water – groundwater interactions in aquifer outcrop areas.

Coal resource development in the Maranoa-Balonne-Condamine subregion may have a wide range of water-related impacts. For example, coal mining may affect surface water drainage, potentially affecting surface water quality, direction, flow and volume. Mining can also affect deep soil drainage in aquifer outcrop areas, which can change groundwater quality, aquifer properties, groundwater composition and pressure. Surface water – groundwater interactions in aquifer outcrops can be affected by coal mining and CSG development, potentially affecting groundwater quality, flow (reduction) and level. Coal resource development can also change groundwater conditions (including groundwater quality, aquifer properties, flow (reduction), level and pressure) in affected aquifers. CSG development primarily affects groundwater pressure in the coal seams, potentially leading to subsurface depressurisation of other aquifers and aquitards where direct hydraulic connections exist. Direct hydraulic connections may occur preferentially via geological structures such as faults, or more diffusely where direct stratigraphic contact exists between layers.

As outlined in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016), different model types and model codes are chosen in a bioregional assessment (BA) depending on the specific requirements of each subregion or bioregion. Specifically, the groundwater model needs to deliver spatially explicit model outputs that are used as inputs to other BA models, that can include surface water modelling, uncertainty analysis and receptor impact modelling, and to directly evaluate impact on water resources. Table 3 lists the criteria used to assess whether a groundwater model is considered to be fit for purpose for BA. Beneath the table, the general BA groundwater modelling requirements and the rationale for whether the approach used in the Maranoa-Balonne-Condamine subregion meets the criteria are discussed.

Table 3 Assessment of groundwater numerical modelling approach in the Maranoa-Balonne-Condamine subregion

Fit-for-purpose assessment criteria	Components	Criteria met
1. Prediction of hydrological response variables	Probabilistic estimates of hydrological change at receptors	Yes
	Integration with receptor impact modelling	No
	Integration with surface water numerical models	No
2. Design and construction	Modelling objectives stated	Yes
	Model confidence level	Yes
	Modelling approach	Yes
3. Integration with sensitivity and uncertainty analysis workflow	Formally address uncertainty	Yes
	Parameterisation	Yes
	Convergence	Yes
4. Water balance components	Conceptual model agreement	Yes
5. Transparent and reproducible model outputs	Model data repository	Yes
	Model code and executables	Yes
	Pre- and post-processing scripts	Yes

Prediction of hydrological response variables

The objective of groundwater modelling undertaken as part of a BA is to probabilistically assess hydrological changes arising from coal resource development at water-dependent assets and receptors (see companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016)). Groundwater modelling predicts hydrological response variables, the hydrological characteristics of the system or landscape class that potentially change due to coal resource development. These outputs from the groundwater modelling can be either fluxes or stores. They need to be decided before the sensitivity analysis begins and also need to be defined precisely – for example, drawdown at receptor location (x, y, z) at time t. The hydrological response variables for groundwater are maximum drawdown (*dmax*) and time to maximum drawdown (*tmax*).

In order to quantify uncertainties associated with model prediction, groundwater models in BA need to be run probabilistically and not deterministically. Consequently, this means that model predictions are not unique values but probability distributions. Mismatches in scale between the regional nature of the modelling and the point-scale nature of the receptors means that the modelling is not able to capture fine-scale complexities of impacts upon receptors. Receptors that are directly relevant to groundwater modelling in the Maranoa-Balonne-Condamine subregion are point locations associated with groundwater bores (economic bores). The source aquifer (or model layer) of each bore is based on information supplied by the Queensland Office of Groundwater Impact Assessment (OGIA) and used in the assessment of cumulative impacts of coal seam gas (CSG) development in the Surat cumulative management area (CMA). In BA, the focus is on the difference between two possible futures – the baseline and the coal resource development pathway (CRDP). Numerical groundwater modelling results are primarily presented as the difference in groundwater drawdown between the baseline and CRDP futures. This approach reduces uncertainty as there is 'less uncertainty when a prediction can be formulated as a subtraction of two model results' (Barnett et al., 2012).

Integration of the groundwater model with a surface water numerical model and receptor impact modelling is not possible at this time in the Maranoa-Balonne-Condamine subregion for two reasons. Firstly, long-term, consistent water quality and water quantity data measurements of surface water and groundwater systems are not available in the Maranoa-Balonne-Condamine subregion (see companion product 1.5 for the Maranoa-Balonne-Condamine subregion (Cassel et al., 2015)). Secondly, the OGIA model (QWC, 2012) is 'a regional groundwater flow model for making predictions of groundwater impacts from the petroleum and gas activities and for developing the Spring Impact Management Strategy' (QWC, 2012). As such, its focus is the deep regional aquifers targeted by CSG development, which means that the OGIA model may not on its own be suitable for assessing hydrological changes in surficial aquifers that are important in representing impacts to surface water – groundwater interactions and groundwater-dependent ecosystems. The combination of limited water quality and quantity data availability and use of a model that is focused on the deeper regional aquifer limits the value of developing a coupled surface water – groundwater numerical model in the Maranoa-Balonne-Condamine subregion at this time.

The implications of not developing a coupled surface water – groundwater numerical model are that several companion products are not required or cannot be produced for the BA in the Maranoa-Balonne-Condamine subregion. Companion product 2.1-2.2 (observations analysis, statistical analysis and interpolation) for the Maranoa-Balonne-Condamine subregion is not required because: (i) the Assessment team did not develop a surface water numerical model; and (ii) the development of the OGIA model is well documented (GHD, 2012; QWC, 2012). Companion product 2.5 (water balance assessment) for the Maranoa-Balonne-Condamine subregion, is not produced; instead, the water balance is documented in Section 2.6.2.7. Companion product 2.7 (receptor impact modelling) for the Maranoa-Balonne-Condamine subregion is not produced because the Assessment team cannot use surface water numerical modelling to define the zone of potential hydrological impact or quantify hydrological response variables related to the surface water systems that are necessary for this product. The analysis of surface water – groundwater interactions using a combination of outputs from the numerical groundwater model and the conceptual model of causal pathways that describes the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water and water-dependent assets will inform the assessment of indirect impacts in companion product 3-4 (risk and impact analysis).

Design and construction

The *Australian groundwater modelling guidelines* (Barnett et al., 2012) advise that it is essential to clearly state the design objectives of the groundwater model and the model confidence level. Modelling objectives are stated above. The model confidence level is an *a priori* categorisation of a groundwater model to reflect its predictive capability as a function of the model complexity, prediction timeframe and data availability. As described in companion submethodology M07 for groundwater modelling (Crosbie et al., 2016), all groundwater models used in BAs, including the OGIA model, are 'Class 1' models as defined by the *Australian groundwater modelling guidelines*

(Barnett et al., 2012). This is the lowest level of certainty within the classification and is a reflection of the data available and predictions required, rather than the quality of the models. Key indicators of Class 1 models include that model predictive time frames are more than ten times longer than the length of the transient model calibration period, and that the magnitude of stresses featured in prediction scenarios is more than five times larger than simulated in the calibration period (Barnett et al., 2012).

The major assumptions and model choices related to model development are described in Section 2.6.2.3. The effect of the assumptions and model choices on predictions are discussed in the qualitative uncertainty analysis in Section 2.6.2.8*.* The level of detail within the conceptual model meets the objectives of Guiding Principle 3.1 and Guiding Principle 3.3, being based on interpretation of available data (Barnett et al., 2012). The groundwater model domain encompasses current and future key stresses related to coal resource development, which meets the modelling guiding principles (Barnett et al., 2012). Model vertical and horizontal discretisation and use of more detailed sub-models (e.g. Condamine Alluvium and transient) represent a compromise between technical and resource requirements for a regional-scale groundwater model, thus meeting the modelling guiding principles (Barnett et al., 2012). The OGIA model uses steady-state calibration to define initial conditions for transient simulations, which meets the modelling guiding principles (Barnett et al., 2012).

The objectives of numerical modelling in BA are not to simulate the state of groundwater under the baseline and coal resource development futures, but to quantify the difference between the two futures. This approach allows a number of simplifying assumptions to be made based on the principle of superposition (Reilly et al., 1987). The principle of superposition means that for linear systems, the solution to a problem involving multiple inputs (or stresses) is equal to the sum of the solutions to a set of simpler individual problems that form the composite problem. To assess the effect of change in a stress, such as depressurisation and dewatering for coal resource development, it is sufficient to only estimate the change in stress. It is not necessary to estimate the initial conditions in the aquifer or other fluxes and stresses, provided these do not change (Barlow and Leake, 2012). The principle of superposition is used for many pump test analyses, where aquifer parameters are inferred from the change in stress (pumping rate) and change in groundwater level (drawdown) (Kruseman and de Ridder, 1994).

The principle of superposition is only valid for linear systems, i.e. systems where the response to a change in stress is proportional to the change in the stress. In other words, where a doubling of stress will result in a doubling of the response. In groundwater flow dynamics this condition is satisfied for confined aquifers. Unconfined aquifers are not strictly linear, as aquifer transmissivity depends on the saturated thickness. Reilly et al. (1987) and Rassam et al. (2004) do show however that the concepts are still valid for mild violations of the linearity conditions.

Surface water and groundwater numerical modelling in BA are run under historical conditions for the 30-year period from 1 January 1983 to 31 December 2012. It is assumed that after 90 years of simulation the coal seam gas (CSG) and large coal mining development that is simulated has ceased operation (Crosbie, et al., 2016). The further into the future that the impacts of large coal mines and coal seam gas developments are simulated, the more uncertainty there is in the estimation of future conditions. These future conditions include the future climate, land use and water sharing rules. In BA, the historical climate time series is repeated three times to create a 90-year time series and modified to be consistent with a median future climate projection as described in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). This 30-year period is repeated to ensure that the effect of droughts and floods does not confound the comparison between time periods. While the same time periods are reported in the Maranoa-Balonne-Condamine subregion, the OGIA model uses long-term mean recharge rates instead of time-varying climate input data. The focus on the difference between two possible futures in BA means that there is no need to assess the effect of climate change assumptions on predictions (e.g. Guiding Principle 6.2 in Barnett et al. (2012)).

Integration with sensitivity and uncertainty analysis workflow

Figure 3 outlines the methodology for propagation of uncertainty within the BA as described in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016). Firstly, the conceptual model is compartmentalised (i.e. subdivided into a number of sub-models without feedback loops) and points of interactions between sub-models are identified. A point of interaction is where the output of one model is input to the linked model. Secondly, a sensitivity analysis is carried out to identify the model factors (parameters and assumptions) that have the largest impact on the hydrological response variables of interest. When carried out for each sub-model, probability distribution functions can be described for each hydrological response variable.

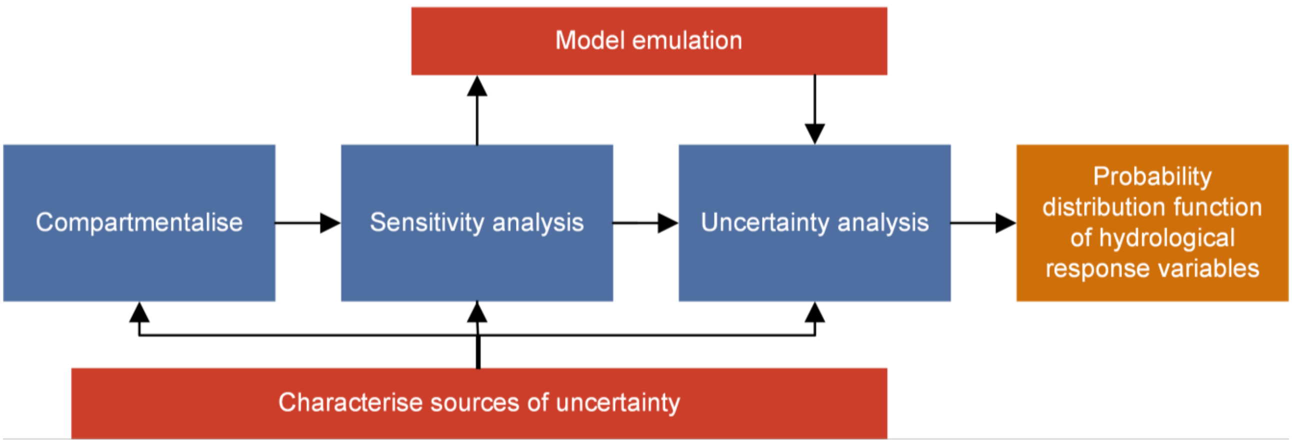

Figure 3 Uncertainty methodology flowchart

Next, quantitative uncertainty analysis numerically evaluates the degree to which each of the model inputs (parameters) affects the model predictions by running the model thousands of times and varying the values of the input parameters through a precisely defined and randomised range of values. However, many model choices and assumptions cannot be evaluated in the quantitative analysis. Instead, the qualitative uncertainty analysis describes the rationale for and scores the effect of each assumption on model predictions. Each assumption is scored on four attributes related to: (i) data availability, (ii) resource availability, (iii) technical and computational limitations and (iv) effect on model predictions. The sensitivity and uncertainty workflow is consistent with the groundwater modelling guiding principles (Barnett et al., 2012).

There is an explicit acknowledgement that not all of the information required to build an ideal groundwater flow model will be available. Therefore, assumptions will need to be made with regards to model conceptualisation and parameterisation. Model assumptions are deemed valid in the context of BA modelling if there is no or minimal effect on predictions, or that it will overestimate hydrological changes. The uncertainties associated with these assumptions are quantified and then propagated from conceptual modelling to receptor impact modelling wherever possible in BAs. The OGIA model uncertainty analysis, while not identical to that used in other BAs, is able to give probabilistic estimates of the hydrological changes associated with coal resource development and thus meets the BA uncertainty analysis requirements (see companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016)).

The sensitivity and uncertainty analyses undertaken for BAs require that groundwater models are robust, that is, capable of converging for a broad range of parameter values. Parameter values are changed in an automated way to enable thousands of model runs using plausible parameter values and extreme parameter combinations for model stress testing. The OGIA sensitivity and uncertainty analysis, that is, 200 calibration-constrained parameter sets, where spatial parameters are defined using pilot points, is consistent with the BA sensitivity and uncertainty analysis requirements. Each parameter set consists of 3300 parameters. Like most inverse-problems, calibration of this highly parameterised groundwater model is an ill-posed problem. However, Null-Space Monte Carlo analysis, as used in this study, provides an efficient method to explore the non-uniqueness of model parameters and resulting model prediction uncertainty. The pilot points give spatial coherence to the model parameter values that is consistent with the model conceptualisation and use regularisation to solve the problem mathematically.

Water balance components

The water balance is reported for a defined control volume in BA that includes all hydrologically connected changes that are potentially predicted by the surface water and groundwater models. The water balance components (e.g. recharge, evapotranspiration, baseflow (discharge to stream), licensed extractions, upward flow from deeper groundwater and change in storage) are compared with estimates of fluxes described in the regional-scale conceptual model and localised groundwater models to provide confidence in model predictions, thus meeting the modelling guiding principles (Barnett et al., 2012). Section 2.6.2.7 compares model estimates of water extraction from CSG and open-cut coal mining with available local and regional estimates.

Estimates of diffuse recharge for BA groundwater models are typically obtained from the Australian Water Resource Assessment (AWRA) models as described in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). In the OGIA model, net recharge values are parameterised spatially using pilot points to define the calibration-constrained parameter sets. Rates of groundwater extraction for stock, domestic, irrigation, industry and town water supplies are modelled as constant and equal to the rates applicable to the last quarter of 2012 (unless actual metered data are available) in BA. The OGIA model estimates extraction volumes using information contained in the relevant water resource plans using a constant rate starting in 1995 in the Base Run that accounts for all non petroleum and gas water extraction. Groundwater extraction associated with CSG and large coal mining development is generally determined based on target groundwater levels rather than extraction rates in BA, which means that groundwater extraction is a function of the hydraulic properties of the aquifers and aquitards involved (which are uncertain) and will be estimated as a probability distribution rather than as a discrete value. This is consistent with using the MODFLOW EVT package to simulate CSG extraction and the Drain package to represent mine pit dewatering in the OGIA model.

Evapotranspiration for areas with shallow watertables is typically represented using a depth-dependent boundary condition in BA groundwater models. This permits hydrological response variables related to terrestrial groundwater-dependent ecosystems to be incorporated into the groundwater models. This assumption is not met by the OGIA model, as it is focused on the deeper regional aquifers targeted by CSG development.

Surface water – groundwater interactions are generally modelled in BA using variously coupled landscape, river and groundwater models. Coupled landscape, river and groundwater models pass river stages, exchange fluxes and coal development fluxes (e.g. co-produced water discharged to streams) between models to estimate hydrological response variables for receptor impact modelling. Subregions that do not have coupled river and groundwater models have limited surface water – groundwater interaction modelling and cannot estimate river stages at receptor locations. This is the case for the Maranoa-Balonne-Condamine subregion. The MODFLOW River and Drain packages are used to represent surface water – groundwater interactions in the OGIA model, which assumes that all surface watercourses act as groundwater discharge boundaries. This is ‘considered to be a conservative assumption from an impact point of view’ and ‘effectively assumes that all surface watercourses act as discharge boundaries and hence cannot leak’ (GHD, 2012).

The OGIA model is able to probabilistically estimate the hydrological response variables for groundwater, that is, maximum drawdown (*dmax*) and time to maximum drawdown (*tmax*) and is used to identify water bores and springs potentially affected by drawdown caused by petroleum and gas extraction in the Surat cumulative management area (QWC, 2012). However, the focus on the deep regional aquifers targeted by CSG development, means that integration of the groundwater model with a surface water numerical model and receptor impact modelling is not possible at this time in the Maranoa-Balonne-Condamine subregion. Assumptions related to the representation of water balance components in the OGIA model are described in Section 2.6.2.4, Section 2.6.2.7 and discussed in Section 2.6.2.8.

Transparent and reproducible model outputs

An over-arching requirement of the BAs is for all model outputs to be transparent and reproducible, which means that the models need to be run as part of a documented workflow that records the provenance of the input data, executables and outputs. This is achieved through the use of scripting in BAs. All pre-processing, model runs and post-processing is done using scripts that are made available along with the products; this ensures that all model inputs, parameters, executables and outputs are traceable, meeting the modelling guiding principles related to transparency (Barnett et al., 2012).

The OGIA model is a proprietary model owned and operated by OGIA. For this reason, the model itself cannot be made publicly available by the Bioregional Assessment Programme. Instead, the Assessment team and OGIA have agreed to make the relevant BA groundwater model inputs and outputs publicly available (Australian Government, 2016).

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2.6.2.2 Review of existing models

Summary

Rapid growth of the coal seam gas (CSG) industry in south-east Queensland has driven the development of regional-scale groundwater modelling of the Surat and Bowen geological basins by gas companies and regulatory and research agencies. A review of six regional-scale groundwater models for the Queensland Water Commission (currently known as Office of Groundwater Impact Assessment, OGIA) recommended that a new groundwater model be developed to assess the cumulative impacts resulting from CSG development in the Surat and Bowen basins.

The Queensland Water Commission developed this regional groundwater model for the Surat cumulative management area (CMA), henceforth referred to as the OGIA model. The primary purpose of the OGIA model is to predict the regional water pressure and water level changes in aquifers within the Surat CMA in response to the depressurisation of the coal seams for CSG production. The OGIA model has the best available representation of CSG development in the Surat CMA and provides a probabilistic estimate of hydrological changes arising from coal resource development. However, groundwater impacts resulting from the operation of the coal mines in the Surat CMA are not currently represented in the OGIA model. The focus on deeper regional aquifers means that the OGIA model is not on its own suitable for assessing hydrological changes to groundwater-dependent ecosystems, such as water-course springs and terrestrial vegetation. In conclusion, the OGIA model meets the fit-for-purpose criteria for groundwater modelling in BA, with the exception of criteria related to the representation of water fluxes in surficial aquifers.

Rapid growth of the coal seam gas (CSG) industry in south-east Queensland has driven the development of regional-scale groundwater modelling of the Surat and Bowen geological basins by gas companies and regulatory and research agencies. The Maranoa-Balonne-Condamine subregion intersects the Great Artesian Basin (GAB) aquifers in the Surat geological basin and parts of the Bowen geological basin. Four whole-of-GAB and 18 notable part-GAB groundwater models are reviewed by Smith and Welsh (2011) who found that the GABtran model is the most suitable existing groundwater model to assess water resource availability for the Great Artesian Basin Water Resource Assessment.

This review focuses on regional-scale groundwater models developed to simulate the groundwater impacts of CSG and coal mining development in the Surat and Bowen geological basins in order to assess the suitability of each model for bioregional assessment (BA) groundwater modelling purposes. Figure 4 shows the boundary geometries of the regional groundwater models that intersect with the Maranoa-Balonne-Condamine subregion:

- APLNG Project model – Worley Parsons (2010) on behalf of Origin Energy Ltd
- Condamine Model – KCB (2011) for Department of Natural Resources and Mines (DNRM) in collaboration with the National Water Commission in Queensland Water Commission (QWC, 2012)

- Dumaresq Border Rivers model – Chen (2003) in Smith and Welsh (2011)
- GABtran model – Bureau of Rural Sciences (Welsh, 2006) for the entire GAB
- GLNG Comet Ridge model – Santos (2010) for the Bowen Basin and URS (2010) on behalf of Santos Ltd for the Surat Basin
- Moree model - Hopkins (1996) in Smith and Welsh (2011)
- OGIA model – GHD (2012) for the Queensland Water Commission (QWC, 2012)
- QCLNG Project models – Golder Associates (2011) on behalf of QGC Pty Ltd
- Surat Gas Project model – Schlumberger Water Services Pty Ltd (SWS, 2010) on behalf of Arrow Energy Pty Ltd
- Upper Condamine model - Barnett and Muller (2008) for the CSIRO Murray-Darling Basin Sustainable Yields Project.

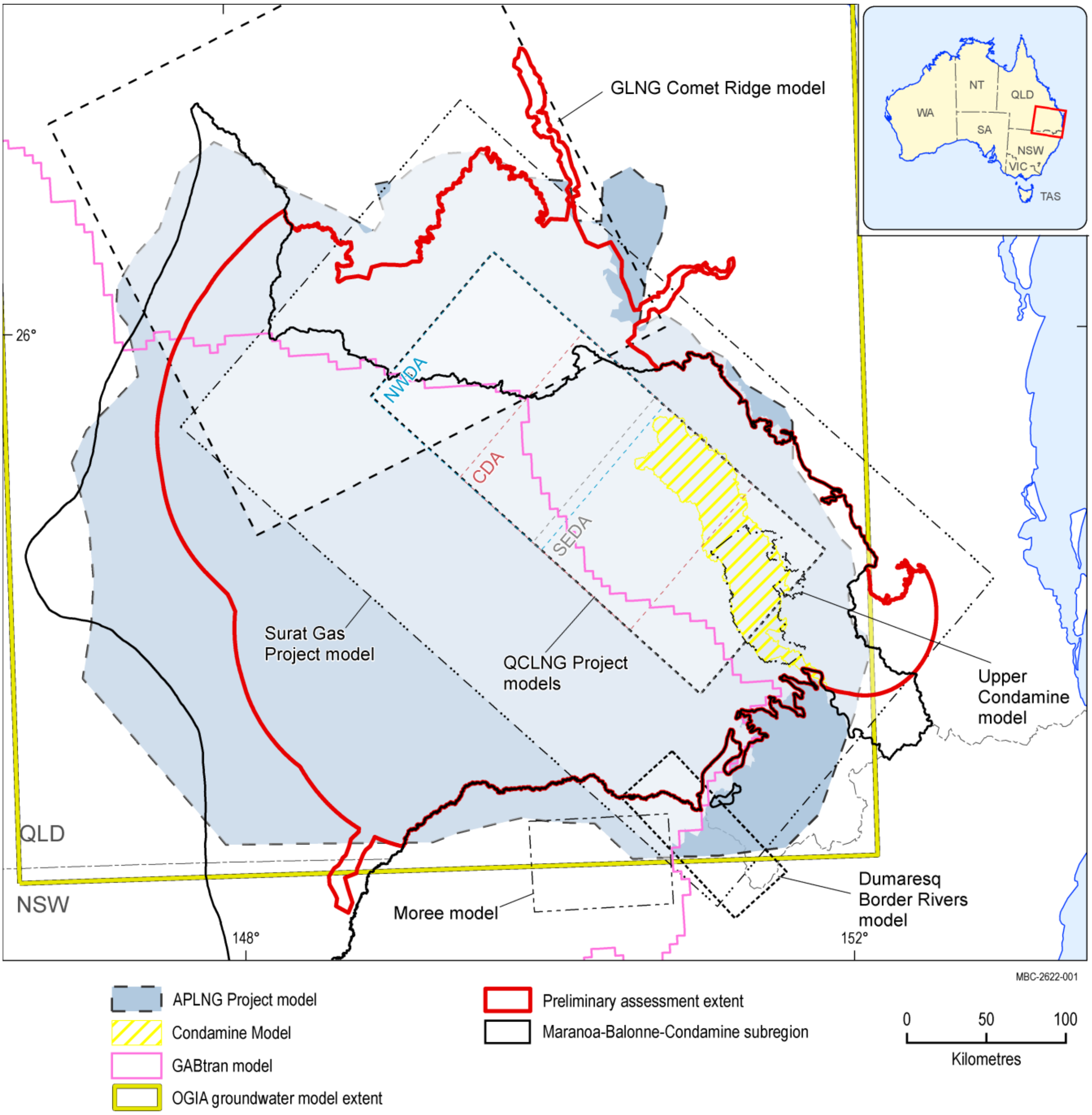

Figure 4 Boundary geometries of regional groundwater models within the Maranoa-Balonne-Condamine subregion

APLNG = Australia Pacific Liquefied Natural Gas, CDA = Central Development Area, GAB = Great Artesian Basin, GLNG = Gladstone Liquefied Natural Gas, NWDA = North West Development Area, OGIA = Office of Groundwater Impact Assessment, QCLNG = Queensland Curtis Liquefied Natural Gas, SEDA = South East Development Area
Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.2.1 Regional-scale groundwater models

Six regional-scale groundwater models of the Surat and Bowen geological basins were reviewed for the Queensland Water Commission (GHD, 2012):

- APLNG Project model
- GABtran model for the entire GAB
- GLNG Comet Ridge model for the Bowen Basin

- GLNG Comet Ridge model for the Surat Basin
- QCLNG Project models
- Surat Gas Project model.

The review recommended that a new groundwater model be developed for the assessment of cumulative groundwater impacts resulting from CSG development in the Surat and Bowen geological basins (GHD, 2012). This recommendation was based on the conclusion that substantial additional data were available to the Queensland Water Commission (QWC) (currently known as the Office of Groundwater Impact Assessment, OGIA) from each of the CSG companies than were accounted for in any of these individual models. Accordingly, QWC developed a regional groundwater model for the Surat cumulative management area (CMA), henceforth referred to as the OGIA model. The OGIA model simulates the cumulative hydrological impacts of CSG development in the Surat and parts of the Bowen geological basins (QWC, 2012). As such, the OGIA model supersedes the groundwater models developed by the individual CSG proponents, which are not considered further in this review.

2.6.2.2.2 Office of Groundwater Impact Assessment groundwater model for the Surat cumulative management area

The primary purpose of the Office of Groundwater Impact Assessment (OGIA) model is to predict regional water pressure and water level changes in aquifers within the Surat CMA in response to the depressurisation of the coal seams for CSG production. Specifically, the model is used to identify the immediately affected areas and the long-term affected areas where water pressures are predicted to decline by 2 m for unconsolidated aquifers (such as sand aquifers) and by 5 m for consolidated aquifers (such as sandstones). The model is also used to identify potentially affected spring sites where the long-term predicted impact on water pressure in the underlying GAB aquifers due to extraction of water for CSG production exceeds 0.2 m (QWC, 2012).

The OGIA model covers a spatial extent of 662 km × 548 km, overlays the entire Surat CMA and includes the coal seam formations and potentially connected aquifers within the Surat, southern Bowen and Clarence-Moreton geological basins. The model is discretised into uniform grid cells of 1.5 km × 1.5 km horizontally and vertically into 19 layers of variable thickness supported by relevant geological and hydrogeological data (QWC, 2012). The OGIA model grid discretisation is comparable to model grids (100s to 1000s m) developed for other subregions in the BA of a similar size.

The OGIA model is set up to run in a predictive mode from 1995, where two runs, a Base Run and a Petroleum & Gas (P&G) Production Run, are used to estimate the groundwater impacts resulting from the CSG operations in the Surat CMA. The Base Run involves running the model with water extraction from 1995 onward accounting only for non P&G groundwater extraction (QWC, 2012). In the P&G Production Run, water extraction from current and proposed P&G activities is added to the Base Run water extraction. The difference in the predicted water levels between these two runs provides an estimate of the water level impacts or groundwater drawdown that are attributed to P&G activities. This is consistent with the approach taken in BA, where rates of groundwater extraction for non P&G groundwater extraction are modelled as constant and equal to the rates after a specified date (the last quarter of 2012 in BA).

The first-generation OGIA model was built in 2012 and has the best available representation of CSG development in the Surat CMA for cumulative groundwater impact assessment. Tenure holders provide updated CSG development pathway information to revise the P&G Production Run each year (QWC, 2012; OGIA, 2013, 2014). This information is generally consistent with the information in the environmental impact statements prepared by tenure holders (QWC, 2012). The OGIA model uncertainty analysis gives probabilistic estimates of the hydrological changes associated with coal resource development, which is a requirement for groundwater modelling in BA. However, hydrological changes resulting from the operation of the coal mines in the subregion are not currently represented in the OGIA model.

The focus on deeper regional aquifers that are targeted by CSG development, means that evapotranspiration in areas with shallow watertables is not represented using a depth-dependent boundary condition. This means that the OGIA model is not on its own suitable for assessing hydrological changes in surficial aquifers (outside of the Condamine Model area) that are important in representing impacts to groundwater-dependent ecosystems, such as water-course springs and terrestrial vegetation.

Queensland's regulatory framework provides that a new underground water impact report (UWIR) is prepared at least every three years. The revised Surat Underground Water Impact Report (UWIR) was released for public comment in early 2016 (OGIA, 2016). As a consequence, the Assessment team are using the 2012 OGIA model with the CSG development pathway reported in the 2014 Annual report (OGIA, 2014).

In conclusion, the OGIA model meets the fit-for-purpose criteria for groundwater modelling in BA, with the exception of criteria related to integration with surface water numerical modelling and receptor impact modelling that are related to the representation of water fluxes in surficial aquifers, as discussed in Section 2.6.2.1.

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2.6.2.3 Model development

Summary

The entire Maranoa-Balonne-Condamine subregion falls within the boundary of the geological Surat Basin, which forms part of the wider Great Artesian Basin (GAB). The regional aquifers are important groundwater supplies for agriculture, industries and towns in the subregion. Coal mining and coal seam gas (CSG) development in the Maranoa-Balonne-Condamine subregion targets the Walloon Coal Measures of the Surat geological basin. Groundwater recharge occurs via infiltration and leakage from streams or overlying aquifers in the aquifer outcrop areas in the north, north-west, north-east and east along the Great Dividing Range. Groundwater flow is predominantly from the recharge areas to the south, south-west, and west. Natural discharge from the Surat Basin occurs via vertical leakage through aquitards, springs, rivers and subsurface flow into adjoining areas.

The Office of Groundwater Impact Assessment (OGIA) model covers an area of 550 km (east–west) × 660 km (north–south), comprising more than three million 1.5 km × 1.5 km grid cells, stacked into 19 layers based on available hydrostratigraphic data. The Walloon Coal Measures are represented by three model layers: an upper aquitard, a composite middle layer representing all coal seams and a lower aquitard. The OGIA model was calibrated in steady state to replicate pre-CSG extraction conditions prior to 1995. Groundwater modelling by OGIA for the Bioregional Assessment Programme estimates hydrological changes arising from coal resource development by comparing the difference in predicted water levels between two possible futures – the baseline and the coal resource development pathway (CRDP). The baseline includes all CSG development included in the 2014 P&G Production Run (OGIA 2014) plus five baseline coal mines. The CRDP includes the baseline plus the additional coal resource development (ACRD – which consists of two coal mines) in the subregion. The difference in predicted water levels between the baseline and CRDP provides an estimate of water level impacts that are attributable to the ACRD.

The OGIA model is a finite difference numerical model based on the MODFLOW–2005 code. The PCG-N solver (preconditioned conjugate gradient solver with improved nonlinear control) is used to solve the finite difference equations in models that are characterised by highly anisotropic hydraulic conductivity values, which is particularly useful for large sedimentary basins where significant contrasts between horizontal and vertical conductivity occur. Model calibration and uncertainty analysis was performed using the parameter estimation (PEST) suite of software.

2.6.2.3.1 Objectives

The objective of groundwater modelling undertaken as part of the bioregional assessment (BA) is to probabilistically assess hydrological changes arising from coal seam gas (CSG) and coal mining development at water-dependent assets and receptors. The Queensland Office of Groundwater Impact Assessment (OGIA) regional groundwater model is considered a fit-for-purpose regional-scale groundwater model for BA. The primary purpose of the OGIA model is to predict the regional water pressure and water level changes in aquifers within the Surat cumulative management area

(CMA) in response to the depressurisation of the coal seams for CSG production. The OGIA model is re-run annually based on the latest available industry development plans and has been revised for the BA to also simulate water-related impacts of coal mine developments in the Maranoa-Balonne-Condamine subregion.

2.6.2.3.2 Hydrogeological conceptual model

The entire Maranoa-Balonne-Condamine subregion falls within the boundary of the geological Surat Basin, which forms part of the wider Great Artesian Basin (GAB). The GAB is not a geological basin but is rather a hydrogeological or groundwater basin (Smerdon et al., 2012). Coal mining and CSG development in the Maranoa-Balonne-Condamine subregion targets the Walloon Coal Measures of the Surat geological basin. The Walloon Coal Measures ‘comprises of a varied sequence of sediments which contain material of high and low permeability. The coal seams are often the main water-bearing layers within a sequence of low permeability mudstones, siltstones or fine-grained sandstones’ (QWC, 2012). Coal seams usually exist as numerous thin non-continuous stringers or lenses separated by bands of low permeability sediments. The Walloon Coal Measures outcrop along the north, north-west, north-east and east of the Surat Basin. Coal mining is located close to the outcrop areas in the north-east and east of the subregion.

Companion product 2.3 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2016) contains a more detailed summary of the key system components, processes and interactions, including maps and cross-sections of the main aquifers and aquitards. The main aquifers within the Maranoa-Balonne-Condamine subregion, listed from deepest to shallowest, are the Precipice, Marburg, Hutton, Springbok, Gubberamunda and Mooga sandstones and the Bungil Formation. The deeper sandstone aquifers of the Clematis Group and equivalent formations of the Bowen Basin are also recognised as GAB aquifers. Major aquitards in the subregion, listed from deepest to shallowest, are the Rewan Group, Evergreen, Birkhead, Westbourne, Orallo, Wallumbilla and Griman Creek formations and their equivalents. The regional aquifers above (Springbok Sandstone) and below (Hutton Sandstone) the Walloon Coal Measures are separated by low permeability aquitard formations. These regional aquifers provide important groundwater supplies for agriculture, industries and towns.

Other than the GAB aquifers, the major aquifer systems in the Maranoa-Balonne-Condamine subregion are the alluvial and basalt aquifers. The Condamine Alluvium is the most significant and highly developed alluvial groundwater system in the subregion. It is heavily used for groundwater supply predominantly for irrigation, but also for town water supply, domestic, stock, watering and industrial uses to a lesser extent. Significant aquifers are contained in the Main Range Volcanics aquifer and are used for irrigation, stock and domestic and town water supplies. Basalt aquifers also occur in the north of the subregion overlying the sedimentary rocks of the Bowen Basin.

Most groundwater recharge occurs in the aquifer outcrop areas in the north, north-west, north-east and east along the Great Dividing Range. Direct recharge from rainfall via infiltration and leakage from streams or overlying aquifers are the two dominant mechanisms by which recharge reaches the aquifers. The major flow directions are from recharge areas to the south, south-west, and west although there is a minor northward flow component in some aquifers. Flow velocities have been estimated to be very small, in the range 1 to 5 mm/year (Habermehl, 1980). Groundwater movement is dominated by sub-horizontal flow in the aquifers, but vertical leakage from the aquifers upwards through the low permeability aquitards occurs throughout the GAB at a much slower rate. Natural discharge from the Surat Basin occurs via vertical leakage through aquitards, springs, rivers, and subsurface flow into adjoining areas.

The Condamine Alluvium is incised into the Walloon Coal Measures by up to 130 m, with the Walloon Coal Measures being the basement unit for most of the central area of the Condamine Alluvium. A layer of weathered clay and low permeability material between the deepest productive parts of the Condamine Alluvium and uppermost coal beds has been reported (Lane, 1979). The thickness and permeability of this weathered material influence the connectivity between the alluvium and the Walloon Coal Measures. Water level in the Walloon Coal Measures is slightly higher than in the Condamine Alluvium. A diagrammatic representation of the hydrogeological conceptualisation is given in Figure 5.

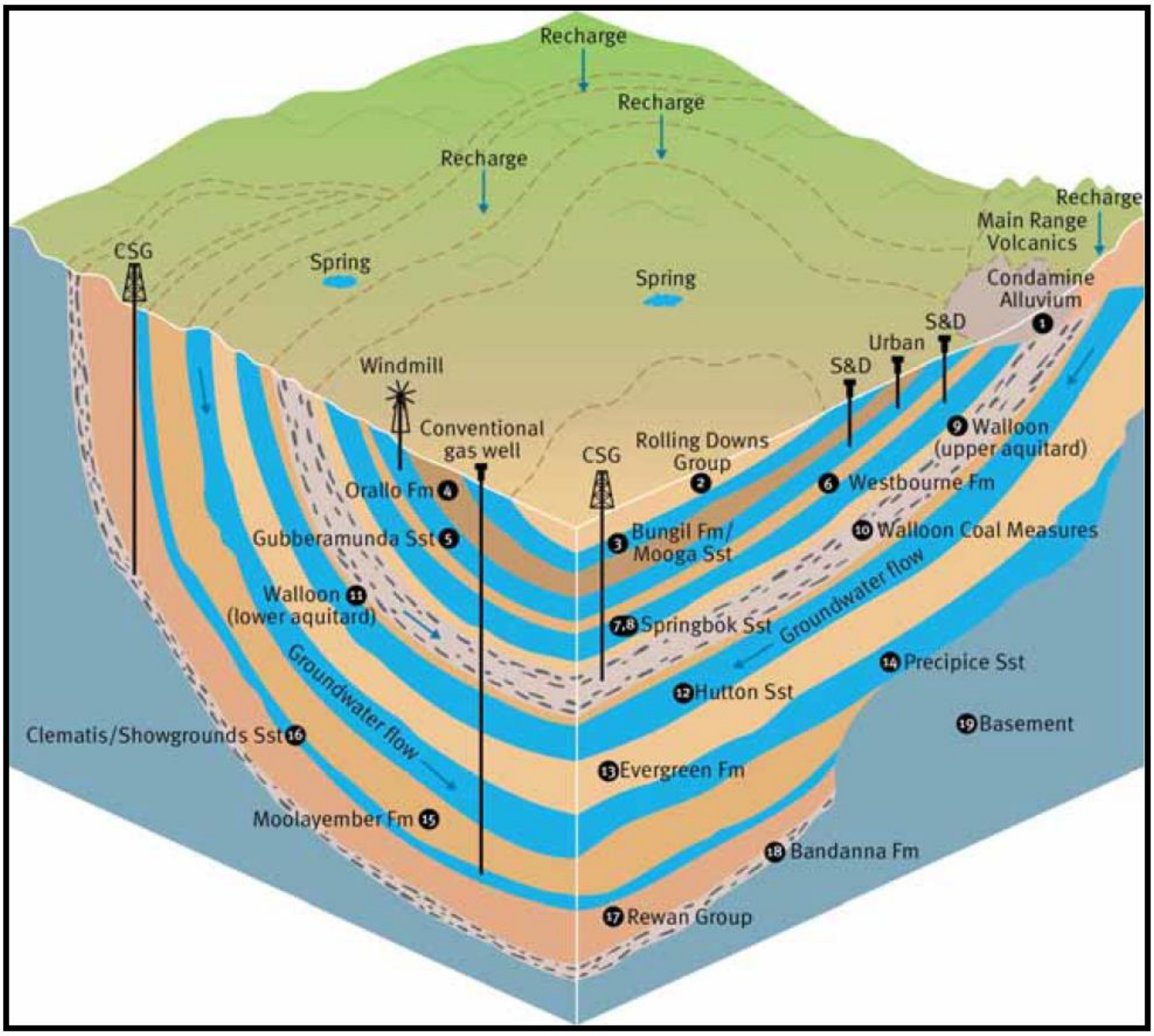

Figure 5 Diagrammatic representation of the hydrogeological conceptualisation of the Office of Groundwater Impact Assessment (OGIA) model used in the Maranoa-Balonne-Condamine subregion

Fm = Formation, Sst = Sandstone, S&D = stock and domestic, CSG = coal seam gas, OGIA = Office of Groundwater Assessment
The circled numbers refer to OGIA model layers.
Source: QWC (2012)

2.6.2.3.3 Design and implementation

The Surat CMA extends north of the Maranoa-Balonne-Condamine subregion, which means that the OGIA model covers parts of three distinct geological basins: the southern Bowen Basin, the Surat Basin and the western Clarence-Moreton Basin. The OGIA model includes groundwater extraction for CSG production from the Walloon Coal Measures within the Surat geological basin (that is relevant to this Assessment) and from the deeper Bandanna Formation of the underlying Bowen geological basin along a north–south trending zone to the east of Injune (that is outside of the Maranoa-Balonne-Condamine subregion). The OGIA model also includes conventional oil and gas production that targets the Evergreen Formation, Precipice Sandstone and Clematis Sandstone in the Surat Basin. The stratigraphy of the three geological basins and corresponding model layers in the OGIA model is shown in Figure 6.

The OGIA model covers an area of 550 km (east–west) × 660 km (north–south). The model has 19 layers to represent all major aquifers, aquitards and productive coal measures (Figure 6). Each model layer is divided into 1.5 km × 1.5 km model cells. This means that all geological formations are collectively represented by more than three million building blocks of 1.5 km × 1.5 km square cells, stacked into 19 layers (QWC, 2012). The thickness of each layer in each column represents the mean formation thickness at that location and was summarised from pre-existing stratigraphic interpretations of borehole logs and surfaces developed by previous studies. Initial values for hydraulic parameters were estimated from various sources, including more than 13,000 drill stem test (DST) data points recorded in the Queensland Petroleum and Gas Exploration Database (QPED) and more than 1,000 pump test records from the Department of Natural Resources and Mines (DNRM) groundwater database (QWC, 2012).

The Walloon Coal Measures are represented in model layers 9 to 11 (QWC, 2012):

- Layer 9 is an upper aquitard layer defined by the vertical distance between the uppermost productive coal seam and the top of the Walloon Coal Measures, that is, the base of the overlying Springbok Sandstone
- Layer 10 is an aquitard layer representing all coal seams from the top of the uppermost productive seam to the base of the lowermost productive seam and the inter-bedded low permeability sediments. Its thickness is defined by the vertical distance between the top of the uppermost and base of the lowermost productive coal seams
- Layer 11 is a lower aquitard layer defined by the vertical distance between the base of the lowermost productive coal seam and the base of the Walloon Coal Measures, that is, the top of the underlying Hutton Sandstone.

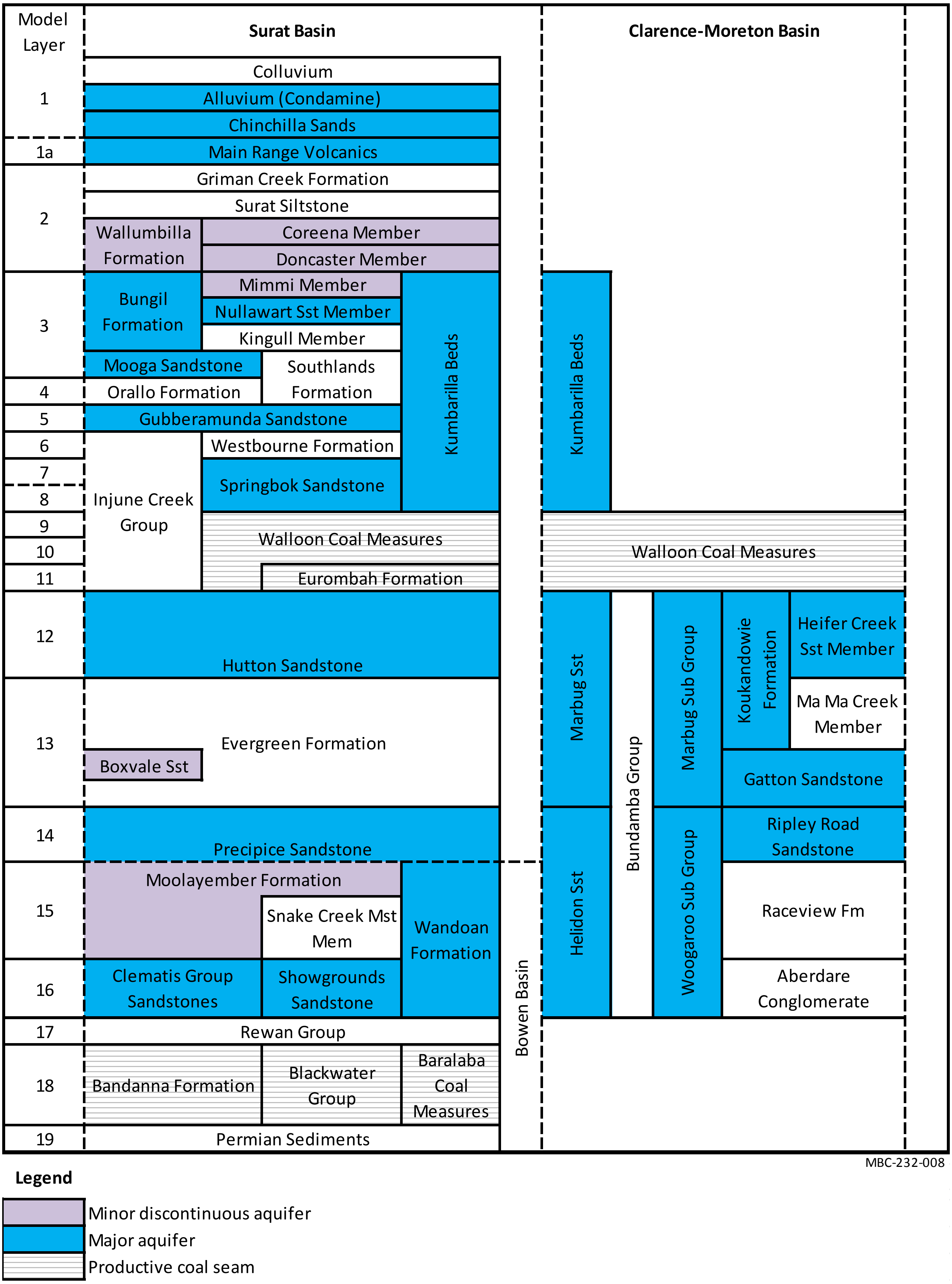

Figure 6 Stratigraphy of the Surat, Bowen and Clarence-Moreton basins and the corresponding model layers in the Office of Groundwater Impact Assessment (OGIA) model

Fm = Formation, Mem = Member, Mst = Mudstone, Sst = Sandstone
Source: GHD (2012)

The OGIA model is a simple, idealised representation of a complex three-dimensional geologic system that is converted into a three-dimensional mathematical representation of the physical system and flow processes. One simplification is the determination of hydraulic properties used to represent the coal seams and interburden in the Walloon Coal Measures. Another is the simulation of single-phase flow, instead of dual-phase flow of water and gas near the extraction wells. These simplifications mean that pressure changes in the immediate vicinity of CSG production wells are not well simulated. However, these effects are expected to be minimal for receptors associated with aquifers other than the Walloon Coal Measures. Single-phase groundwater modelling tends to over-predict water level drawdown, thus providing a conservative estimate of impacts at receptors. Moore et al. (2015) describes the unique challenges of representing processes that operate at two very different scales in regional-scale models.

The OGIA model was calibrated in steady state to replicate pre-CSG extraction conditions, corresponding to the historical conditions of the groundwater system prior to the first development of CSG activities for the period 1960 to 1995. It was assumed that a steady-state model provided a practical representation of the system at that time for regional modelling, where the majority of boreholes show relatively minor trends over the period 1960 to 1995 in the Surat CMA (QWC, 2012).

The Condamine Alluvium is an exception to this generalisation. In the Condamine Alluvium, groundwater levels have continually declined during recent years due to the high levels of extraction from the aquifer. An alternative integrated approach was therefore adopted for the Condamine Alluvium (QWC, 2012). Calibrated values of aquifer thickness and hydraulic parameters, and time-variant water level conditions (500 m × 500 m cell size) were imported from the detailed transient Condamine Model (QWC, 2012). The regional model was used to predict the exchange fluxes between the Condamine Alluvium and the Walloon Coal Measures. The Condamine Model was then used to estimate impacts on groundwater levels in the Condamine Alluvium that result from the above change in flow (QWC, 2012).

The OGIA model was set up to make predictions starting from 1995 using initial boundary conditions from the steady-state model (QWC, 2012). The steady-state run accounted for the water extraction for all existing water use in 1995, that is, all non petroleum & gas (P&G) water extraction. A more detailed transient sub-model of the existing Daandine Coal Seam Gas Project field was used to calibrate storage coefficients. Calibrated storage, hydraulic conductivity, recharge and general head conductance from the steady-state model calibration were used in the predictive runs.

Two separate predictive runs were made for the underground water impact report (UWIR): a Base Run and a P&G Production Run (QWC, 2012). The Base Run involved running the model with water extraction from 1995 onwards accounting only for non P&G extraction. In the P&G Production Run, water extraction from current and proposed P&G activities was added to the Base Run water extraction. The difference in predicted water levels between the P&G Production Run and the Base Run provides an estimate of water level impacts that are attributed to P&G activities. This is identical to the approach used in the BA, where numerical groundwater modelling results are primarily presented as the probabilistic estimates of the difference in groundwater drawdown between two possible futures – the baseline and the coal resource development pathway (CRDP).

The first stress period in the transient OGIA model was the same as the steady-state OGIA model, simulating historical conditions from 1960 to 1995 (QWC, 2012). Subsequent stress periods were added to simulate the groundwater flow system accounting for the stresses caused by groundwater extraction for CSG development together with groundwater stresses from other activities including water use for irrigation and water supply. A total of 259 stress periods were considered for simulation of the flow system over a period of 3000 years. Simulated well spacing and the sequence of development was in accordance with the information provided by the tenure holders to the Queensland Water Commission (currently known as OGIA) through the main extraction period from 1995 to 2050. The OGIA model is re-run annually based on the latest available industry development plans. Changes since the previous report was prepared are described in the annual reports (e.g. OGIA, 2014).

Groundwater modelling by OGIA for BA in the Maranoa-Balonne-Condamine subregion follows a similar approach. Hydrological changes arising from coal resource development for two possible futures – the baseline and the CRDP – are estimated using a probabilistic approach. Developments included in the baseline and CRDP futures are described in Section 2.6.2.5. For BA, the baseline includes all CSG development included in the 2014 P&G Production Run (OGIA, 2014) plus five baseline coal mines. The CRDP includes the baseline plus the additional coal resource development (ACRD – which consists of two coal mines) in the subregion. The difference in predicted water levels between the baseline and CRDP provides an estimate of water level impacts that are attributable to the ACRD.

Uncertainty analysis by OGIA for BA groundwater modelling in the Maranoa-Balonne-Condamine subregion uses 200 calibration-constrained parameter sets to calculate probabilistic estimates of hydrological changes arising from coal resource development. The 200 parameter sets are not re-calibrated after the model boundary conditions are altered to represent the open-cut coal mines. The uncertainty analysis is discussed in Section 2.6.2.8.

2.6.2.3.4 Model code and solver

The OGIA model is a finite difference numerical model based on the MODFLOW–2005 code (Harbaugh, 2005). Details of the OGIA model development are documented in GHD (2012) and summarised in QWC (2012). Section2.6.2.4, Section 2.6.2.5 and Section 2.6.2.6 describe aspects of model development relevant to BA. One benefit of using the MODFLOW code is the large number of different modules available for simulating different groundwater flow processes and solving the finite difference flow equations. The PCG-N solver (preconditioned conjugate gradient solver with improved nonlinear control) is used to solve the finite difference equations because it is typically able to achieve convergence in models that are characterised by highly anisotropic hydraulic conductivity values, that is, hydraulic conductivity values that differ based on the direction of measurement. This solver is particularly useful for large sedimentary basins like the Surat and Bowen geological basins where significant contrasts between horizontal and vertical conductivity occur.

Model calibration and uncertainty analysis was performed using the parameter estimation (PEST) suite of software that allows model-independent parameter estimation and parameter/predictive-uncertainty analysis (Doherty, 2010). Details of the uncertainty analysis are documented in WaterMark Numerical Computing (2012) and summarised in Section 2.6.2.8.

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2.6.2.4 Boundary and initial conditions

Summary

No-flow boundary conditions are assigned to the mapped geological boundaries in the north-west and north-east where the Surat and Bowen geological basins are absent and along the Nebine Ridge (western model boundary). MODFLOW General Head Boundary cells are used to simulate groundwater flows in the east across the Kumbarilla Ridge and in the south along the Queensland state border. Modelled drawdown indicates that lateral boundary conditions are sufficiently remote from current and future coal resource development to reduce their impact on the model predictions.

MODFLOW Drain cells are used to establish topographic control of groundwater levels and to calculate net recharge. Net recharge is equivalent to the modelled flux to the deeper confined system and represents the proportion of potential or watertable recharge that is rejected via shallow groundwater systems and/or surface watercourses. Net recharge values are estimated for 20 recharge zones during steady-state model calibration using upper and lower estimates of long-term mean recharge. Evapotranspiration is not modelled explicitly in the Office of Groundwater Impact Assessment (OGIA) model, which means that hydrological response variables related to terrestrial groundwater-dependent ecosystems, cannot be predicted by the OGIA model.

The MODFLOW Wells package is used to represent all groundwater extractions from approximately 19,000 bores, including licensed volumetric entitlements, stock and domestic and conventional oil and gas abstractions. The MODFLOW EVT package is used to represent groundwater extraction associated with coal seam gas (CSG) production by allowing extraction rates to gradually reduce as the head falls toward a user-defined extinction depth. Total groundwater extractions in the OGIA model are about 215,000 ML/year for non-CSG production and about 95,000 ML/year for CSG production over the life of the industry.

It is assumed that all surface watercourses act as discharge boundaries with respect to the underlying aquifer. The MODFLOW River package is used to represent surface water – groundwater interactions in the major alluvial systems and watercourses. Using River cells means that changes to baseflow volumes from groundwater level drawdown can be estimated for the major alluvial systems and watercourses. The more-detailed Condamine Model is used to estimate impacts on groundwater levels in the Condamine Alluvium that result from the change in flow from the Condamine Alluvium to the Walloon Coal Measures predicted by the regional model. Temporary watercourses that are losing or losing – disconnected with respect to the underlying aquifer are represented in the OGIA model by Drain cells.

2.6.2.4.1 Lateral

The Surat geological basin dips in the south-west direction, which means that the main geological units are absent in the north of the model extent. Similarly, the main geological units of the Bowen Basin are absent to the east and west of the mapped boundaries of this basin. There is no evidence of groundwater connectivity across the Surat and Bowen geological basin boundaries (GHD, 2012). For this reason, no-flow boundary conditions are assigned to all model cells in the north-west and north-east of the modelled areas (GHD, 2012) (Figure 7). No-flow boundary conditions are also assigned to the western boundary of the model area as 'little or no interaction is thought to occur across the Nebine Ridge' (GHD, 2012, p. 56).

Potentially significant groundwater flows are thought to occur across the mapped boundary between the Surat and Clarence-Moreton geological basins in the east across the Kumbarilla Ridge (GHD, 2012; Ransley and Smerdon, 2012). MODFLOW General Head Boundary (GHB) cells are assigned to the model layers corresponding to the Walloon Coal Measures, Hutton Sandstone and Precipice Sandstone along this boundary (GHD, 2012).

Groundwater in the Surat Basin along the southern boundary of the model along the Queensland state border continues to flow in a southerly direction. For this reason, groundwater flow in this area is simulated by assigning GHB cells at the modelled ground surface in each of the productive coal or aquifer units present at this location (GHD, 2012).

No flow and GHB cell locations over the entire OGIA model extent are shown in Figure 7. The groundwater model domain encompasses current and future key stresses related to coal resource development. Modelled drawdown does not extend to the lateral boundaries within the prediction period, indicating that coal resource development is sufficiently remote to reduce the impact of the boundary conditions on the model predictions.

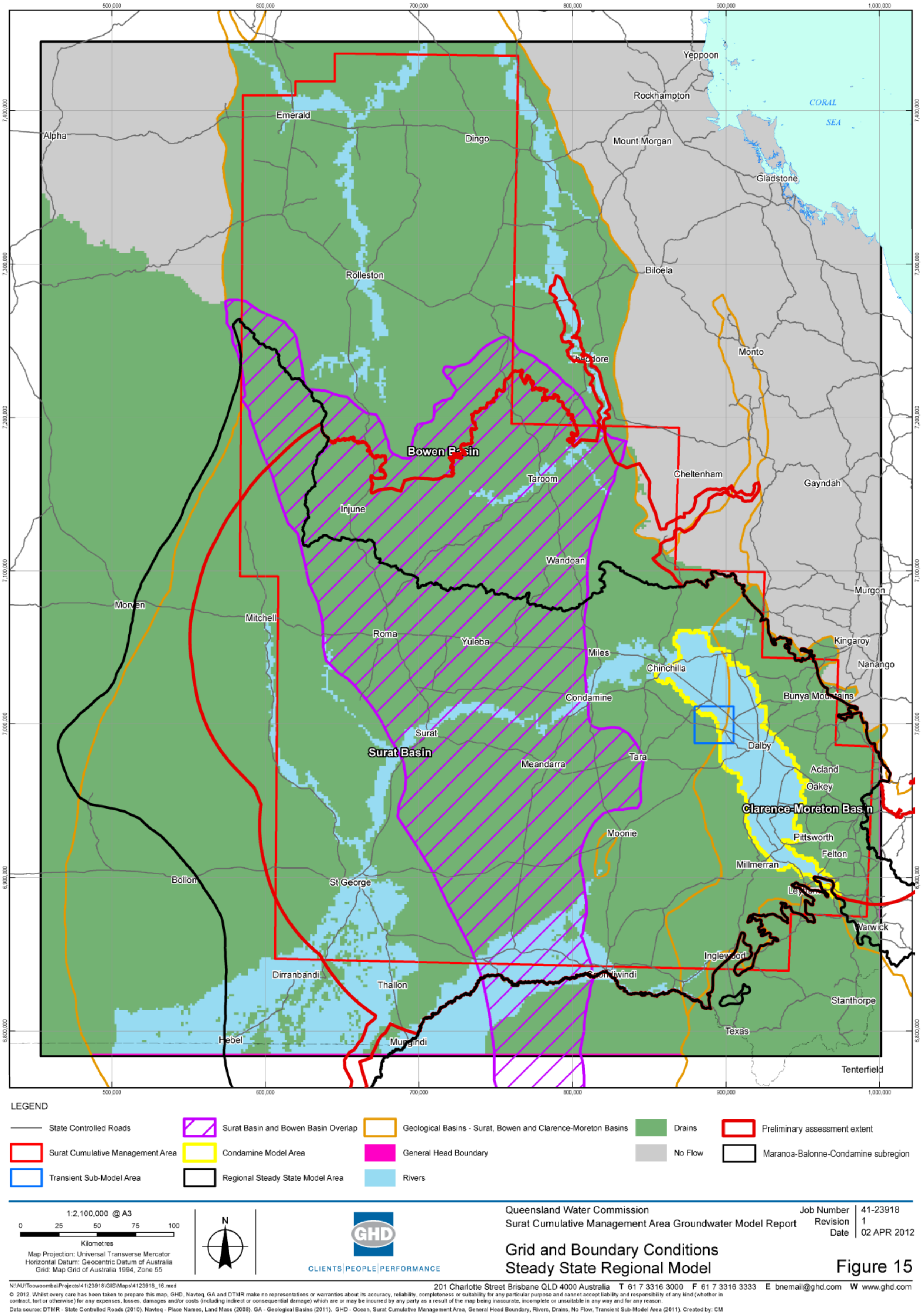

Figure 7 Office of Groundwater Impact Assessment (OGIA) model grid and boundary conditions showing the outline of the Maranoa-Balonne-Condamine subregion boundary and preliminary assessment extent for reference

Source: adapted from Figure 15 Grid and Boundary Conditions. Steady State Regional Model (GHD, 2012)

2.6.2.4.2 Recharge

Net recharge values are estimated in the steady-state model calibration by allowing recharge rates to vary on a zonal basis in the uppermost model cell in each active layer. 'In most zones, recharge was allowed to vary between 1 and 30 mm/yr based on maximum and minimum long-term average estimates included in Kellett et al. (2003)' (GHD, 2012, p. 59). Watertable recharge values are considered to be potential recharge values as 'a significant proportion of these applied potential rates will be rejected, resulting in modelled net or effective recharge rates which are comparable with the estimates of Kellett et al. (2003)' (GHD, 2012, p. 60). Watertable recharge to the Main Range Volcanics is allowed to vary between 20 and 30 mm/year to maintain consistency with regional-scale recharge estimates of 23 to 28 mm/year included in the Murray–Darling Basin Authority Basin Plan (GHD, 2012). Initial watertable recharge values used in the OGIA model are shown in Table 4.

The Condamine Alluvium is modelled using an integrated approach, where the regional model is used to predict the exchange fluxes between the Condamine Alluvium and the Walloon Coal Measures. A zero recharge rate is assumed for the Condamine Alluvium in the regional model to ensure 'consistency between the regional model and the Condamine Model (KCB, 2011)' (GHD, 2012, p. 59). 'Under this arrangement, modelled groundwater levels in the Condamine are insensitive to recharge' (GHD, 2012, p. 59).

Net recharge is defined for the OGIA model as 'Modelled water table recharge – modelled discharge to local shallow groundwater systems + net inflow from adjacent layers. Net recharge is therefore equivalent to the modelled flux to the deeper confined system. The difference between the two different modelled recharge values quoted therefore represents the proportion of potential or water table recharge that is rejected via shallow groundwater systems and/or surface water courses' (GHD, 2012, p. 60). Calibrated net recharge values used in the OGIA model are shown in Table 4 and Figure 8.

Table 4 Initial watertable recharge and calibrated net recharge values used in the Office of Groundwater Impact Assessment (OGIA) model

Dominant unit	Model layer	Watertable recharge (mm/y)	Watertable recharge (ML/y)	Net recharge (mm/y)	Net recharge (ML/y)
Condamine Alluvium	1	0.0	0	0.0	0
Main Range Volcanics	1	20.0	158,910	5.2	41,373
Alluvium outside Condamine area	1	1.1	28,120	0.0	72
Rolling Downs Group	2	3.2	303,512	0.0	2,028
Bungil/Mooga Sandstone	3	2.5	23,176	1.7	15,280
Orallo Formation	4	1.0	8,929	0.0	188
Gubberamunda Sandstone	5	6.1	58,510	2.7	26,346

Dominant unit	Model layer	Watertable recharge (mm/y)	Watertable recharge (ML/y)	Net recharge (mm/y)	Net recharge (ML/y)
Westbourne Formation	6	1.0	5,684	0.0	23
Springbok Sandstone	7/8	1.0	7,751	0.6	3,626
Walloon Coal Measures (upper aquitard)	9	30.0	278,126	0.0	0
Walloon Coal Measures (productive coal)	10	2.1	19,529	1.1	10,360
Walloon Coal Measures (lower aquitard)	11	5.8	2,117	0.2	89
Hutton Sandstone	12	19.2	251,773	1.3	17,265
Evergreen Formation	13	7.6	34,374	0.0	0
Precipice Sandstone	14	20.7	85,012	1.3	17,265
Moolayember Formation	15	30.0	34,374	0.0	0
Clematis Sandstone	16	30.0	177,408	0.4	2,540
Rewan Group	17	6.7	126,191	0.0	0
Bandanna Formation	18	1.0	27,196	0.0	0
Pre-Bandanna age units	19	14.7	729	0.0	0
Averages (mm/y) and totals (ML/y)	na	6.8	1,901,331	0.4	125,267

na = not applicable
Source: Table 11 Initial Values and Permissible Ranges – Water Table Recharge and Table 17 Calibrated Values – Recharge (GHD, 2012)

2.6.2.4 Boundary and initial conditions

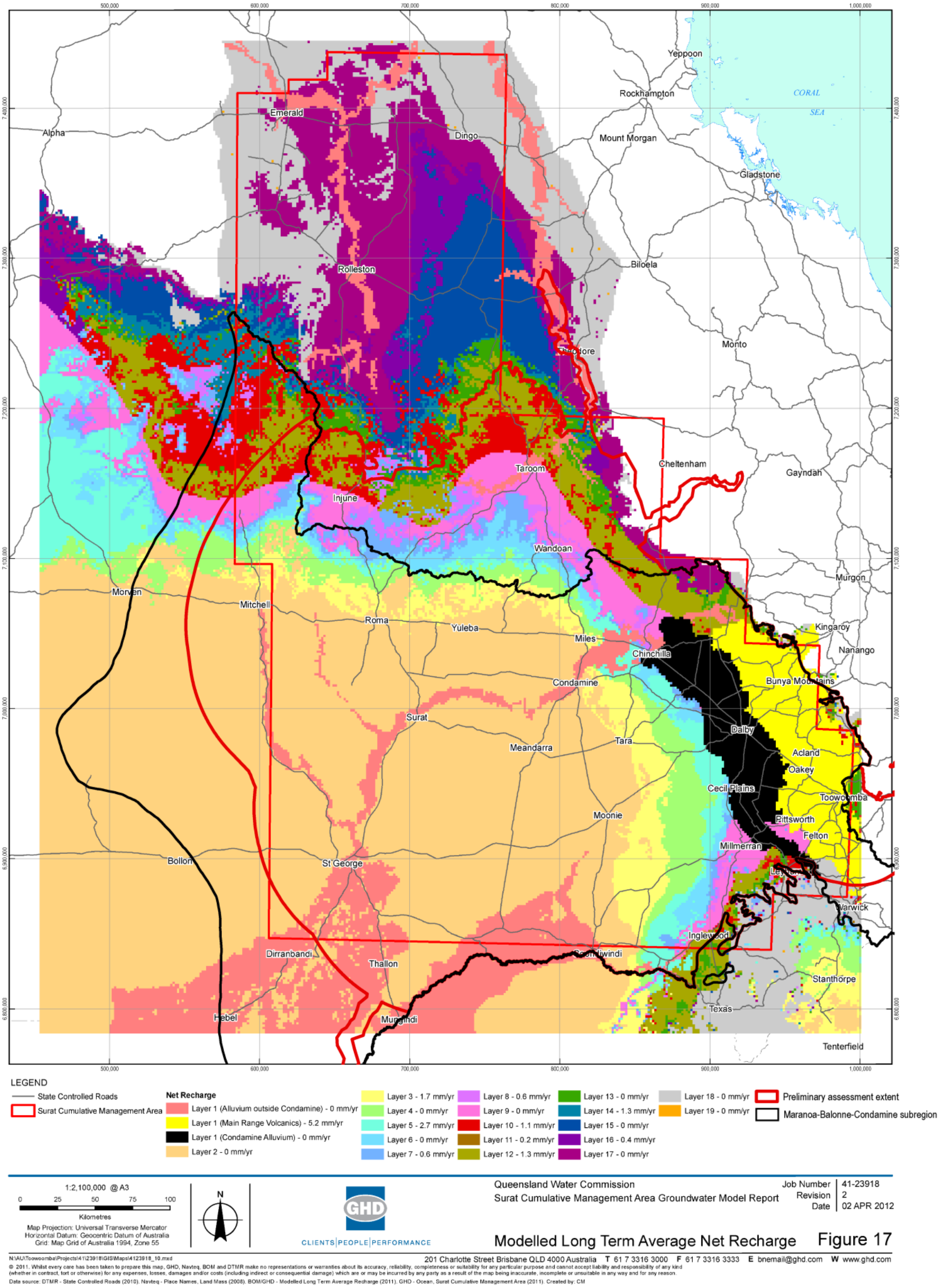

Figure 8 Modelled long-term average net recharge over the entire Office of Groundwater Impact Assessment (OGIA) model extent showing the outline of the Maranoa-Balonne-Condamine subregion boundary and preliminary assessment extent for reference

Source: adapted from Figure 17 Modelled Long Term Average Net Recharge (GHD, 2012)

2.6.2.4.3 Discharge

Topographic control of groundwater levels is established using the MODFLOW Drain package (Figure 7). Drain cells are assigned at modelled ground level in the uppermost active layer in each model cell to remove recharge in excess of the modelled flux to the deeper confined system from the model. Drain cells are assigned a conductance value of 2500 m^2/day, which is a relatively high value. 'Given that all of the modelled drain and river cells have been parameterised as discharge boundaries and hence cannot leak then modelled impact predictions are considered unlikely to be sensitive to the conductance value assigned' (GHD, 2012, p. 58).

Evapotranspiration is not modelled explicitly in the OGIA model. Instead, Drain cells remove excess recharge that is not transmitted to the deeper model layers in order to estimate net recharge during the steady-state model calibration. A consequence of this modelling approach is that hydrological response variables related to terrestrial groundwater-dependent ecosystems, cannot be predicted by the OGIA model as discussed in Section 2.6.2.1

Groundwater extractions

The MODFLOW Wells package is used to represent all groundwater extractions, except CSG depressurisation and mine dewatering. 'Estimated extraction rates in 1995 from approximately 19,000 abstraction bores have been included in the model via the MODFLOW well package' (GHD, 2012, p. 59). These include:

- licensed volumetric entitlements (Great Artesian Basin (GAB), Condamine Alluvium and Main Range Volcanics aquifers for agriculture, industrial and urban uses)
- estimated stock and domestic abstractions
- conventional oil and gas abstractions.

'Total water extraction is about 215,000 ML/year, of which about 85,000 ML/year is from the GAB formation and 130,000 ML/year is from other aquifers' (QWC, 2012, p. 42). Companion product 1.5 for the Maranoa-Balonne-Condamine subregion (Cassel et al., 2015) details the number of bores and estimated non-petroleum and gas groundwater extractions represented in the OGIA model. The OGIA model includes water extraction from '154 conventional oil and gas wells extracting water from GAB formations and 83 extracting water from older Permian and Devonian formations underlying the Bandanna Formation' (QWC, 2012, p. 42).

Coal seam gas production

The MODFLOW EVT package is used to represent groundwater extraction associated with coal seam gas (CSG) production in the OGIA model. The EVT package allows extraction rates to gradually reduce as the head falls toward a user-defined extinction depth. This is useful for predictive simulations since the actual rate of extraction is not known in advance. The timing and volume of water extraction is based on annually updated actual extraction data for the historical period and estimated future production rates provided to OGIA by the tenure holders (OGIA, 2014). 'It is estimated that over the life of the industry, water extraction will average about 95,000 ML/year' (QWC, 2012, p. 59).

Water management for coal resource development in the Maranoa-Balonne-Condamine subregion is described in greater detail in companion product 2.3 (conceptual modelling) (Holland et al., 2016).

The MODFLOW Drain package is used to represent water extraction for open-cut coal mines, which is described in Section 2.6.2.5.

2.6.2.4.4 Surface water – groundwater interactions

The MODFLOW River package is used to represent surface water – groundwater interactions in the major alluvial systems and watercourses (Figure 7). In alluvial areas outside the Condamine Alluvium, river stages are set at modelled ground level, which 'effectively assumes that all surface watercourses act as discharge boundaries and hence cannot leak is considered to be a conservative assumption from an impact point of view. This assumption is consistent with work undertaken by Hillier (2010) which suggested that alluvial strata within the GAB typically act as a drain for the underlying sediments' (GHD, 2012, p. 57). The MODFLOW River package reports baseflow (discharge to stream) water balances for each River cell. In this way, the OGIA model water balance can be used to make conservative estimates of changes to baseflow volumes for major alluvial systems and watercourses represented in the model.

The Condamine Alluvium is modelled using an integrated approach, where calibrated values of aquifer thickness and hydraulic parameters, and time-variant water level conditions from the detailed transient Condamine Model (KCB, 2011) are imported into the regional model (QWC, 2012). Groundwater levels calibrated to historical water level conditions in the detailed Condamine Alluvium model are used to define MODFLOW River cell elevations in the regional model. The Condamine Model is used to estimate impacts on groundwater levels in the Condamine Alluvium that result from the change in flow from the Condamine Alluvium to the Walloon Coal Measures predicted by the regional model (QWC, 2012).

Temporary watercourses that are losing or losing – disconnected with respect to the underlying aquifer are represented in the model by Drain cells that cover the rest of the active model domain. Drain cell elevations are set at modelled ground level, which assumes that all temporary watercourses represented by Drain cells act as groundwater discharge boundaries.

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2.6.2.5 *Implementation of coal resource development pathway*

Summary

Numerical groundwater modelling results are primarily presented as the difference in groundwater drawdown between two possible futures – the baseline and the coal resource development pathway (CRDP). In bioregional assessments (BA) the baseline includes all coal mines and CSG fields that are commercially producing as of December 2012. The CRDP includes all baseline plus any additional coal resource developments (ACRD) continuing into the future. The ACRD is defined as all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012. The Maranoa-Balonne-Condamine subregion coal resource development pathway (CRDP) includes five baseline open-cut coal mines, five baseline coal seam gas (CSG) projects and two open-cut coal mine project proposals.

Open-cut coal mines are represented in the revised Office of Groundwater Impact Assessment (OGIA) model using the MODFLOW Drain package. The five baseline coal mines are: Cameby Downs Mine, Commodore Mine, Kogan Creek Mine, New Acland Coal Mine Stage 2 and Wilkie Creek Mine (which ceased operations in December 2013). The two proposed coal mines are: New Acland Coal Mine Stage 3 and The Range. For each mine, OGIA and the Assessment team used publicly available information to delineate the extent of operational and proposed pits to represent coal mines in the revised OGIA model. The Drain cell elevation in the model layer representing the Walloon Coal Measures is set to either the mean coal seam depth or the bottom of the model grid cell. This approach means that groundwater levels are drawn down over the entire model grid cell where a pit is present, which may tend to overestimate groundwater drawdown associated with open-cut mine pit dewatering.

Groundwater extraction associated with CSG is simulated in the OGIA model using the MODFLOW EVT package. The five baseline CSG projects are: Australia Pacific LNG Project, Queensland Curtis LNG Project, Santos Gladstone LNG and GLNG Gas Field Development projects, Surat Gas Project and Ironbark Project. To ensure consistency with OGIA reporting, the baseline includes all CSG projects in the Maranoa-Balonne-Condamine subregion that are reported in the 2014 annual report for the Surat cumulative management area. The OGIA model includes information on historical and predicted future CSG extraction rates provided to OGIA by the tenure holders each year.

Numerical groundwater modelling results are primarily presented as the difference in groundwater drawdown between two possible futures – the baseline and the coal resource development pathway (CRDP). In bioregional assessments (BAs), the CRDP includes all baseline plus any additional coal resource development (ACRD) continuing into the future. The baseline is defined as a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012. The ACRD is defined as all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012. To ensure consistency with Office of Groundwater Impact

Assessment (OGIA) reporting, the baseline includes all CSG projects in the Maranoa-Balonne-Condamine subregion that are reported in the 2014 annual report for the Surat cumulative management area (CMA) (OGIA, 2014).

The Maranoa-Balonne-Condamine subregion CRDP includes five baseline open-cut coal mines, five baseline CSG projects and two open-cut coal mine project proposals. The CRDP is informed by companion product 1.2 for the Maranoa-Balonne-Condamine subregion (Sander et al., 2014) and is described in more detail in companion product 2.3 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2016). The CRDP is based on information available as of July 2015 and was finalised after feedback provided at the CRDP workshop that was held in December 2014 in Toowoomba. The location and development timeline of the coal resource development projects represented in the numerical groundwater model for the Maranoa-Balonne-Condamine subregion are shown in Figure 9 and Figure 10, respectively.

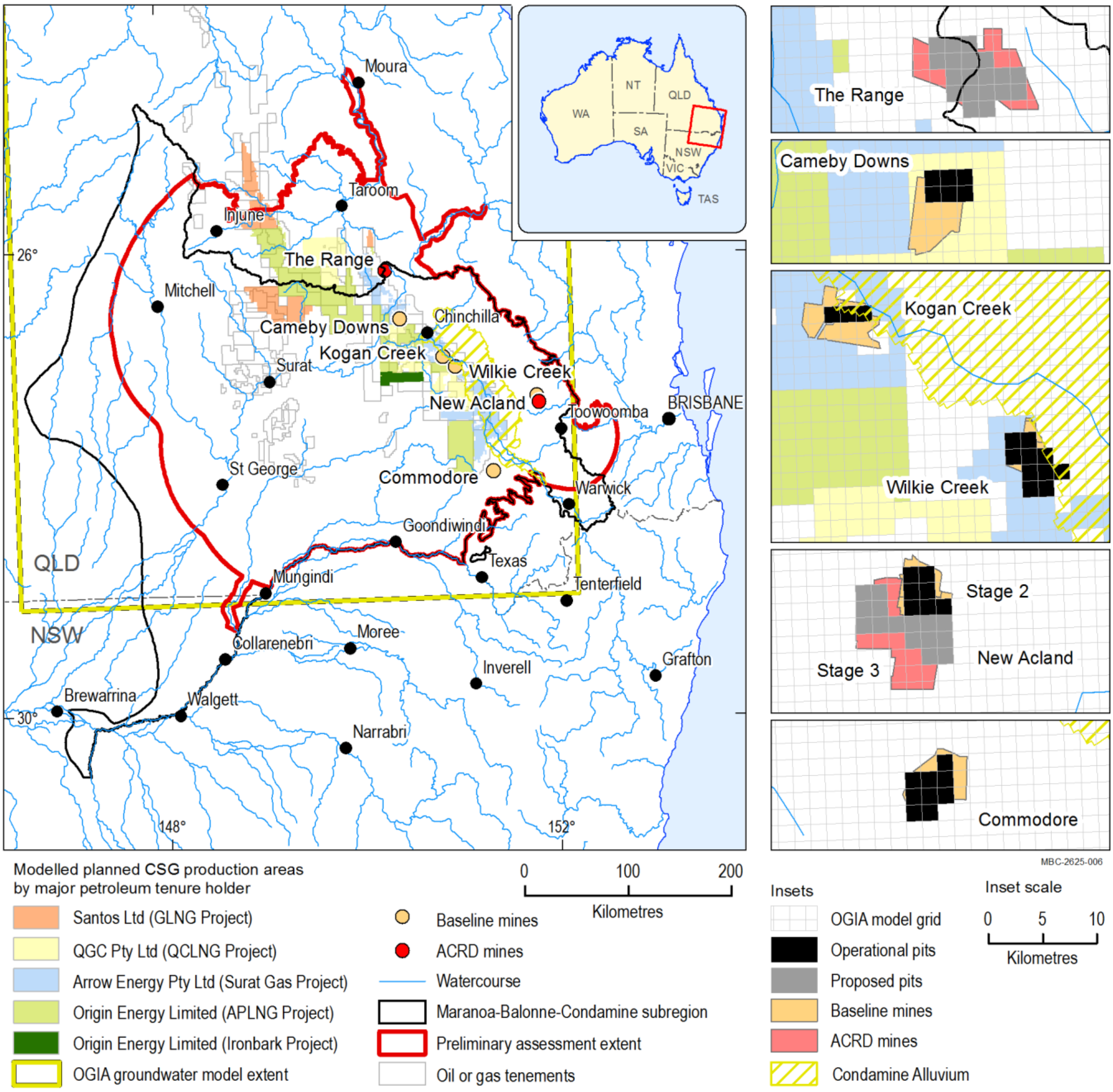

Figure 9 Modelled coal resource development in the Maranoa-Balonne-Condamine subregion

In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled. ACRD = additional coal resource development, APLNG Project = Australia Pacific LNG Project , LNG = Liquefied Natural Gas, OGIA = Office of Groundwater Impact Assessment, QCLNG Project = Queensland Curtis LNG Project , QGC = Queensland Gas Company, GLNG Project = Santos Gladstone LNG Project + GLNG Gas Field Development Project

Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3), Office of Groundwater Impact Assessment (Dataset 4).

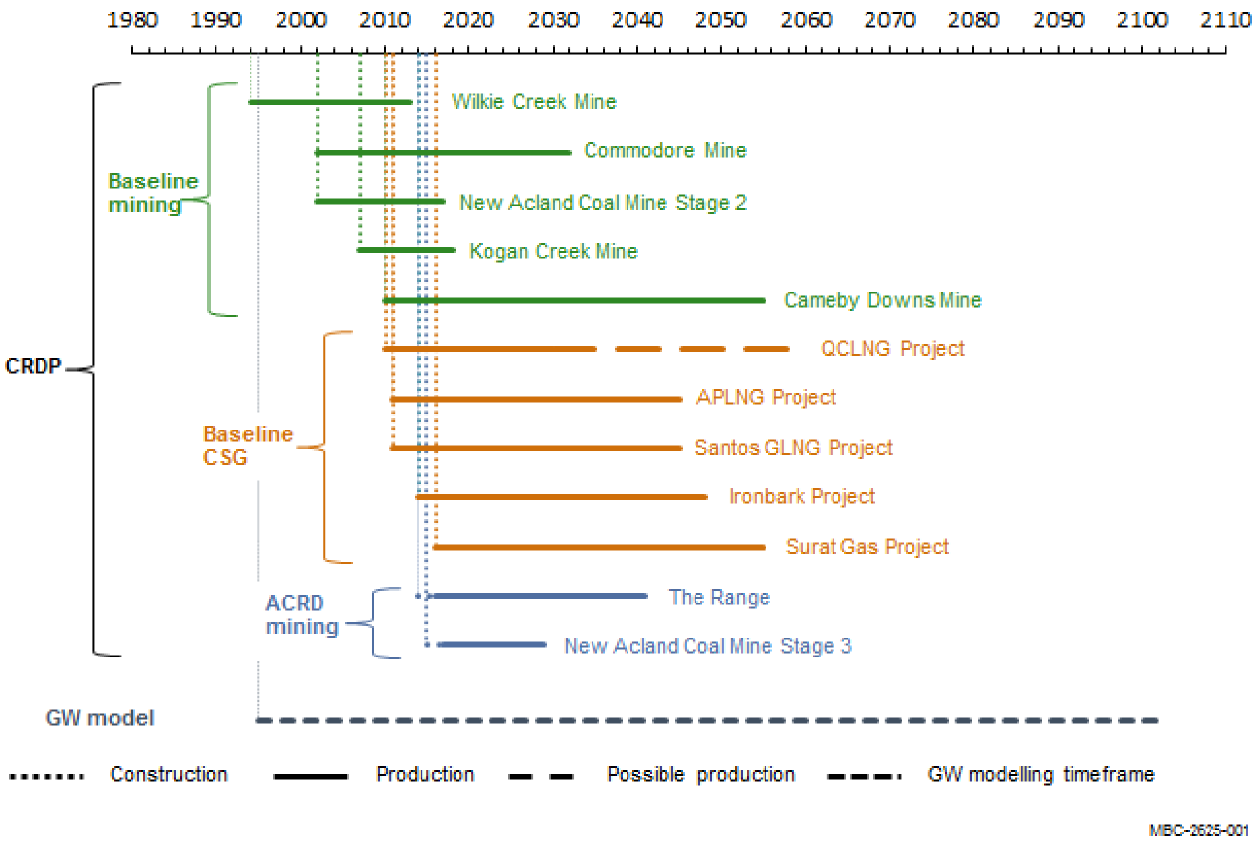

Figure 10 Timeline for coal resource development and the groundwater model in the Maranoa-Balonne-Condamine subregion

In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled. Construction and production are assumed to occur concurrently due to the staged development process of the coal seam gas development projects.

ACRD = additional coal resource development, APLNG Project = Australia Pacific LNG Project, GW = groundwater, LNG = Liquefied Natural Gas, QCLNG Project = Queensland Curtis LNG Project, QGC = Queensland Gas Company, Santos GLNG Project = Santos Gladstone LNG Project + GLNG Gas Field Development Project

2.6.2.5.1 Open cut mines

The five baseline coal mines are: Cameby Downs Mine, Commodore Mine, Kogan Creek Mine, New Acland Coal Mine Stage 2 and Wilkie Creek Mine (which ceased operations in December 2013). The two proposed coal mines in the CRDP are: New Acland Coal Mine Stage 3 and The Range. Table 5 summarises the open-cut coal mines modelled in the Maranoa-Balonne-Condamine subregion.

Table 5 Open-cut coal mines modelled in the Maranoa-Balonne-Condamine subregion

In this table, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.

Project name	Company	Tenement(s)	Timeline	Mine pit area (ha)	Target seam depth (m BGL)	Estimated water extraction (ML/year)	Comments
Cameby Downs Mine	Yancoal Australia Ltd	ML 50233	Baseline (2010–2055)	15	50–60	36.5	Operating mine
Commodore Mine	InterGen Australia Pty Ltd and Marubeni Corporation / Downer EDI Mining	ML 50151	Baseline (2002–2032)	40	70–80*	no data available	Operating mine
Kogan Creek Mine	Aberdare Collieries Pty Ltd	ML 50074	Baseline (2007–2018)	100	70–80	140–150	Operating mine
New Acland Coal Mine Stage 2	New Hope Group	ML 50170, 50216	Baseline (2002–2017)	55	30–60	110–150	Operating mine
Wilkie Creek Mine	Peabody Energy Inc	ML 5908, 50208, 50214, 50215	Baseline (1994–2013)	20	no data available	no data available	Mine closed
New Acland Coal Mine Stage 3	New Acland Coal Pty Ltd	MLA 50232	ACRD (2015–2029)	75*	50–80*	180–1280	Mine expansion subject to approval
The Range	Stanmore Coal Limited	MLA 55001	ACRD (2014–2041)	50*	60*	150–490	Approved mine

ACRD = additional coal resource development, BGL = below ground level, ML = mining lease, MLA = mining lease application, * = estimated

A conservative approach is used to simulate mine pit dewatering to account for the relatively coarse regional-scale model grid (1.5 km × 1.5 km grid cells). The MODFLOW Drain package is used to set the boundary conditions in the model cells corresponding to the mine pit footprints. For each mine, OGIA and the Assessment team used publicly available information to delineate the extent of operational and proposed pits, referred to as mine footprints, to represent coal mines in the revised OGIA model (Table 5). All model grid cells intersected by operational and proposed pit extents are assumed to be part of the modelled open-cut coal mine. The model grid cells for each of the modelled operational and proposed mine pits are shown in the insets in Figure 9.

It is assumed that mine pits are dewatered to the depth of the coal seams to enable coal mining operations. This is represented in the groundwater model by activating and deactivating the Drain cells to replicate the modelled development timeline shown in Figure 10. The Drain cell elevation in the Walloon Coal Measures model layer (Layer 10) is set to either the mean coal seam depth or, if the mean coal seam depth is below the bottom elevation of the model cell, then the Drain cell elevation is set to the bottom of the model grid cell. This means that the groundwater model draws the groundwater level down over the entire model grid cell where a pit is present and does not adjust for the proportion of the grid cell covered by the actual pit area. This approach may tend to overestimate groundwater drawdown associated with open-cut coal mine pit dewatering.

2.6.2.5.2 Coal seam gas wells

Five baseline CSG projects are modelled in the Maranoa-Balonne-Condamine subregion (Figure 9). This includes three large-scale gas field developments supporting the three liquefied natural gas (LNG) projects on Curtis Island near Gladstone. These projects are considered to be baseline development, being commercially producing as of December 2012. The Queensland Curtis LNG (QCLNG) Project commenced in 2010, Australia Pacific LNG (APLNG) Project in 2011 and Santos Gladstone LNG (GLNG) Project in 2011. The Surat Gas Project and the Ironbark project have planned commencement dates after December 2012 and so do not meet the baseline definition for bioregional assessments (BAs). However, these two projects are reported in the Surat underground water impact report (UWIR) (QWC, 2012) and annual report (OGIA, 2014) based on information provided to OGIA by the tenure holders each year. Therefore, to ensure consistency with OGIA reporting, all five CSG projects in the Maranoa-Balonne-Condamine subregion that are represented in the current OGIA model (QWC, 2012) and reported in the 2014 annual report (OGIA, 2014) are considered to be part of the baseline for this Assessment. Table 6 summarises the CSG projects modelled by OGIA for this Assessment, including all CSG and conventional petroleum tenements.

Table 6 Coal seam gas projects modelled in the Maranoa-Balonne-Condamine subregion

In this table, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.

Project name	Company	Tenements	Timeline	Comments
Australia Pacific LNG Project	Australia Pacific LNG Pty Limited	PL 209, 215, 226, 265, 266, 267, 272, 297, 404, 408; ATP 606, 663, 692, 972, 973	Baseline (2011–2045)	CSG tenements located within the Maranoa-Balonne-Condamine subregion
Australia Pacific LNG Project	Australia Pacific LNG Pty Limited	PL 101, 195, 200, 203, 204, 219, 220, 297, 404, 408, 417 41, 42, 43, 44, 45, 54, 67, 173, 183, 218	OGIA 2014 P&G Production Run (2011–2045)	CSG tenements included in the OGIA model that are outside the subregion
Other	Origin Energy Limited	PL 14, 21, 22, 27, 30, 53, 70, 71, 74, 174, 227, 264	Baseline (2011–2045)	Conventional P&G tenements included in the OGIA model
Santos Gladstone LNG Project + GLNG Gas Field Development Project	Santos GLNG Pty Ltd	PL 3, 6, 7, 8, 9, 13, 93, 309, 310, 314, 315, 10, 11; ATP 336, 631	Baseline (2011–2045)	CSG tenements located within the Maranoa-Balonne-Condamine subregion
Santos Gladstone LNG Project + GLNG Gas Field Development Project	Santos GLNG Pty Ltd (Arcadia, Fairview, and Scotia gas fields)	PL 90, 91, 92, 99, 100, 176, 232, 233, 234, 235, 236; ATP 526, 653	OGIA P&G Production Run (2011–2045)	CSG tenements included in the OGIA model that are outside the subregion
Other	Santos Ltd	PL 1, 2, 12, 28, 69, 89	OGIA P&G Production Run (2011–2045)	Conventional P&G tenements located within the Maranoa-Balonne-Condamine subregion
Queensland Curtis LNG Project	QGC Pty Limited (BG Group)	PL 179, 180, 201, 211, 212, 228, 229, 247, 257, 262, 273, 274, 275, 276, 277, 278, 279, 442, 443, 474, 458, 459, 461, 466, 472; ATP 574, 621, 632, 648	Baseline (2010–2030) (maximum 2060)	CSG tenements located within the Maranoa-Balonne-Condamine subregion
Queensland Curtis LNG Project	QGC Pty Limited (BG Group)	PL 171, 263, 398, 399, 401, 464, 467; ATP 647, 768	OGIA P&G Production Run (2011–2045)	CSG tenements included in the OGIA model that are outside the subregion
Surat Gas Project	Arrow Energy Pty Ltd	PL 194, 198, 230, 238, 252, 258, 260; ATP 676, 683, 746, 474, 747, 810	Baseline (2014–2048)	CSG tenements located within the Maranoa-Balonne-Condamine subregion

Project name	Company	Tenements	Timeline	Comments
Ironbark Project	Origin Energy Limited	ATP 788	Baseline (2016–2055)	CSG tenement located within the Maranoa-Balonne-Condamine subregion
Other	Ranger Energy Pty Ltd	PL 46 oil	OGIA P&G Production Run	Conventional P&G tenement included in the OGIA model
Bris	Brisbane Petroleum Ltd	PL 18 gas PL 40 oil PL 280 petroleum	OGIA P&G Production Run	Conventional P&G tenements included in the OGIA model
Southern	Southern Cross Petroleum and Exploration Pty Ltd	PL 17 oil	OGIA P&G Production Run	Conventional P&G tenement included in the OGIA model

ATP = authority to prospect, MLA = mining lease application, ML = mining lease, OGIA = Office of Groundwater Impact Assessment, PL = petroleum lease, P&G = Petroleum & Gas

The Surat Gas Project includes expansion of production at existing CSG fields operated by Arrow Energy Pty Ltd, including Stratheden, Kogan North, Daandine and Tipton West. While still undergoing formal approval, the staged expansion plans have been included in the OGIA model based on information provided to OGIA by the tenure holders each year. Projected water extraction from the expanded Surat Gas Project ranges from 13–35,000 ML/year over the 6100 km^2 development area (Arrow Energy, 2013).

Origin Energy Limited's Ironbark Project currently consists of a number of pilot CSG wells, appraisal wells and monitoring wells and therefore does not meet the baseline definition. However, it is included in the current OGIA model with a planned commencement date of 2016 based on information provided to OGIA by the tenure holders each year. The Ironbark Project occupies a relatively small area along the southern boundary of the Queensland Gas Company (QGC) central development area (Figure 11). Water extraction estimates are not publically available for the Ironbark Project at this time.

Projected additional water extraction from these two development projects represents a relatively small proportion of the 95,000 ML/year total water extracted from the Surat cumulative management area for petroleum and gas (P&G) production (and the Maranoa-Balonne-Condamine subregion) (QWC, 2012). The extraction volumes and their location among existing development projects mean that the consequences of their inclusion in the baseline for this Assessment are considered to be negligible. Therefore, the Surat Gas and Ironbark projects are both considered part of the baseline for this Assessment to ensure consistency with the Surat UWIR (QWC, 2012) and annual report (OGIA, 2014).

The planned commencement and cessation dates for each development that are provided to OGIA by the tenure holders each year are implemented in the OGIA model using the MODFLOW EVT package to represent groundwater extraction associated with CSG activities within each model grid cell. Optimal gas flow is typically achieved from CSG wells when the groundwater pressure is approximately 35–40 m above the coal seam. Maximum water extraction occurs in the initial years and the volume of water extracted reduces exponentially with time (QWC, 2012). The EVT package provides a convenient means by which a user-defined volume of water can be removed from the model that is constrained by additional control on the groundwater pressure. Figure 11 shows the planned commencement and Figure 12 the planned cessation of CSG production in the Surat CMA (OGIA, 2014). As gas field development is a progressive process, the tenements are not all developed and produced at the same time, but the process will occur in stages.

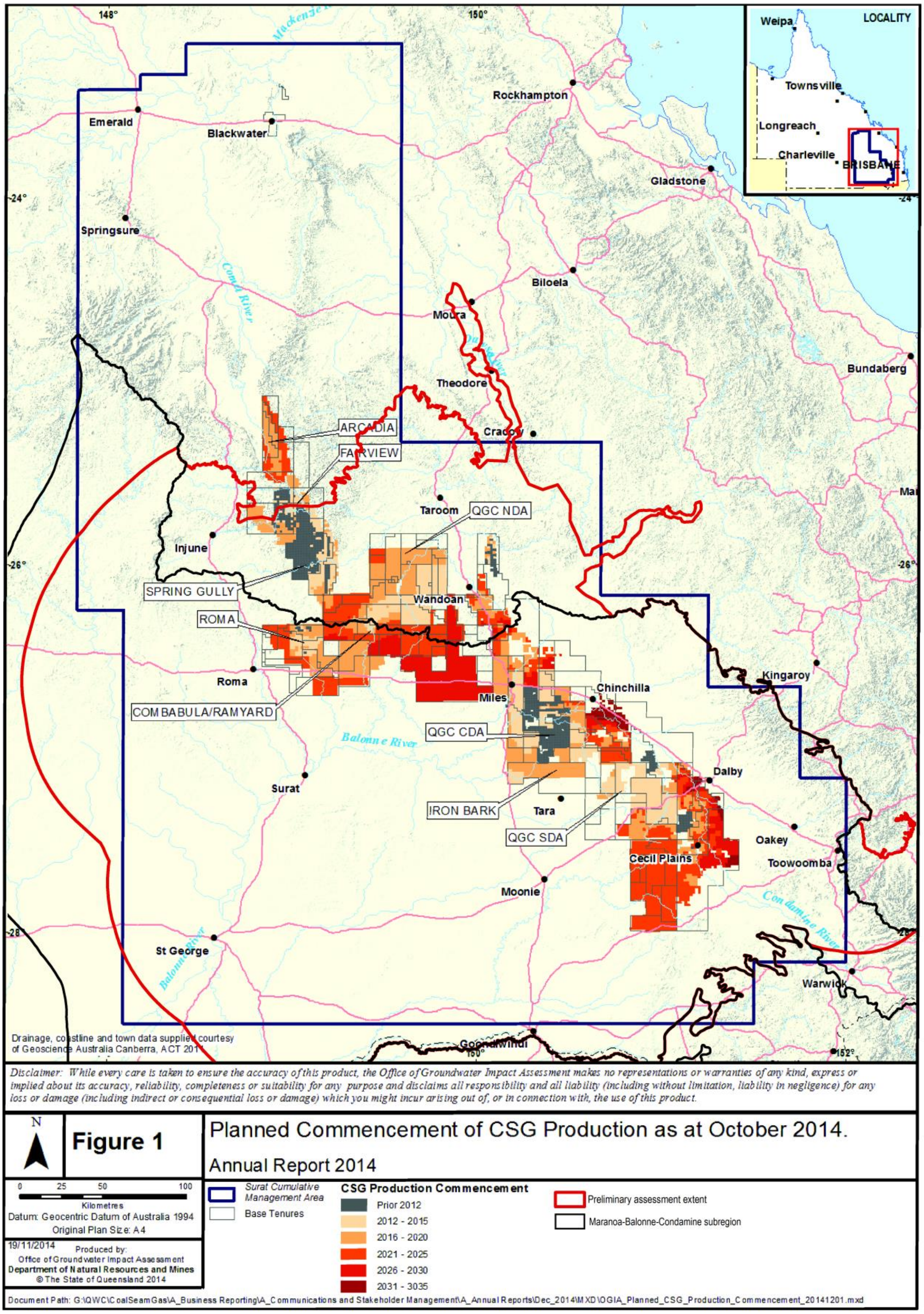

Figure 11 Planned commencement of coal seam gas production for the Maranoa-Balonne-Condamine subregion

In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled. CDA = Central Development Area, CSG = coal seam gas, NDA = Northern Development Area, QGC = Queensland Gas Company, SDA = Southern Development Area

Source: adapted from Figure 1 Planned commencement of CSG production as at October 2014 in OGIA (2014)

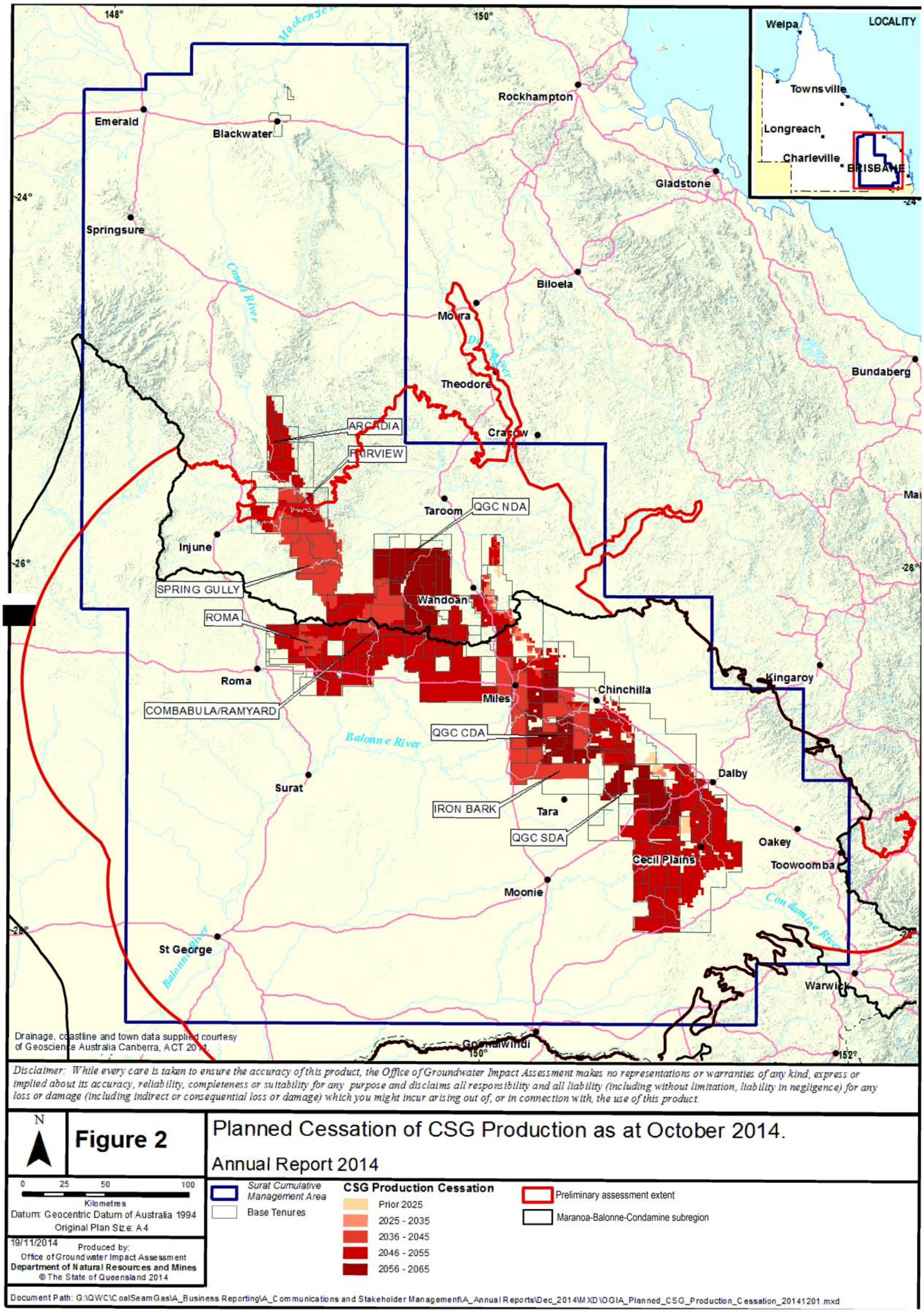

Figure 12 Planned cessation of coal seam gas production for the Maranoa-Balonne-Condamine subregion

In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled. CDA = Central Development Area, CSG = coal seam gas, NDA = Northern Development Area, QGC = Queensland Gas Company, SDA = Southern Development Area

Source: adapted from Figure 1 Planned cessation of CSG production as at October 2014 in OGIA (2014)

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Datasets

Dataset 1 Bioregional Assessment Programme (2015) MBC Groundwater model domain boundary. Bioregional Assessment Derived Dataset. Viewed 20 April 2016, http://data.bioregionalassessments.gov.au/dataset/54720636-9fe5-4c13-8be5-4195e5e58a96.

Dataset 2 Bioregional Assessment Programme (2015) MBC Groundwater model mine pit cells. Bioregional Assessment Derived Dataset. Viewed 20 April 2016, http://data.bioregionalassessments.gov.au/dataset/0e47f3ed-0c3b-4fa4-8e95-003edef6a313.

Dataset 3 Bioregional Assessment Programme (2015) Production Tenures within the Surat CMA. Bioregional Assessment Derived Dataset. Viewed 19 April 2016, http://data.bioregionalassessments.gov.au/dataset/0e93c000-6e4d-46d4-90de-b1a1a53ab177.

Dataset 4 Office of Groundwater Impact Assessment (2015) Coal Seam Gas company development proposals. Bioregional Assessment Source Dataset. Viewed 20 April 2016, http://data.bioregionalassessments.gov.au/dataset/297b5b8b-5138-4de9-acf3-c9301428052a.

2.6.2.6 Parameterisation

Summary

The Office of Groundwater Impact Assessment (OGIA) model is calibrated to replicate long-term groundwater conditions pre 1995 (i.e. pre coal seam gas (CSG) extraction). Model calibration is carried out using the parameter estimation (PEST) suite of software in three steps. Firstly, a preliminary calibration of the steady-state regional model is used to provide initial heads and boundary conditions for the transient sub-model. Secondly, the transient sub-model is calibrated using detailed groundwater level data for the Walloon Coal Measures near the existing Kogan North/Daandine CSG field. Finally, the steady-state regional model is recalibrated using calibrated hydraulic conductivity values from the calibration of the transient sub-model.

The calibrated horizontal hydraulic conductivity values for the main aquifer layers are generally higher than for the aquitard layers. Specific storage (Ss) varies spatially in the Walloon Coal Measures and is constrained by observed groundwater levels in the transient sub-model area. A constant storage value is used for other confined model layers. Specific yield is used to define unconfined storage values for the aquifer outcrop areas, Condamine Alluvium, Main Range Volcanics and alluvium outside the Condamine area.

The Great Artesian Basin comprises an alternating sequence of permeable sandstone aquifers and lower permeability siltstone and mudstone aquitards in the Surat cumulative management area (CMA). Flow in the aquifers is dominated by subhorizontal flow (QWC, 2012), which is governed by the horizontal hydraulic conductivity (Kh). Vertical leakage from the aquifers through the low permeability aquitards, which occurs at a much slower rate (QWC, 2012) is governed by the vertical hydraulic conductivity (Kv) of the aquitards. Storage values represent the capacity of an aquifer to release groundwater, where specific storage (Ss) relates to confined aquifers and specific yield (Sy) relates to unconfined aquifers. Parameter values are estimated during model calibration and uncertainty analysis as summarised below and described in GHD (2012):

> ‘Calibration of the steady-state regional model and transient sub-model was carried out using the PEST suite of software (Doherty, 2010) and adopting the following overall framework:
>
> 1. A preliminary calibration of the steady-state regional model to provide initial heads and boundary conditions for the transient sub-model;
> 2. Calibration of the transient sub-model using detailed groundwater level data for the WCM in the vicinity of the existing Kogan North/Daandine CSG gas field; and
> 3. Re-calibration of the steady-state regional model but this time adopting calibrated hydraulic conductivity values for the WCM (model layers 9, 10 and 11) from the transient calibration within the sub-model area.’ (GHD, 2012, p. 72)

Preliminary calibration of the steady-state Office of Groundwater Impact Assessment (OGIA) model replicated long-term mean conditions pre 1995 (i.e. pre coal seam gas (CSG) extraction) through reference to mean groundwater levels from 1541 boreholes (GHD, 2012). This approach maximises the size of the data set by collating information from a number of different sources, completing missing information on the strata monitored by each bore and calibrating to average groundwater levels at each bore largely independent of the date of the reading (GHD, 2012). GHD (2012) states that '… while there are some notable exceptions, these plots also suggest a general lack of long-term trends in groundwater levels, particularly post 1960. The use of calibration targets based on average groundwater levels is therefore not considered likely to bias the model calibration significantly.'

Modelled hydraulic conductivity and storage parameters were refined during the calibration process by adjusting initial hydraulic conductivity values within the adopted permissible range to minimise overall residuals in each layer (GHD, 2012). Further refinement of these parameter values was then achieved using pilot points that were adjusted to reduce the residual errors further. The calibrated mean hydraulic conductivity values for the main aquifer layers are generally higher than for the aquitard layers. Further pilot points were used to adjust the conductance of the General Head Boundary (GHB) cells located at the southern and eastern boundaries of the regional model (GHD, 2012). Table 7 lists the minimum, average and maximum Kh and Kv calibrated values used in the predictive model runs and uncertainty analysis.

Storage values for both the Walloon Coal Measures and the Bandanna Formation model layers are not well calibrated, since only limited transient calibrations have been possible to date (GHD, 2012). A more detailed transient sub-model is used to calibrate specific yield (Sy) and specific storage (Ss) parameter values for the Walloon Coal Measures model layers. The transient sub-model is constructed using 250 m × 250 m cells around the existing Daandine Coal Seam Gas Project production field, which has been operational since 2005 and where detailed groundwater levels are available. Storage values are varied spatially in the productive coal layers (Walloon Coal Measures and Bandanna Formation) based on a relationship with depth and constrained by previously modelled data. 'As observed groundwater levels were only available for the productive coal of the WCM (model layer 10) in the Kogan North/Daandine area, only the storage value for this layer can be considered to have been calibrated using this model' (GHD, 2012). A constant storage value for other model layers is assumed to be 5.0 x 10^{5} (m^{-1}). Storage values for the aquifer outcrop areas, Condamine Alluvium, Main Range Volcanics and alluvium outside the Condamine area (i.e. unconfined storage) are based on specific yield estimates. Table 7 lists the adopted storage values for each OGIA model layer.

Table 7 Calibrated hydraulic conductivity (minimum, average, maximum) and storage values used in the predictive Office of Groundwater Impact Assessment (OGIA) model

Dominant unit	Model layer	Min Kh (m/d)	Ave Kh (m/d)	Max Kh (m/d)	Min Kv (m/d)	Ave Kv (m/d)	Max Kv (m/d)	Sy (-)	Ss (m^{-1})
Condamine Alluvium	1	1.90x10^{0}	1.60x10^{1}	4.00x10^{1}	1.90x10^{0}	1.60x10^{1}	4.00x10^{1}	1.60x10^{1}	NA
Main Range Volcanics	1	3.70x10^{4}	1.10x10^{-1}	1.70x10^{0}	1.50x10^{-6}	4.40x10^{-4}	6.90x10^{-3}	4.40x10^{-4}	NA
Alluvium outside Condamine area	1	3.70x10^{-4}	1.80x10^{1}	5.00x10^{1}	1.50x10^{-6}	2.70x10^{0}	4.00x10^{1}	2.70x10^{0}	NA
Rolling Downs Group	2	5.50x10^{-3}	2.10x10^{-2}	9.40x10^{-2}	5.50x10^{-6}	2.10x10^{-5}	9.40x10^{-5}	2.10x10^{-5}	5.0x10^{-5}
Bungil/Mooga Sandstone	3	3.30x10^{-1}	1.50x10^{0}	5.00x10^{0}	1.80x10^{-2}	8.10x10^{-2}	2.70x10^{-1}	8.10x10^{-2}	5.0x10^{-5}
Orallo Formation	4	1.00x10^{-2}	3.20x10^{-2}	3.70x10^{-1}	1.00x10^{-5}	3.20x10^{-5}	3.70x10^{-4}	3.20x10^{-5}	5.0x10^{-5}
Gubberamunda Sandstone	5	4.90x10^{-2}	6.90x10^{-1}	5.00x10^{0}	3.90x10^{-3}	5.50x10^{-2}	3.90x10^{-1}	5.50x10^{-2}	5.0x10^{-5}
Westbourne Formation	6	2.50x10^{-4}	1.40x10^{-3}	2.80x10^{-2}	1.00x10^{-6}	5.70x10^{-6}	1.10x10^{-4}	5.70x10^{-6}	5.0x10^{-5}
Springbok Sandstone	7/8	1.70x10^{-3}	6.50x10^{-1}	5.00x10^{0}	2.90x10^{-4}	1.10x10^{-1}	8.40x10^{-1}	1.10x10^{-1}	5.0x10^{-5}
Walloon Coal Measures (Upper Aquitard)	9	4.00x10^{-7}	6.10x10^{-4}	4.00x10^{-3}	1.00x10^{-8}	1.50x10^{-5}	1.00x10^{-4}	1.50x10^{-5}	5.0x10^{-5}
Walloon Coal Measures (Productive coal)	10	2.10x10^{-5}	3.10x10^{-2}	1.00x10^{0}	1.00x10^{-8}	6.00x10^{-6}	1.00x10^{-4}	6.00x10^{-6}	1.0x10^{-7} to 3.4x10^{-5}
Walloon Coal Measures (Lower Aquitard)	11	1.70x10^{-6}	2.20x10^{-3}	8.50x10^{-3}	2.00x10^{-8}	2.60x10^{-5}	1.00x10^{-4}	2.60x10^{-5}	5.0x10^{-5}
Hutton Sandstone	12	1.00x10^{-4}	5.20x10^{-1}	5.00x10^{0}	5.40x10^{-6}	2.80x10^{-2}	2.70x10^{-1}	2.80x10^{-2}	5.0x10^{-5}
Evergreen Formation	13	2.30x10^{-5}	1.30x10^{-4}	8.80x10^{-4}	1.00x10^{-7}	5.70x10^{-7}	3.90x10^{-6}	5.70x10^{-7}	5.0x10^{-5}
Precipice Sandstone	14	9.80x10^{-3}	3.40x10^{-1}	5.00x10^{0}	7.40x10^{-4}	2.60x10^{-2}	3.80x10^{-1}	2.60x10^{-2}	5.0x10^{-5}
Moolayember Formation	15	3.70x10^{-6}	1.40x10^{-3}	1.40x10^{0}	3.60x10^{-7}	1.30x10^{-4}	1.10x10^{-1}	1.30x10^{-4}	5.0x10^{-5}
Clematis Sandstone	16	7.60x10^{-4}	2.00x10^{-1}	5.00x10^{0}	1.00x10^{-4}	2.70x10^{-2}	6.90x10^{-1}	2.70x10^{-2}	5.0x10^{-5}
Rewan Group	17	1.00x10^{-4}	5.40x10^{-2}	1.40x10^{0}	1.00x10^{-7}	9.70x10^{-5}	1.10x10^{-1}	9.70x10^{-5}	5.0x10^{-5}
Bandanna Formation	18	1.00x10^{-5}	3.20x10^{-2}	1.00x10^{0}	2.00x10^{-9}	6.40x10^{-6}	2.00x10^{-4}	6.40x10^{-6}	1.0x10^{-7} to 3.4x10^{-5}
Pre-Bandanna Age Units	19	5.00x10^{-7}	8.50x10^{-6}	5.00x10^{-3}	5.00x10^{-8}	8.50x10^{-7}	5.00x10^{-4}	8.50x10^{-7}	5.00x10^{-5}

Ave = average, Kh = horizontal hydraulic conductivity values, Kv = vertical hydraulic conductivity values, Max = maximum, Min = minimum, NA = not applicable, Ss = specific storage, Sy = specific yield

Source: Table 18 Calibrated values - Horizontal hydraulic conductivity, Table 19 Calibrated values - Vertical hydraulic conductivity, Table 28 Predictive modelling - Adopted storage values (GHD, 2012)

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2.6.2.7 Observations and predictions

Summary

The regional steady-state model, which is intended to replicate long-term average conditions pre 1995 (i.e. pre coal seam gas (CSG) extraction), was calibrated to average groundwater levels from 1541 boreholes. Pre-1995 groundwater levels represent a period before significant CSG and open-cut coal mine development in the Surat cumulative management area (CMA). For this reason, the Office of Groundwater Impact Assessment (OGIA) model was not recalibrated when the open-cut coal mine boundary conditions were added for the bioregional assessment (BA) groundwater modelling in the Maranoa-Balonne-Condamine subregion. Calibration of the regional steady-state model and transient sub-model using the parameter estimation (PEST) suite of software considered model sensitivity to different combinations of parameters, representation of the Walloon Coal Measures, recharge estimates and model robustness.

For each bore, the OGIA model produces a time series of drawdown caused by the historical and baseline coal resource development (baseline) conditions and a time series of additional drawdown caused by the historical and coal resource development pathway (CRDP) conditions. Two measures are used to summarise these time series: dmax, the maximum difference between the baseline and CRDP drawdown; and tmax, the time when maximum drawdown occurs.

The water balance assessment presents a quantitative water balance for the Maranoa-Balonne-Condamine subregion for both the baseline and CRDP futures in order to quantify the effects of depressurisation of the coal seams for CSG production and mine pit dewatering. The water balance is reported for a defined control volume that includes all model grid cells where additional drawdown is greater than the minimum detectable difference (0.02 m) for the groundwater model.

Modelled *CSG water production* in The Range water balance area falls from 17% to 0% of modelled losses following modelled cessation of CSG production in 2065. Coal mine dewatering accounts for 2% of modelled losses in the first 30-year period and zero after modelled mine closure in 2041. In the New Acland Coal Mine water balance area, *CSG water production* falls from 3% to 0% of modelled losses over successive 30-year periods following modelled cessation of CSG production in 2065. Modelled coal mine dewatering during mine operation (2012 to 2029, 0.85 GL/year) is consistent with values reported in the New Acland Coal Mine Stage 3 environmental impact assessment documents (maximum of 1.4 GL/year).

2.6.2.7.1 Observation data

The primary purpose of the Office of Groundwater Impact Assessment (OGIA) model is to predict the regional water pressure and water level changes in aquifers within the Surat cumulative management area (CMA) in response to depressurisation of the coal seams for coal seam gas (CSG) production. GHD (2012, p. 74) states:

> 'Calibration of the regional steady-state model, which is intended to replicated [sic] long-term average conditions pre 1995 (i.e. pre CSG extraction), was undertaken through reference to average groundwater levels from 1,541 boreholes.'

Pre-1995 groundwater levels represent a period before significant CSG extraction and open-cut coal mine development in the Surat CMA. The Wilkie Creek Coal Mine commenced production in 1994, but is unlikely to have significantly affected the regional groundwater levels used in model calibration. For this reason, the OGIA model was not recalibrated when the open-cut coal mine boundary conditions were added for the bioregional assessment (BA) groundwater modelling in the Maranoa-Balonne-Condamine subregion.

> 'Storage values were calibrated, as far as possible, using the transient sub-model developed for the Kogan North and Daandine well-field. As observed groundwater levels were only available for the productive coal of the WCM (model layer 10) in the Kogan North/Daandine area, only the storage value for this layer can be considered to have been calibrated using this model' (GHD, 2012, p. 93).

2.6.2.7.2 Predictions

For each bore, the OGIA model produces a time series of drawdown caused by the historical and baseline coal resource development (baseline) conditions and a time series of additional drawdown caused by the historical and coal resource development pathway (CRDP) conditions. The effect of implementing the CRDP, is the difference between these two time series. Two measures are used to summarise this time series: dmax and tmax. The maximum change in drawdown in the simulation period is dmax – that is, the maximum difference between the baseline and CRDP drawdown. Therefore, dmax can be either positive or negative. The time when this maximum drawdown occurs is tmax.

Figure 13 shows one of 200 possible realisations of the two possible coal resource development pathway futures from the calibrated predictive model. It plots groundwater drawdown through time from 1995 to 2102 for the baseline and CRDP. In this example, the maximum difference in drawdown between the baseline and CRDP is shown for bores in the Walloon Coal Measures, Hutton Sandstone and Main Range Volcanics model layers. In these examples, less than 0.35 m additional drawdown is predicted at RN30203 in the Walloon Coal Measures, less than 1.5 m additional drawdown is predicted at RN66782 in the Hutton Sandstone and over 5 m of additional drawdown is predicted at RN87532 in the Main Range Volcanics aquifer. The magnitude and timing of additional drawdown is a function of the distance of the bore from the modelled additional coal resource development (two open-cut coal mines) and modelled hydraulic properties.

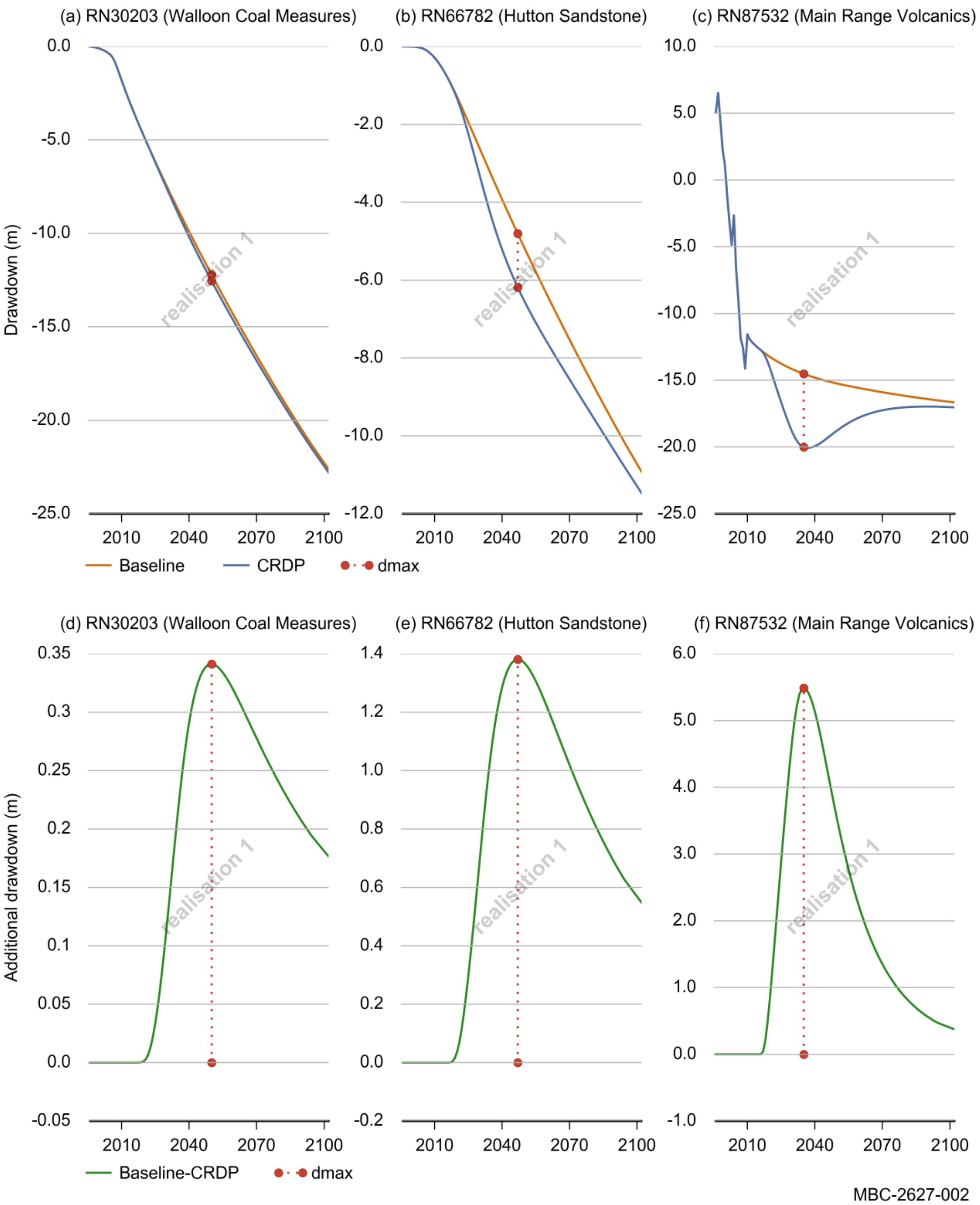

Figure 13 Example of regional groundwater model output time series for the baseline and coal resource development pathway (CRDP) model runs for three groundwater bores (receptors) in the Maranoa-Balonne-Condamine subregion

In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
dmax = maximum change in drawdown
Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.7.3 Sensitivity analysis

Model sensitivity to different combinations of parameters was assessed during calibration of the regional steady-state model and transient sub-model using the parameter estimation (PEST) suite of software in a two-stage process as described by GHD (GHD, 2012, pp. 72–73):

1. Calculation of the sensitivities of each of the parameters to be estimated with respect to all observation targets used in the calibration process. This task involved the computation of a Jacobian Matrix holding information on the sensitivity of each observation to each parameter. This first calibration step required the model to be run as many times as the number of base parameters (i.e. 3,366 times for the regional model and 895 times for the transient sub-model);
2. Use of the Singular Value Decomposition Assist (SVDA) methodology and Tikhonov Regularisation to optimise the model parameters. A key part of this process was the production of a user defined number of 'super-parameters' i.e. linear combinations of base parameters. For the final regional model calibration 430 such 'super-parameters' were adopted based on the maximum number recommended by the PEST SUPCALC utility. Each iteration of the model optimisation process involves at least as many runs as 'super parameters' (i.e. 430 in the case of the final regional model calibration) and multiple iterations are typically required. A detailed explanation of the SVDA methodology is outside the scope of this Report, thus the interested reader is directed to the PEST manual (Doherty, 2010) for more information.

Calibration of the OGIA model also considered model sensitivity to how the Walloon Coal Measures were represented, recharge estimates and model robustness. 'The potential impact of different layering systems for representation of the Walloon Coal Measures has not been assessed at this stage. However, the sensitivity of model predictions to different parameterisation of the three Walloon Coal Measures layers has been assessed as part of the model uncertainty analysis' (GHD, 2012, p. 106). 'It is recognised that revisions to recharge quantities may not significantly affect predictions of CSG impacts, at least in the short to medium-term. The sensitivity of model predictions to different recharge estimates has been considered further as part of the model uncertainty analysis' (GHD, 2012, pp. 106–107). Model robustness is evidenced by the use of 200 calibration-constrained parameter sets that all achieve a reasonable match to the adopted calibration data.

2.6.2.7.4 Water balance assessment

The water balance assessment presents a quantitative water balance for the Maranoa-Balonne-Condamine subregion for both the baseline and the CRDP. It was conducted under the guidance of companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). The purpose of the water balance assessment is to quantify the effects of regional water pressure and water level changes in aquifers within the Maranoa-Balonne-Condamine subregion in response to depressurisation of the coal seams for CSG production and mine pit dewatering. The water balance is reported for a defined control volume in BA that includes all hydrologically connected changes predicted by the numerical models. The water balance components (e.g. recharge, evapotranspiration, baseflow (discharge to stream), licensed extractions, upward flow from deeper groundwater and change in storage) are compared with estimates of fluxes described in the regional-scale conceptual model and localised groundwater models to provide confidence in model predictions. Modelled losses are CSG water production, coal mine dewatering, licensed extractions, baseflow (discharge to streams) and negative change in storage fluxes. Modelled gains are recharge and positive change in storage fluxes.

The focus on the deep regional aquifers targeted by CSG development means that the OGIA model

> 'includes a relatively simple representation of shallow groundwater systems, which is considered to be consistent with the regional scale and the overall aims of the model. In particular losses from near surface evapotranspiration and groundwater extraction are not represented in the model. Current estimates of modelled discharge to river and drain boundary cells exclude these losses and should therefore not be taken as estimates of baseflow to surface watercourses in the area. Where evapotranspiration and groundwater extraction from these shallow systems were included then a potentially significant proportion of the 93% of watertable recharge that is rejected from the current model would be subsequently lost via groundwater extractions and/or evapotranspiration from near surface systems' (GHD, 2012, p. 109).

Spatial and temporal extent of the water balance

Coal resource development in the Maranoa-Balonne-Condamine subregion occurs predominantly in the Condamine river basin. The five baseline coal mines are located in the eastern part of the Condamine river basin, outside of the Condamine Alluvium. The five baseline CSG operations cover a large part of the Condamine river basin, the southern edge of the Fitzroy river basin, central parts of the Moonie river basin and north-eastern edge of the Border Rivers river basin. Geological units near the five baseline coal mines includes the Condamine Alluvium, Quaternary alluvia, Main Range Volcanics, Bungil Formation and Mooga Sandstone, Gubberamunda Sandstone and Walloon Coal Measures outcrop areas. The two open-cut coal mine project proposals are located on Walloon Coal Measures outcrop areas. The Range coal mine has adjoining Springbok Sandstone outcrop areas and Quaternary alluvium, and the New Acland Coal Mine has adjoining Main Range Volcanics and Quaternary alluvium. Companion product 2.3 (conceptual modelling) for the Maranoa-Balonne-Condamine subregion (Holland et al., 2016) includes cross-sections and maps of surface geology in the subregion.

Water balance reporting areas encompass all model grid cells where additional drawdown is greater than the minimum detectable difference (0.02 m) for the groundwater model. The locations of the two water balance areas are shown in Figure 14. The Range water balance area covers 13,497 km^2 and the New Acland Coal Mine water balance area covers 6,688 km^2. Water balances are reported for three 30-year periods (2013 to 2042; 2043 to 2072; and 2073 to 2102) to be consistent with the reported time periods for other BA bioregions. In the other bioregions, a 30-year historical climate sequence is modified and repeated to generate future climate input data for surface water and groundwater models. This 30-year period is repeated to ensure that the effect of droughts and floods does not confound the comparison between time periods. While the same time periods are reported, groundwater modelling in the Maranoa-Balonne-Condamine subregion uses long-term mean recharge rates instead of time-varying climate input data. The focus on the difference between two possible futures in BA means that climate change assumptions will not affect model predictions.

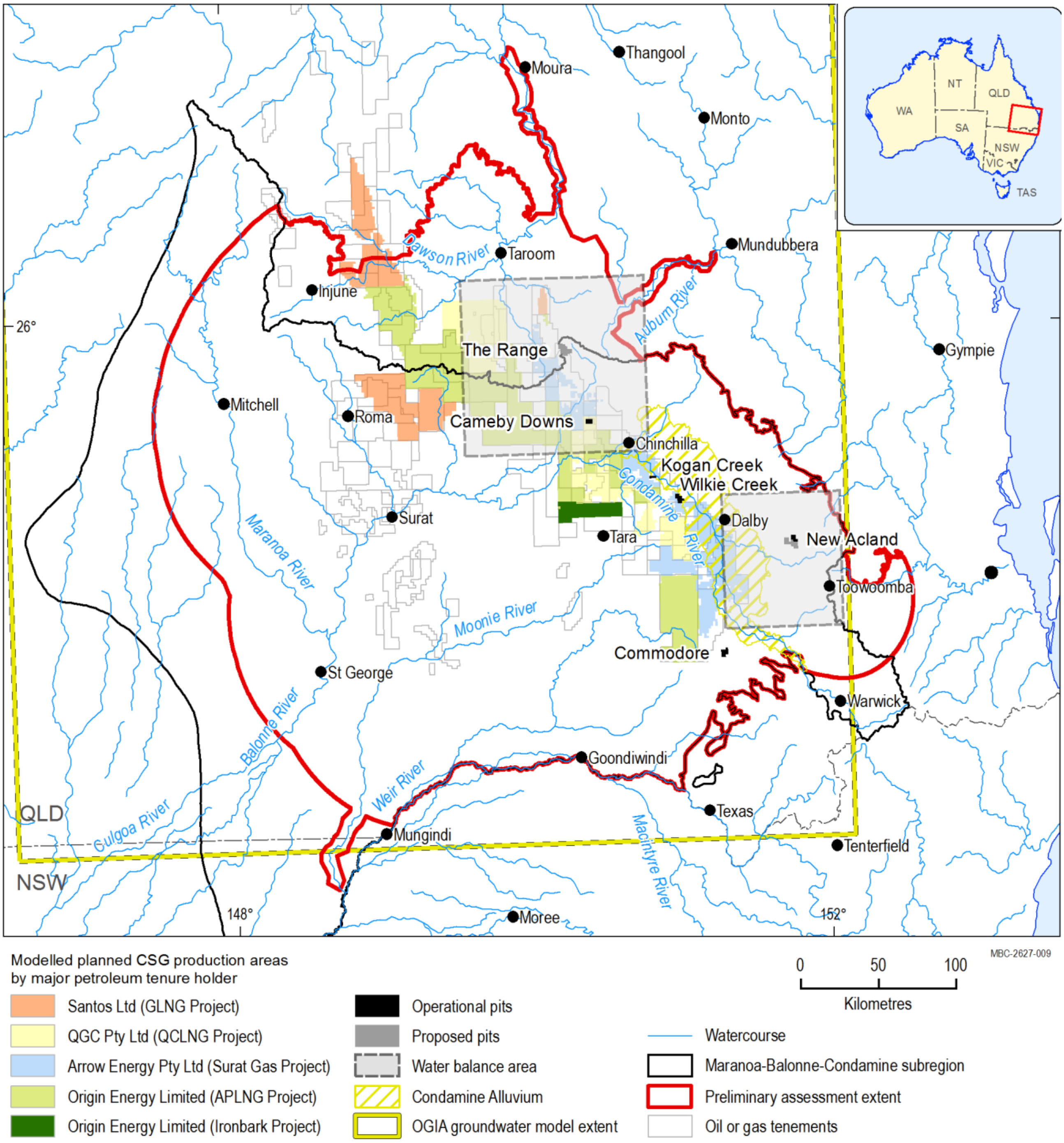

Figure 14 Location of water balance reporting areas in the Maranoa-Balonne-Condamine subregion

APLNG Project = Australia Pacific LNG Project, CSG = coal seam gas, GLNG Project = Santos Gladstone LNG Project + GLNG Gas Field Development Project, LNG = Liquefied Natural Gas, QCLNG Project = Queensland Curtis LNG Project, QGC = Queensland Gas Company

Data: Bioregional Assessments Programme (Dataset 2, Dataset 3)

Water balance uncertainty

The components of the water balance are calculated from a single run of the calibrated groundwater model, represent a different set of model outputs to the hydrological response variables generated at receptor locations and are therefore not included in the uncertainty analysis reported in Section 2.6.2.8. Drain cell conductance, which represents mine pit dewatering and has a major effect on modelled drawdown and water balance, is not considered in the formal uncertainty analysis. Drain cells are assigned a high conductance value (2500 m^3/day) in the OGIA model, which means that 'modelled impact predictions are considered unlikely to be sensitive' to the assigned conductance value (GHD, 2012, p. 58).

The approach used to calculate water balance terms is described in Table 8.

Table 8 Calculation of water balance terms for the Maranoa-Balonne-Condamine subregion

Water balance term	Calculation approach
Recharge	The *recharge* component of the water balance represents the volume of water that enters the uppermost model layer, with much of this water being discharged via drain cells to establish topographic control of modelled groundwater levels.
CSG water production	The MODFLOW EVT package is used to represent *CSG water production.* Evapotranspiration is not modelled explicitly in the OGIA model, which means that losses from near surface evapotranspiration that are reported for other bioregional assessment regions cannot be reported.
Drains	The MODFLOW Drain package is used to establish topographic control of groundwater levels and to simulate coal mine dewatering in model layers between the surface and the modelled coal seam. The *drain* component of the water budget represents rejected recharge and mine pit dewatering. The difference between the baseline and CRDP drain values represents the simulated coal mine dewatering volume for the two additional coal mines.
Licensed extractions	The MODFLOW Wells package is used to simulate *licensed extractions* from approximately 19,000 bores, including licensed volumetric entitlements, stock and domestic and conventional oil and gas abstractions.
Baseflow (discharge to stream)	The MODFLOW River package is used to simulate *baseflow (discharge to stream)*. However, losses from near surface evapotranspiration and groundwater extraction are not represented in the model. This means that estimates of modelled discharge to river and drain boundary cells that exclude these losses should not be taken as estimates of baseflow to surface watercourses in the area.
Change in storage	The *change in storage* component of the water balance represents the addition or removal of water from the model layers within the water balance reporting area, where a positive value represents water coming into the model from storage.
Net water balance	The *net water balance* (sum of all water balance components) shows whether there is lateral flux into or out of the water balance control volume.

CSG = coal seam gas, OGIA = Office of Groundwater Impact Assessment, CRDP = coal resource development pathway

The Range water balances

Table 9 shows The Range water balances for three 30-year periods. Most of the water that enters the model as *recharge* (126.36 GL/year) is discharged via the drain cells (104.53 to 106.09 GL/year), which is consistent with using drain cells to establish topographic control of modelled groundwater levels. Modelled *CSG water production* in the water balance area falls from 21.94 GL/year (17% of modelled losses) to zero over successive 30-year periods. This is consistent with the modelled cessation date for CSG production of 2065 in the Surat CMA (OGIA, 2014).

Table 9 Mean annual water balances for The Range water balance area for three 30-year periods

Period	Water balance term	Under baseline (GL/y)	Under CRDP (GL/y)	Difference (GL/y)*
2013 to 2042	Recharge	126.36	126.36	0.00
	CSG water production	–21.94	–21.94	0.00
	Drains	–105.54	–106.09	–0.54
	Licensed extractions	–4.38	–4.38	0.00
	Baseflow (discharge to stream)	–0.61	–0.61	0.00
	Change in storage	23.35	23.90	0.54
	Net water balance	17.24	17.24	0
2043 to 2072	Recharge	126.36	126.36	0.00
	CSG water production	–2.45	–2.45	0.00
	Drains	–105.07	–104.53	0.55
	Licensed extractions	–4.38	–4.38	0.00
	Baseflow (discharge to stream)	–0.51	–0.51	0.00
	Change in storage	3.33	2.78	–0.55
	Net water balance	17.28	17.27	0
2073 to 2102	Recharge	126.36	126.36	0.00
	CSG water production	0.00	0.00	0.00
	Drains	–104.82	–104.71	0.10
	Licensed extractions	–4.39	–4.39	0.00
	Baseflow (discharge to stream)	–0.41	–0.41	0.00
	Change in storage	0.08	–0.04	–0.11
	Net water balance	16.82	16.81	–0.01

*The net impact of the additional coal resource development (ACRD) is defined as the difference between results for the coal resource development pathway (CRDP) and the baseline.
Data: Bioregional Assessments Programme (Dataset 1)

The *drain* cells used to represent coal mine dewatering remove water from modelled storage, that is, the drain and *change in storage* components of the water balance are equivalent during modelled coal mine operation, which is consistent with localised drawdown near the coal mines. Mean annual coal mine dewatering (equal to the difference in the *drain* component between the CRDP and baseline futures) is 0.54 GL/year in the first 30-year period, becoming positive after modelled mine closure in 2041 when the drain cells are deactivated in the regional model and water returns to storage. Coal mine dewatering accounts for 2% of modelled losses in the first 30-year period and zero thereafter in The Range water balance area.

Licensed extractions increase slightly from 4.38 GL/year in the first 30-year period (2013 to 2042) to 4.39 GL/year in the third 30-year period (2073 to 2102). However, its relative importance in each 30-year period increases from 16% of modelled losses (CSG water production, coal mine dewatering, licensed extractions and baseflow) in 2013 to 2042, when CSG water production and the coal mines are operational, to 91% of modelled losses in 2073 to 2102, when water extraction for CSG and coal mining has ceased.

Baseflow (discharge to streams) is negative, meaning that water is leaving the model via river cells within the water balance area, which is consistent with the conceptualisation of surface water – groundwater interactions in the regional model. Baseflow fluxes are identical under the baseline and CRDP for each 30-year period, but decrease through time. This may be an artefact of the regional model construction, as the OGIA model assumes that all surface watercourses act as groundwater discharge boundaries (QWC, 2012). A net lateral flux into The Range water balance area is observed in each 30-year period.

New Acland Coal Mine water balances

Table 10 shows the New Acland Coal Mine water balances for three 30-year periods. About a third of the water that enters the model as *recharge* (96.32 GL/year) is discharged via the drain cells, with the remainder discharged as CSG water production, licensed extractions and baseflow (discharge to stream). *CSG water production* is projected to fall from 3.72 GL/year (3% of modelled losses) to zero over successive 30-year periods following modelled cessation of CSG production in 2065 in the Surat CMA (OGIA, 2014).

Coal mine dewatering (equal to the difference in the *drain* component between the CRDP and baseline futures) averages 0.09 GL/year over the first 30-year period (Table 10). Model predictions are negative (–0.85 GL/year) during mine operation (2012 to 2029) and positive (0.64 GL/year) after modelled mine closure in 2029 when the drain cells are deactivated in the regional model and water returns to storage. These values are consistent with the mine dewatering volume reported in the New Acland Coal Mine Stage 3 environmental impact assessment documents (maximum of 1.4 GL/year; SKM, 2013).

Licensed extractions are 77.07 GL/year in each 30-year period and account for 86% of modelled losses in 2013 to 2042 when CSG water production and the coal mines are operational to 92% of modelled losses in 2073 to 2102 when CSG water production and the coal mines have ceased operation. This is consistent with the high density of licensed bores in the Condamine Alluvium within the New Acland Coal Mine water balance area.

Baseflow (discharge to streams) decreases from 8.85 GL/year in 2013 to 2029 to 6.61 GL/year in 2073 to 2102 and is identical under the baseline and CRDP for each 30-year period. This means that coal resource development does not affect modelled baseflow to the river cells. A net lateral flux out of the New Acland Coal Mine water balance area is observed in each 30-year period.

Table 10 Mean annual water balance for New Acland Coal Mine water balance area for three 30-year periods

Period	Water balance term	Under baseline (GL/y)	Under CRDP (GL/y)	Difference (GL/y)*
2013 to 2042	Recharge	96.32	96.32	0
	CSG water production	–3.72	–3.72	0
	Drains	–35.92	–36.01	–0.09
	Licensed extractions	–77.07	–77.07	0
	Baseflow (discharge to stream)	–8.85	–8.85	0
	Change in storage	23.04	23.13	0.09
	Net water balance	–6.2	–6.2	0
2043 to 2072	Recharge	96.32	96.32	0
	CSG water production	–0.18	–0.18	0
	Drains	–34.19	–33.98	0.2
	Licensed extractions	–77.07	–77.07	0
	Baseflow (discharge to stream)	–7.38	–7.38	0
	Change in storage	14.94	14.73	–0.2
	Net water balance	–7.56	–7.56	0
2073 to 2102	Recharge	96.32	96.32	0
	CSG water production	0	0	0
	Drains	–33.22	–33.15	0.07
	Licensed extractions	–77.07	–77.07	0
	Baseflow (discharge to stream)	–6.61	–6.61	0
	Change in storage	12.26	12.18	–0.07
	Net water balance	–8.32	–8.33	0

*The net impact of the additional coal resource development (ACRD) is defined as the difference between results for the coal resource development pathway (CRDP) and the baseline.
Data: Bioregional Assessments Programme (Dataset 1)

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SKM (2013) New Acland Coal Mine Stage 3 Project environmental impact assessment groundwater numerical modelling report version 3 – QE06644. August 2013. Prepared for New Hope Group by Sinclair Knight Merz (SKM) Global. http://www.aclandproject.com.au/files/files/stage-3-eis-2014/Appendix%20G4.5%20Groundwater%20Numerical%20Modelling%20Report.pdf

Datasets

Dataset 1 Bioregional Assessment Programme (2016) MBC Groundwater drawdown plots. Bioregional Assessment Derived Dataset. Viewed 20 April 2016, http://data.bioregionalassessments.gov.au/dataset/352a2f65-ddbf-4251-a401-c7070d2c9208.

Dataset 2 Bioregional Assessment Programme (2015) MBC Groundwater model water balance areas. Bioregional Assessment Derived Dataset. Viewed 20 April 2016, http://data.bioregionalassessments.gov.au/dataset/4553363e-cc10-43e7-b842-463465c1640d.

Dataset 3 Bioregional Assessment Programme (2015) MBC Groundwater model mine pit cells. Bioregional Assessment Derived Dataset. Viewed 20 April 2016, http://data.bioregionalassessments.gov.au/dataset/0e47f3ed-0c3b-4fa4-8e95-003edef6a313.

2.6.2.8 Uncertainty analysis

Summary

The formal uncertainty analysis considered hydraulic conductivity, recharge and storage values, but not model conceptualisation or the parameters used to specify drain and river boundary conditions. However, model predictions of groundwater drawdown are unlikely to be sensitive to the relatively high Drain and River cell conductance values. Posterior distributions of calibration-constrained hydraulic conductivity parameters (*Kh* and *Kv*) vary over several orders of magnitude in the OGIA model layers. Modelled recharge values have a skewed distribution, with most values being less than 10 mm/year (Figure 15).

Hydrological changes arising from coal resource development for two possible futures – the baseline and the coal resource development pathway (CRDP) – are assessed using a probabilistic approach. Thresholds used to describe hydrological changes in the Maranoa-Balonne-Condamine subregion are consistent with those described in the Surat Underground Water Impact Report (UWIR). Maximum baseline groundwater drawdown associated with coal seam gas (CSG) production (in excess of 700 m) is predicted near the towns of Chinchilla and Roma. Hydrological changes in excess of 0.2 m baseline groundwater drawdown in the vicinity of the five baseline coal mines are generally within 5 to 10 km (maximum 15 to 20 km) of the modelled pits.

Additional groundwater drawdown in the vicinity of proposed coal mines in excess of 0.2 m (probability, p=0.05) is generally within 20 to 40 km (maximum 50 to 60 km) of the modelled pits. Hydrological changes in excess of 5 m (p=0.05) additional drawdown are predicted in 153 of the 9213 bores in New Acland Coal Mine water balance area and 7 of the 411 bores in The Range water balance area. Overall, 86 of the 19,000 economic bores are predicted to experience more than 5 m additional groundwater drawdown in the Maranoa-Balonne-Condamine subregion.

The qualitative uncertainty analysis describes the rationale for and scores the effect of nine assumptions or model choices on model predictions. The representation of surface water – groundwater interactions, mine pit dewatering, CSG activities and horizontal and vertical discretisation in the model and the quantitative uncertainty analysis are judged to have the greatest potential effect on model predictions.

This section describes the quantitative and qualitative uncertainty analyses used to give probabilistic estimates of the hydrological changes associated with coal resource development in the Maranoa-Balonne-Condamine subregion. The quantitative uncertainty analysis numerically evaluates the degree to which each of the model inputs (parameters) affects the model predictions. Model predictions of groundwater drawdown associated with coal resource development are presented in two ways. Firstly, the 95th percentile of groundwater drawdown under the baseline future and the probability of exceeding additional groundwater drawdown thresholds under the CRDP future are presented spatially for each model layer. Secondly, the maximum additional drawdown and time to maximum drawdown at the economic bores within the two water balance areas is presented. The qualitative uncertainty analysis describes the rationale for and scores the effect of each assumption on model predictions.

2.6.2.8.1 Quantitative uncertainty analysis

The OGIA model is calibrated in steady state to replicate long-term mean conditions pre 1995 (i.e. pre CSG extraction) using the PEST suite of software in three steps as described in Section 2.6.2.6 (Parameterisation). Firstly, a preliminary calibration of the steady-state regional model is used to provide initial heads and boundary conditions for the transient sub-model. Secondly, the transient sub-model is calibrated using detailed groundwater level data for the Walloon Coal Measures near the existing Kogan North/Daandine CSG field. Finally, the steady-state regional model is recalibrated using calibrated hydraulic conductivity values for the Walloon Coal Measures from the transient calibration within the sub-model area.

The overall process is referred to as calibration-constrained uncertainty analysis and is also known as Null-space Monte Carlo Analysis (Tonkin and Doherty, 2009). Similar to standard Monte Carlo approaches, 200 stochastic parameter fields are generated using an appropriate covariance matrix of innate parameter variability defined by the modeller. Then for each of these parameter fields, the difference between the random field and the calibrated parameter field are obtained and projected onto the calibration null space. The parameter field arising from the calibration then replaces the solution-space component of the stochastically generated field. Calibration solution space and null space mentioned herein refers respectively to the combination of parameter sets that, respectively, can and cannot be estimated using the calibration dataset. Details of this uncertainty analysis method are documented in WaterMark Numerical Computing (2012). The mathematical implementation of this uncertainty analysis differs from the approach for other bioregional assessments described in companion submethodology M09 (Propagating uncertainty through models) (Peeters et al., 2016). However, the underlying concept of stochastically generating a posterior predictive probability distribution, constrained by relevant observation data is equivalent. The OGIA model uncertainty analysis is able to give probabilistic estimates of the hydrological changes associated with coal resource development and thus meets the BA uncertainty analysis requirements.

The 200 calibration-constrained parameter sets varied net recharge values spatially for 20 recharge zones as described in Section 2.6.2.4 (Boundary and initial conditions). GHD (2012) state ‘modelled net or effective recharge rates … are comparable with the estimates of Kellett et al. (2003)’. Specific storage (*Ss*) varies spatially in the productive coal layers (Walloon Coal Measures and Bandanna Formation) or is assigned a constant storage value for other confined model layers for which observed groundwater levels were not available. Specific yield is used to define unconfined storage values for the aquifer outcrop areas, Condamine Alluvium, Main Range Volcanics and alluvium outside the Condamine area. Model storage values for each model layer are described in Section 2.6.2.6 (Parameterisation).

The formal uncertainty analysis considered hydraulic conductivity, recharge and storage values, but did not consider model conceptualisation or the parameters used to specify drain and river boundary conditions. However, model predictions are unlikely to be sensitive to the assigned Drain and River cell conductance values as the ‘use of a relatively high value ensures that:

- Modelled groundwater levels do not significantly exceed the modelled ground surface; and
- Modelled discharges are typically controlled by the hydraulic properties of the underlying layers' (GHD, 2012, p. 58).

The posterior distributions of hydraulic conductivity (Figure 15) show that the calibration-constrained hydraulic conductivity parameters (*Kh* and *Kv*) vary over several orders of magnitude in each layer of the OGIA model. Most parameter values vary by at least one order of magnitude from the median value for that model layer. Modelled recharge values have a skewed distribution, with most values being less than 10 mm/year (Figure 15). Storage values for each model layer are described in Section 2.6.2.6 (Parameterisation).

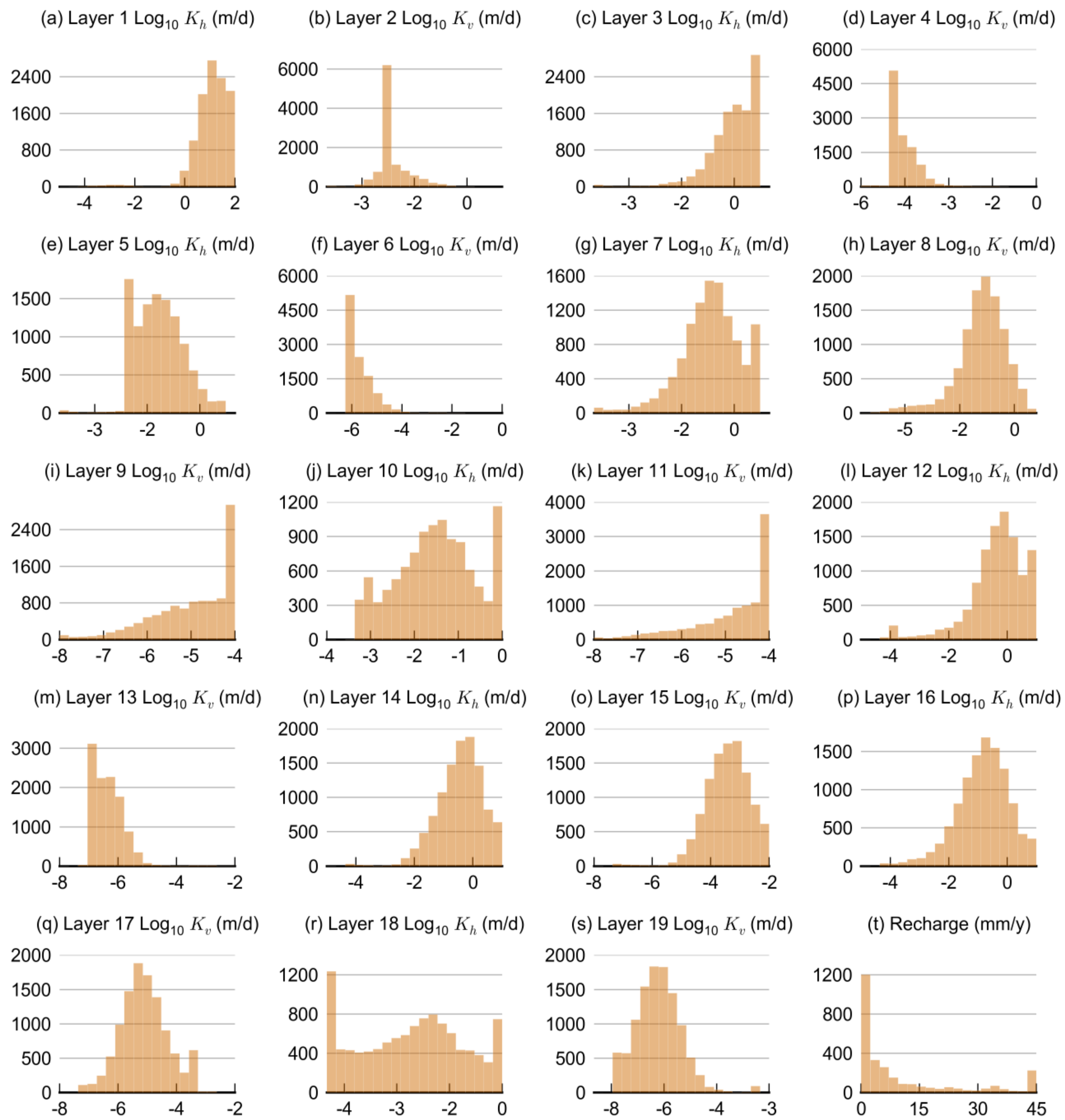

Figure 15 Histograms of posterior distributions of (a-s) hydraulic conductivity (m/day) and (t) recharge (mm/year) for model layers in the Office of Groundwater Impact Assessment (OGIA) regional groundwater model

Model layer names are described in Figure 6 (Section 2.6.2.3). Horizontal hydraulic conductivity (Kh) values are shown for aquifers and vertical hydraulic conductivity (Kv) values are shown for aquitards.
Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.8.2 Model predictions

The OGIA model is used to probabilistically assess hydrological changes arising from coal resource development at water-dependent assets and receptors in the Maranoa-Balonne-Condamine subregion. Hydrological changes arising from coal resource development for two possible futures – the baseline and the coal resource development pathway (CRDP) – are assessed using a probabilistic approach. The baseline future includes all CSG developments included in the most recent Petroleum & Gas (P&G) Production Run (OGIA, 2014) and the five baseline open-cut coal mines: Cameby Downs, Commodore, Kogan Creek, New Acland Stage 2 and Wilkie Creek. The CRDP future includes the baseline coal resource developments plus the additional coal resource developments (ACRD – which consists of two open-cut coal mines) in the subregion. The difference in predicted water levels between the baseline and CRDP provides an estimate of water level impacts that are attributable to the ACRD.

Thresholds used to describe hydrological changes in the Maranoa-Balonne-Condamine subregion are consistent with those described in the Surat Underground Water Impact Report (UWIR) (QWC, 2012). Long-term affected areas in the Surat UWIR are defined as 'the area within which water levels are predicted to fall, due to water extraction by petroleum tenure holders, by more than the trigger thresholds at any time in the future. The trigger thresholds are … 5 m for consolidated aquifers (such as sandstone) and 2 m for unconsolidated aquifers (such as sands)' (QWC, 2012, p. 55).

Baseline groundwater drawdown

Hydrological changes in excess of 0.2 m baseline groundwater drawdown within the extent of each relevant geological layer are shown spatially in Figure 16 to Figure 21. Baseline groundwater drawdown in the vicinity of the five baseline coal mines is summarised in Table 11.

Model layer 1 – Alluvium (Condamine) and Main Range Volcanics extent includes watertable aquifers in the alluvium (including the Condamine Alluvium) and Main Range Volcanics. Figure 16 shows baseline groundwater drawdown predicted by the regional model in Model layer 1 – Alluvium (Condamine) and Main Range Volcanics, overlaid by predictions of groundwater drawdown associated with baseline CSG production from the Condamine Model within the Condamine Alluvium (QWC, 2012, Figure F-9). The data presented in Figure F-9 (QWC, 2012) from the Condamine Model is used to estimate impacts on groundwater levels within the Condamine Alluvium extent because groundwater drawdown associated with the baseline mines is not predicted in Model layer 10 – Walloon Coal Measures by the regional groundwater model within the Condamine Alluvium extent. Groundwater drawdown in the Condamine Alluvium is associated with baseline CSG production.

Baseline groundwater drawdown associated with CSG production near the mines is 10 m near Cameby Downs, 1.2 m near Kogan Creek and 0 m near New Acland Stage 2. The regional model predicts baseline groundwater drawdown in Model layer 1 – Alluvium (Condamine) and Main Range Volcanics within the mine pits at Cameby Downs (20–50 m), Kogan Creek (30–60 m) and New Acland Stage 2 (10–45 m). This groundwater drawdown is contained within the modelled pit extent, except in the vicinity of New Acland Stage 2 where baseline groundwater drawdown is less than 5 m within 5 to 10 km of the mine. The Wilkie Creek and Commodore coal mines are located outside of this model layer extent.

Baseline groundwater drawdown in excess of 0.2 m is predicted along the northern edge of **Model layer 3 – Bungil Formation and Mooga Sandstone** extent (Figure 17) and along the northern and eastern edges of **Model layer 5 – Gubberamunda Sandstone** (Figure 18). Maximum predicted baseline groundwater drawdown is 1.4 m in Model layer 3 – Bungil Formation and 19.7 m in Model layer 5 – Gubberamunda Sandstone. The five baseline coal mines are located outside of the extent of these model layers, which indicates that modelled baseline groundwater drawdown in these model layers is associated with CSG production.

Maximum predicted baseline groundwater drawdown is 113 m in **Model layer 8 – Lower Springbok Sandstone** in an area to the south-west of Chinchilla, which is associated with CSG production (Figure 19). Baseline groundwater drawdown in this model layer is approximately 30 m in an area north-east of Roma. The extent of this model layer includes two of the baseline mines: Kogan Creek and Wilkie Creek where drawdown is 50 to 60 m within the modelled mine pits and 15 to 30 m within 5 to 10 km of the mines. Baseline groundwater drawdown associated with CSG production in the area is 10 to 15 m. The Cameby Downs, Commodore and New Acland Stage 2 coal mines are located outside of this model layer extent.

Model layer 10 – Walloon Coal Measures is the target model layer for CSG production and open-cut coal mining. Maximum predicted baseline groundwater drawdown is 791 m in this model layer (Figure 20). Groundwater drawdown in excess of 700 m occurs in an area south-east of Roma and to the south-west of Chinchilla, which is associated with CSG production. The extent of Model layer 10 – Walloon Coal Measures includes the five baseline mines. Baseline groundwater drawdown associated with CSG production near the mines is 20 to 40 m near Cameby Downs and Kogan Creek, 10 to 30 m near Wilkie Creek, 0 m near New Acland Stage 2 and 3 to 5 m near the Commodore Mine. Groundwater drawdown in addition to that associated with CSG production is observed near the New Acland Stage 2 (<5 m) and Commodore (5–10 m) coal mines. Within the modelled pit areas, baseline groundwater drawdown is 20 to 30 m at Cameby Downs, 35 to 55 m at Kogan Creek, 10 to 35 m at Wilkie Creek, 15 to 20 m at New Acland Stage 2, and 20 to 30 m at the Commodore Mine. Baseline groundwater drawdown outside the modelled pit areas is not evident at Cameby Downs, Kogan Creek and Wilkie Creek. Groundwater drawdown is 0.2 to 5 m within 10 to 15 km of New Acland Stage 2 and 5 to 25 m within 15 to 20 km of the Commodore Mine in Model layer 10 – Walloon Coal Measures.

Maximum predicted baseline groundwater drawdown in **Model layer 12 – Hutton / Marburg Sandstone** is 18.7 m in an area north-east of Roma and 10 to 15 m in an area south-west of Chinchilla. Groundwater drawdown in both areas is associated with CSG production. Baseline groundwater drawdown associated with the modelled pit areas is evident within 10 to 15 km of New Acland Stage 2 (<1 m) and 5 to 10 km of Commodore (1–2 m) in this model layer.

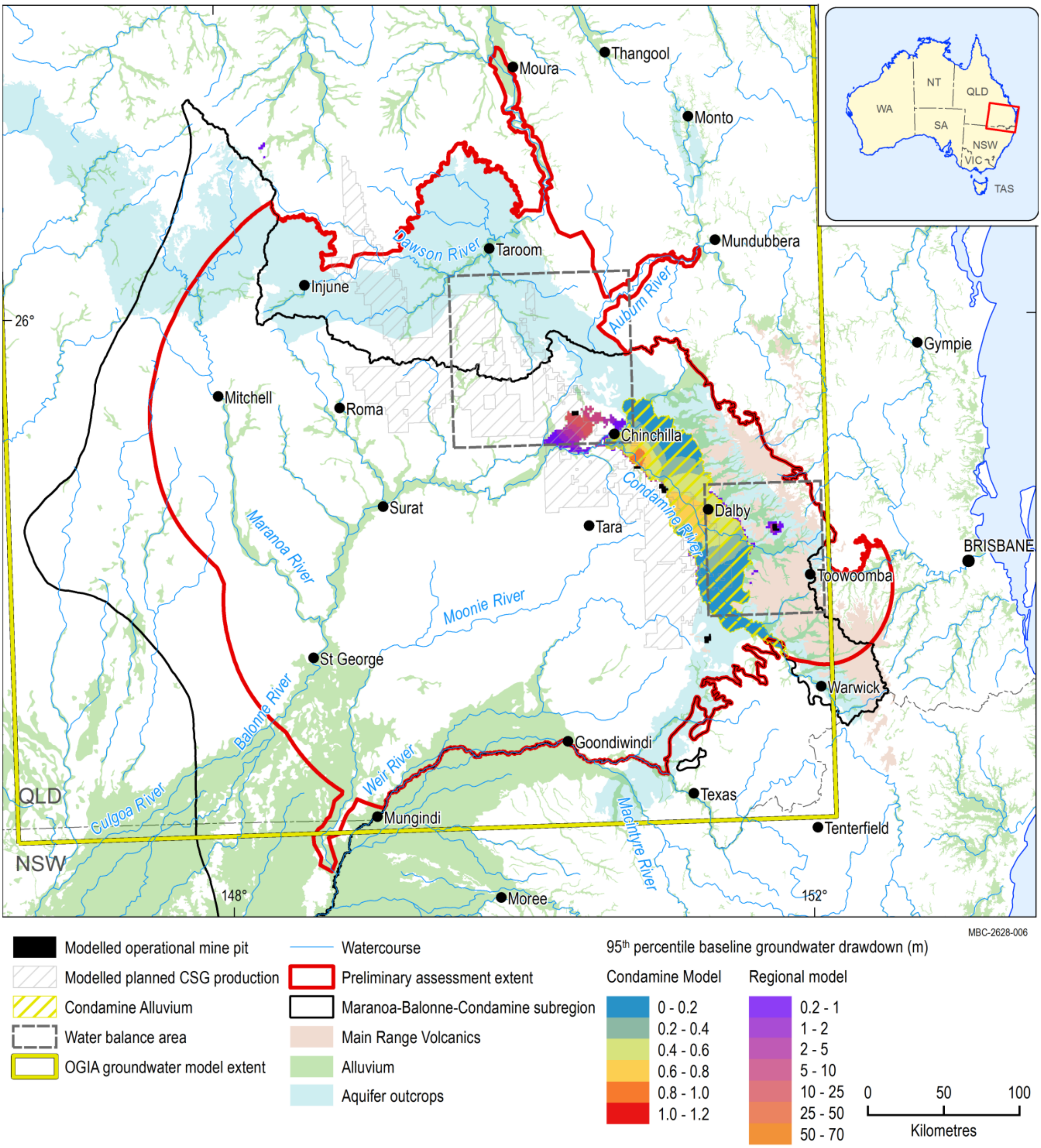

Figure 16 Baseline groundwater drawdown (m) for Model layer 1 – Alluvium (Condamine) and Main Range Volcanics in the Maranoa-Balonne-Condamine subregion

The figure shows the 95th percentile of modelled baseline drawdown from the 200 uncertainty runs after 90 years (2013–2102) in excess of 0.2 m within the model layer extent.
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3, Dataset 4), Geoscience Australia (Dataset 5, Dataset 6), Bioregional Assessment Programme (Dataset 7)

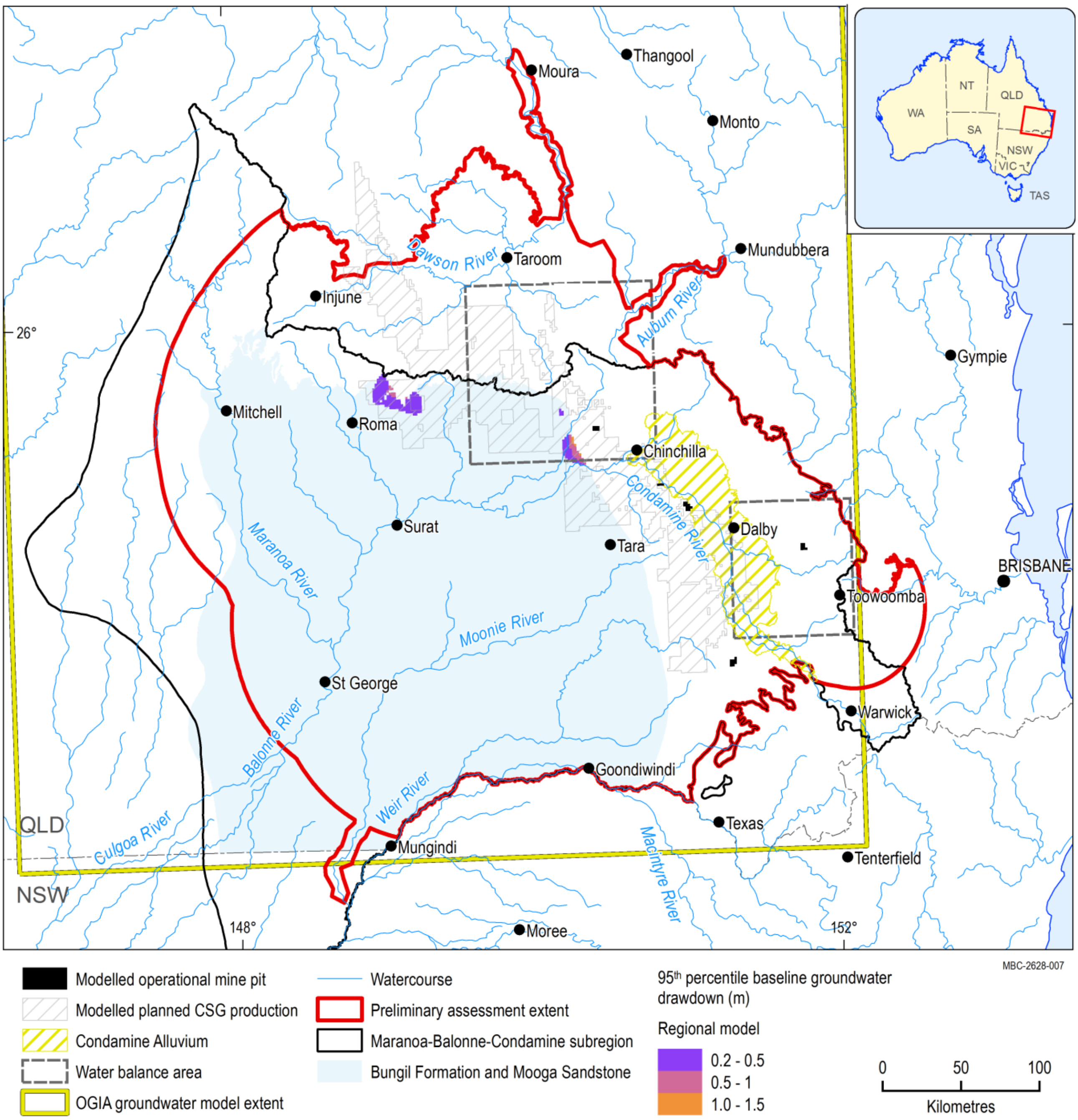

Figure 17 Baseline groundwater drawdown (m) for Model layer 3 – Bungil Formation and Mooga Sandstone in the Maranoa-Balonne-Condamine subregion

The figure shows the 95th percentile of modelled drawdown from the 200 uncertainty runs after 90 years (2013–2102) in excess of 0.2 m within the model layer extent.
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Bioregional Assessment Programme (Dataset 7)

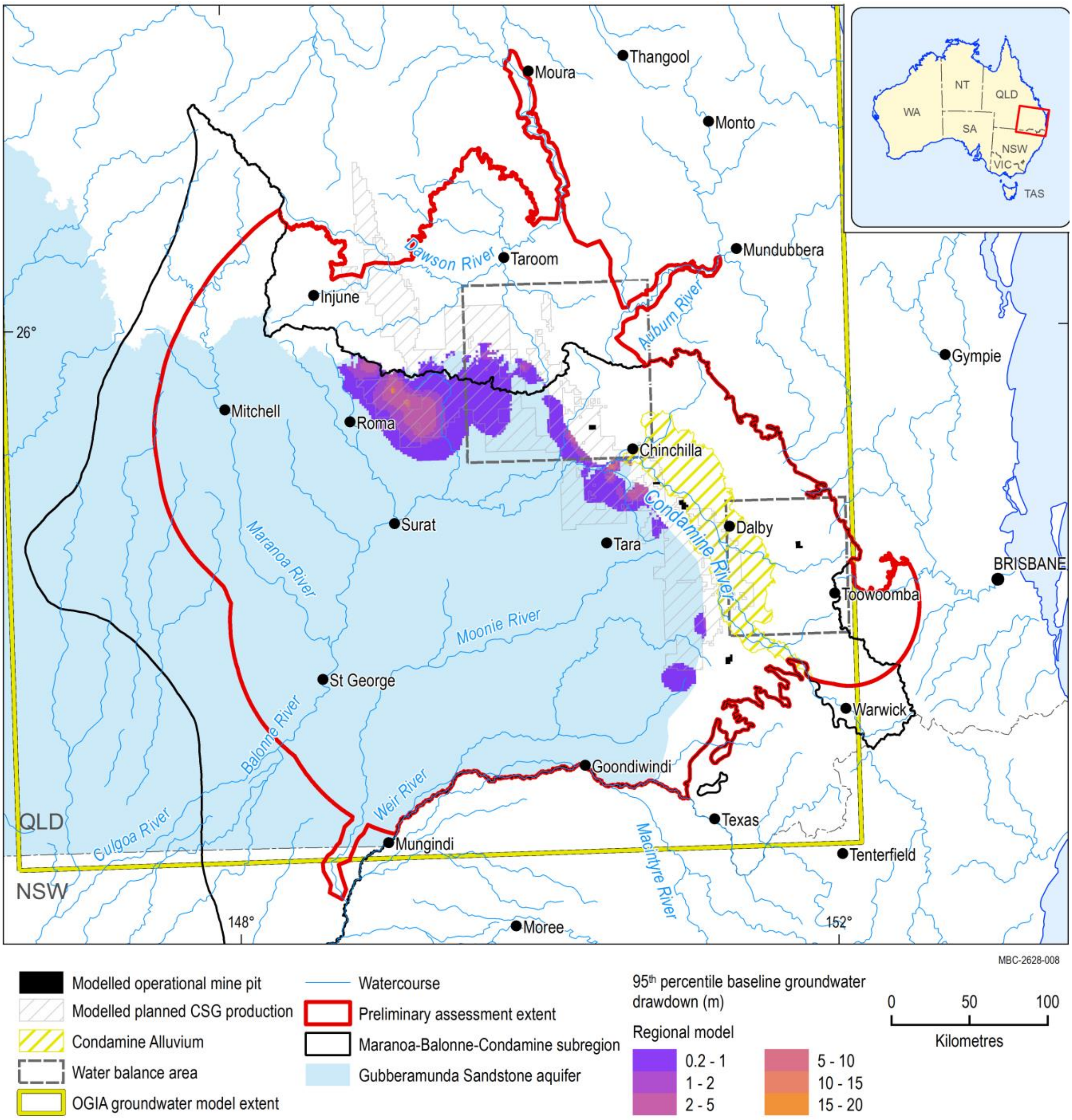

Figure 18 Baseline groundwater drawdown (m) for Model layer 5 – Gubberamunda Sandstone in the Maranoa-Balonne-Condamine subregion

The figure shows the 95th percentile of modelled drawdown from the 200 uncertainty runs after 90 years (2013–2102) in excess of 0.2 m within the model layer extent.
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Bioregional Assessment Programme (Dataset 7)

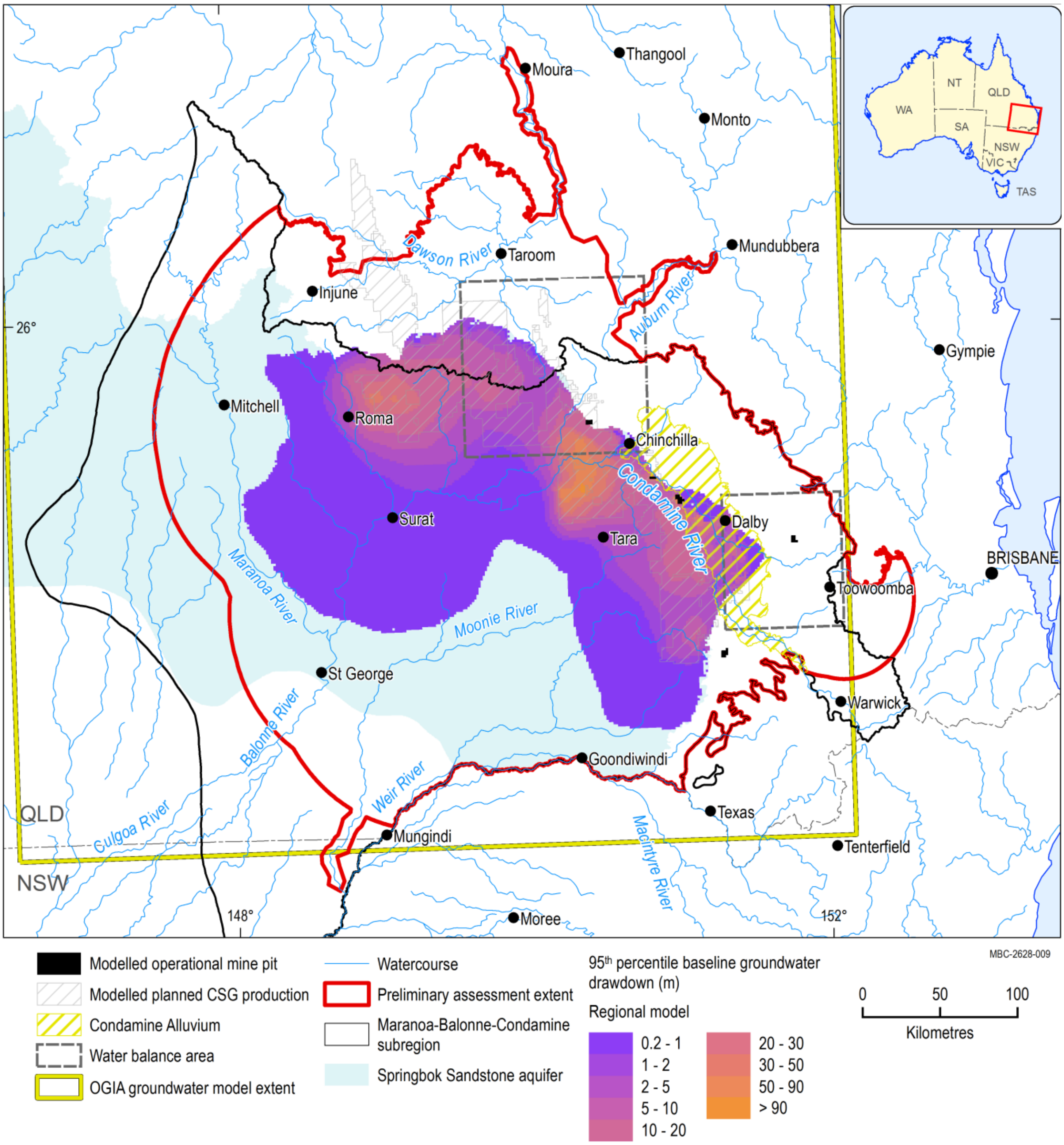

Figure 19 Baseline groundwater drawdown (m) for Model layer 8 – Lower Springbok Sandstone in the Maranoa-Balonne-Condamine subregion

The figure shows the 95th percentile of modelled drawdown from the 200 uncertainty runs after 90 years (2013–2102) in excess of 0.2 m within the model layer extent.
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Bioregional Assessment Programme (Dataset 7)

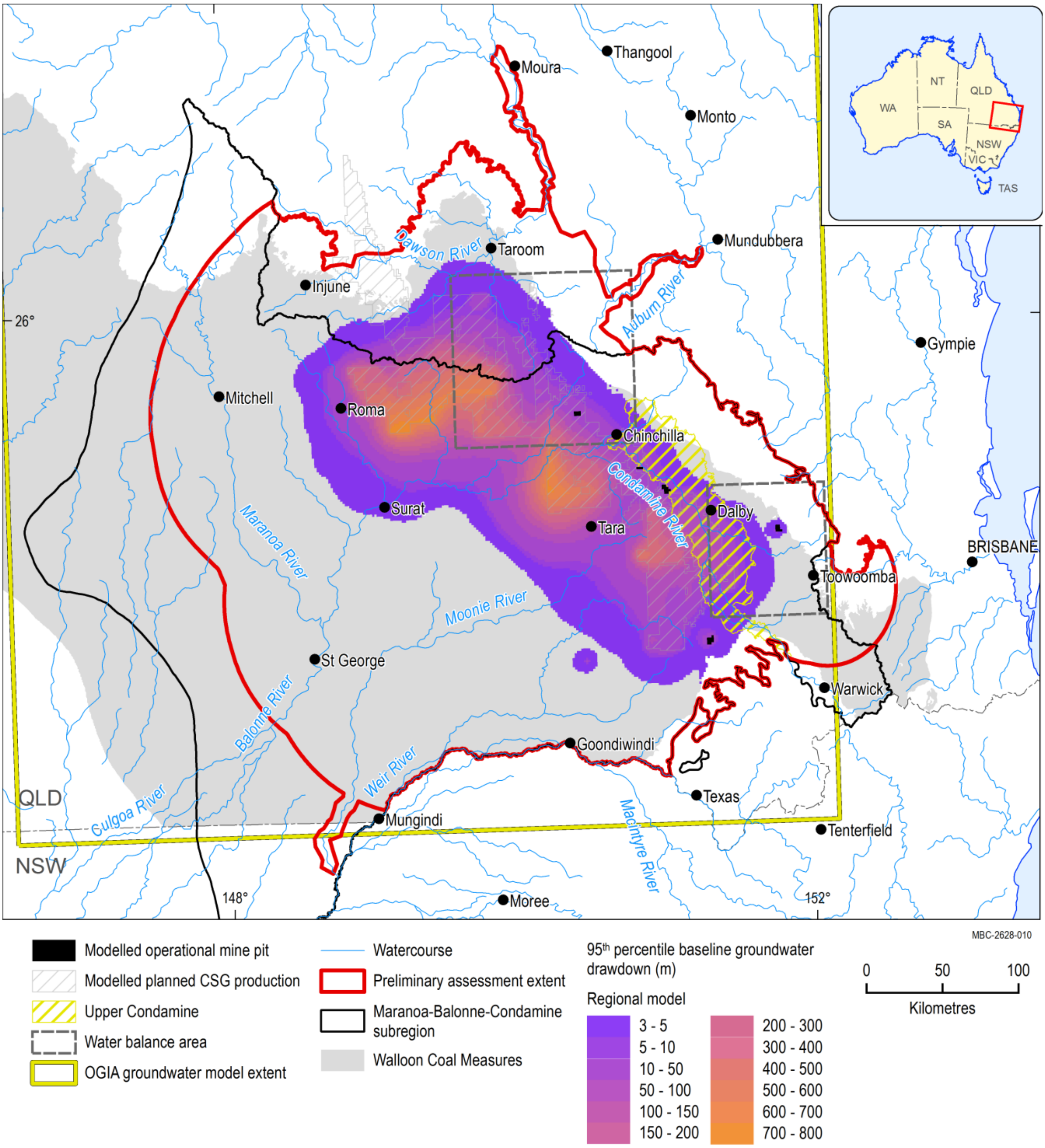

Figure 20 Baseline groundwater drawdown (m) for Model layer 10 – Walloon Coal Measures in the Maranoa-Balonne-Condamine subregion

The figure shows the 95th percentile of modelled drawdown from the 200 uncertainty runs after 90 years (2013–2102) in excess of 0.2 m within the model layer extent.
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Bioregional Assessment Programme (Dataset 7)

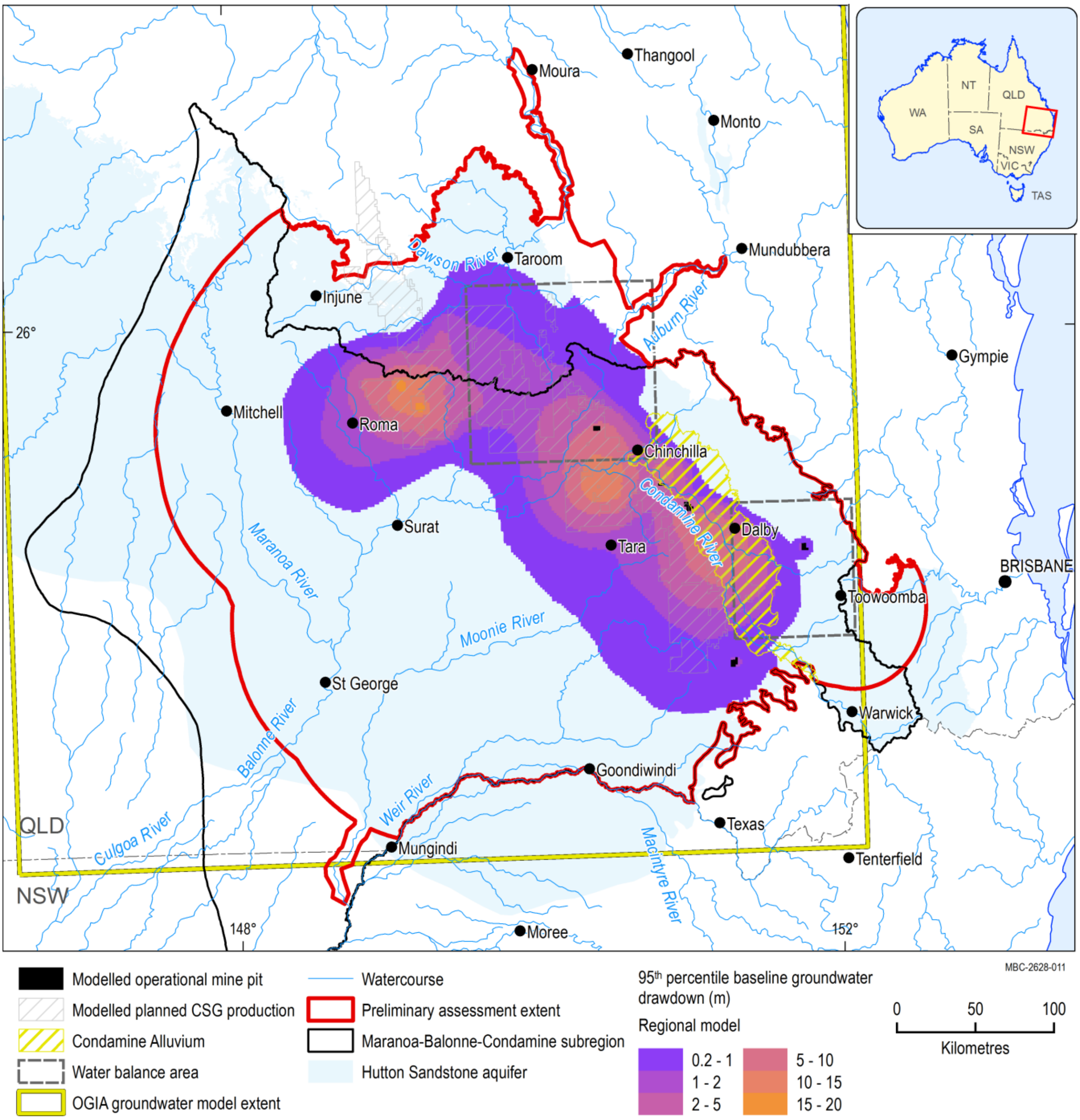

Figure 21 Baseline groundwater drawdown (m) for Model layer 12 – Hutton / Marburg Sandstone in the Maranoa-Balonne-Condamine subregion

The figure shows the 95th percentile of modelled drawdown from the 200 uncertainty runs after 90 years (2013–2102) in excess of 0.2 m within the model layer extent.
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Bioregional Assessment Programme (Dataset 7)

Table 11 Summary of 95th percentile baseline groundwater drawdown in the vicinity of the five baseline coal mines for the Maranoa-Balonne-Condamine subregion

Baseline groundwater drawdown predicted by the regional-scale Office of Groundwater Impact Assessment (OGIA) model associated with each coal mine is summarised by: CSG – drawdown associated with CSG production; DD – estimate of the extent of cumulative groundwater drawdown in the vicinity of each coal mine; and Pit – drawdown values in the modelled mine pits.

Model layer – Formation	Cameby Downs	Kogan Creek	Wilkie Creek	New Acland Coal Mine Stage 2	Commodore
Model layer 1 – Alluvium (Condamine) and Main Range Volcanics	CSG: 10 m DD: none Pit: 20–50 m	CSG: 1.2 m[a] DD: none Pit: 30–60 m	Not within model layer extent	CSG: 0 m DD: 5 to 10 km Pit: 10–45 m	Not within model layer extent
Model layer 3 – Bungil Formation and Mooga Sandstone	Not within model layer extent	Not within model layer extent	Not within model layer extent	Not within model layer extent	Not within model layer extent
Model layer 5 – Gubberamunda Sandstone	Not within model layer extent	Not within model layer extent	Not within model layer extent	Not within model layer extent	Not within model layer extent
Model layer 8 – Lower Springbok Sandstone	Not within model layer extent	CSG: 10–15 m DD: 5 to 10 km Pit: 50–60 m	CSG: 10–15 m DD: 5 to 10 km Pit: 50–60 m	Not within model layer extent	Not within model layer extent
Model layer 10 – Walloon Coal Measures	CSG: 20–40 m DD: none Pit: 20–30 m	CSG: 20–40 m DD: none Pit: 35–55 m	CSG: 10–30 m DD: none Pit: 10–35 m	CSG: 0 m DD: 5 to 10 km Pit: 15–20 m	CSG: 3–5 m DD: 15 to 20 km Pit: 20–30 m
Model layer 12 – Hutton / Marburg Sandstone	CSG: 5–6 m DD: none Pit: 5–6 m	CSG: 4–5 m DD: none Pit: 5 m	CSG: 2–5 m DD: none Pit: 2–4 m	CSG: 0 m DD: 10 to 15 km Pit: 1–2 m	CSG: 1 m DD: 5 to 10 km Pit: 1–2 m

CM = Condamine Model, CSG = coal seam gas, DD = drawdown
[a]groundwater drawdown predicted by the Condamine Model presented in Figure F-9 (QWC, 2012)

Additional groundwater drawdown

Numerical groundwater modelling results of the difference in predicted water levels between the baseline and CRDP futures after 90 years (2013–2102) provides an estimate of water level impacts that are attributable to the ACRD. The CRDP future includes the baseline coal resource developments plus the two proposed open-cut coal mines: The Range and New Acland Stage 3 coal mines. Hydrological changes in excess of 0.2 m and 5 m additional groundwater drawdown (p=0.05) within the extent of each relevant geological layer are shown spatially in Figure 22 to Figure 24. The 0.05 probability of exceeding 0.2 m and 5 m additional drawdown is equivalent to the 95th percentile groundwater drawdown reported by OGIA. Additional groundwater drawdown in the vicinity of the two additional coal mines in excess of 0.2 m (p=0.05) is not predicted within the extent of Model layer 3 – Bungil Formation and Mooga Sandstone, Model layer 5 – Gubberamunda Sandstone or Model layer 8 – Lower Springbok Sandstone. Table 12 summarises modelled additional groundwater drawdown in the vicinity of the two proposed coal mines.

Figure 22 shows additional groundwater drawdown predicted by the regional model in **Model layer 1 – Alluvium (Condamine) and Main Range Volcanics** extent, which includes watertable aquifers in the alluvium (including the Condamine Alluvium) and Main Range Volcanics. Additional groundwater drawdown is not predicted in the vicinity of The Range coal mine in this model layer as it is situated on a Walloon Coal Measures outcrop and so is not represented in Model layer 1. The regional model predicts additional groundwater drawdown in excess of 0.2 m (p=0.05) within 20 to 30 km and in excess of 5 m within 10 to 15 km of the New Acland Stage 3 modelled pits. Geology near the New Acland Coal Mine includes Main Range Volcanics, alluvium and aquifer outcrop areas that are represented in Model layer 1.

Additional groundwater drawdown is predicted by the regional model in **Model layer 10 – Walloon Coal Measures** in the vicinity of the two additional coal mines (Figure 23). The proposed coal mines are near the eastern edge of the Walloon Coal Measures extent, which outcrops in this area. Additional groundwater drawdown is predicted in excess of 0.2 m (p=0.05) within 30 to 40 km of the New Acland Stage 3 and within 50 to 60 km of The Range modelled pits. The extent of modelled additional groundwater drawdown in excess of 5 m (p=0.05) is 15 km (p=0.05) in the vicinity of both The Range and New Acland Stage 3 coal mines in this model layer.

Additional groundwater drawdown of 0.2 to 1.0 m (p=0.05) is predicted in Model layer 10 – Walloon Coal Measures under the eastern edge of the Condamine Alluvium in the vicinity of the New Acland Coal Mine (Figure 23). The Condamine Model was not rerun for the bioregional assessment (BA). Instead, values of baseline groundwater drawdown predicted by the regional and Condamine models are used to estimate the maximum additional groundwater drawdown in this area. Baseline groundwater drawdown predicted in this area by the Condamine Model is 0.15 to 0.35 m (Model Layer 1 – Condamine Alluvium) and is 1 to 5 m in Model layer 10 – Walloon Coal Measures by the regional model. This indicates that 0.2 to 1.0 m additional groundwater drawdown predicted in Model layer 10 – Walloon Coal Measures in this area should result in less than 0.2 m additional groundwater drawdown in the Condamine Alluvium. This is consistent with the extent of additional groundwater drawdown predicted by the regional model in Model layer 1, which does not extend under the Condamine Alluvium (Figure 22).

Figure 24 shows the spatial extent of additional groundwater drawdown in **Model layer 12 – Hutton / Marburg Sandstone**. Additional groundwater drawdown is predicted in excess of 0.2 m (p=0.05) within 50 to 60 km of The Range coal mine, which coincides with the eastern edge of this model layer. The extent of modelled additional groundwater drawdown in excess of 0.2 m (p=0.05) is 30 to 40 km (p=0.05) in the vicinity of New Acland Stage 3 coal mine in this model layer. Additional groundwater drawdown in excess of 5 m (p=0.05) is not predicted in this model layer.

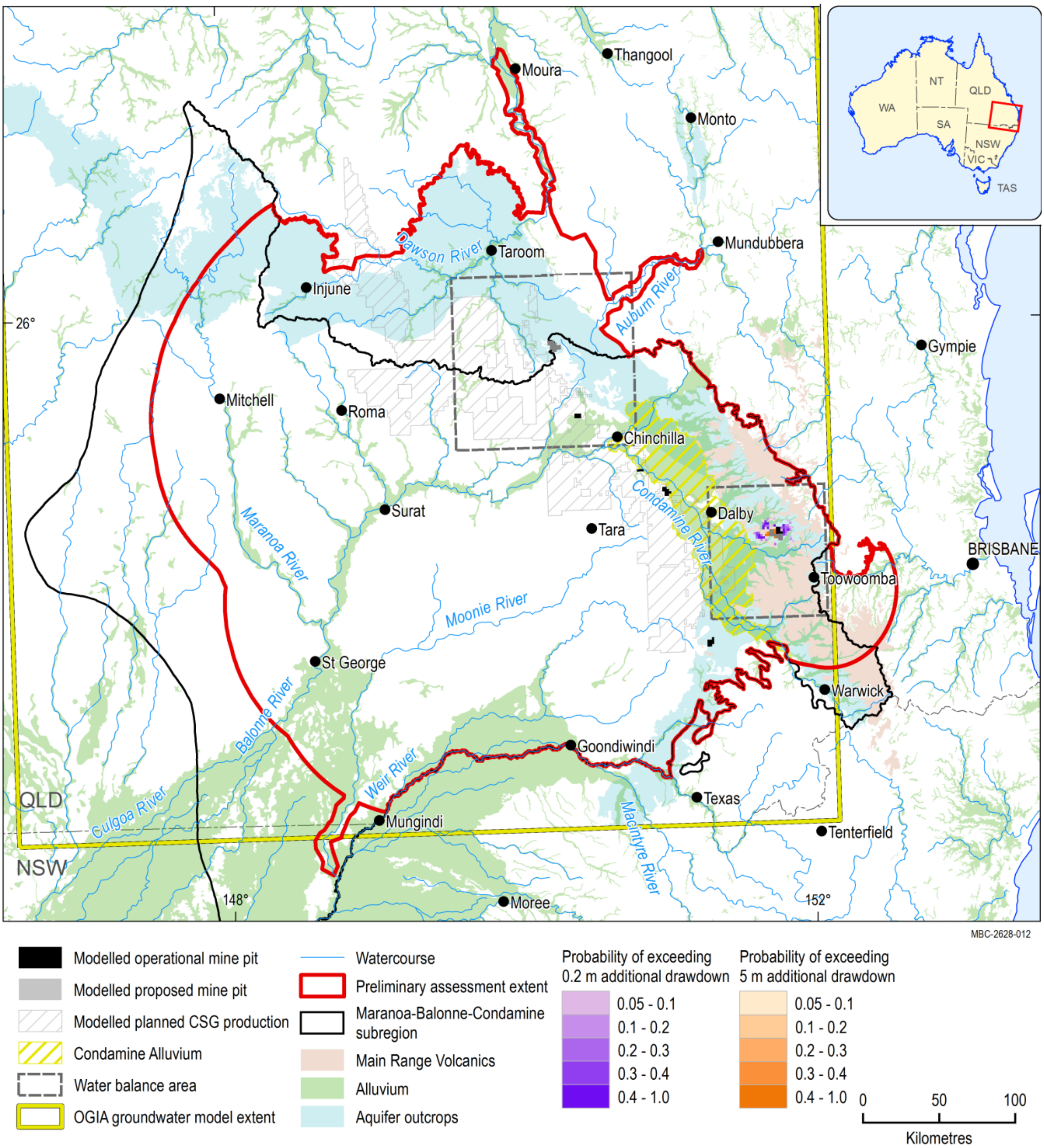

Figure 22 Probability of exceeding 0.2 m and 5 m additional groundwater drawdown for Model layer 1 – Alluvium (Condamine) and Main Range Volcanics in the Maranoa-Balonne-Condamine subregion

The drawdown contours show the 0.05 probability, or 95th percentile of the 200 uncertainty runs, of exceeding 0.2 m and 5 m additional drawdown after 90 years (2013–2102).
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Geoscience Australia (Dataset 5, Dataset 6), Bioregional Assessment Programme (Dataset 7)

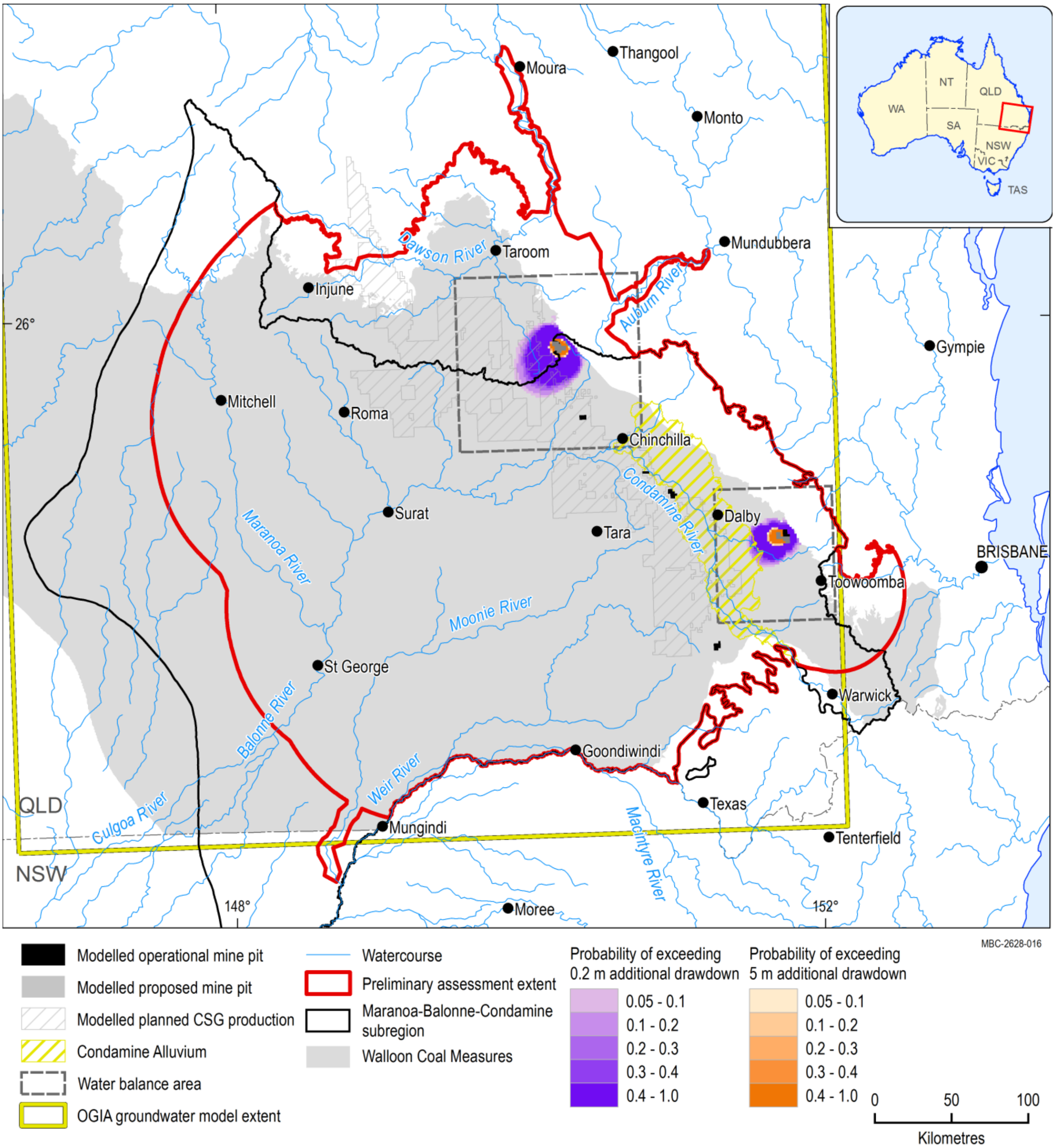

Figure 23 Probability of exceeding 0.2 m and 5 m additional drawdown for Model layer 10 – Walloon Coal Measures in the Maranoa-Balonne-Condamine subregion

The drawdown contours show the 0.05 probability, or 95th percentile of the 200 uncertainty runs, of exceeding 0.2 m and 5 m additional drawdown after 90 years (2013–2102).
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Bioregional Assessment Programme (Dataset 7)

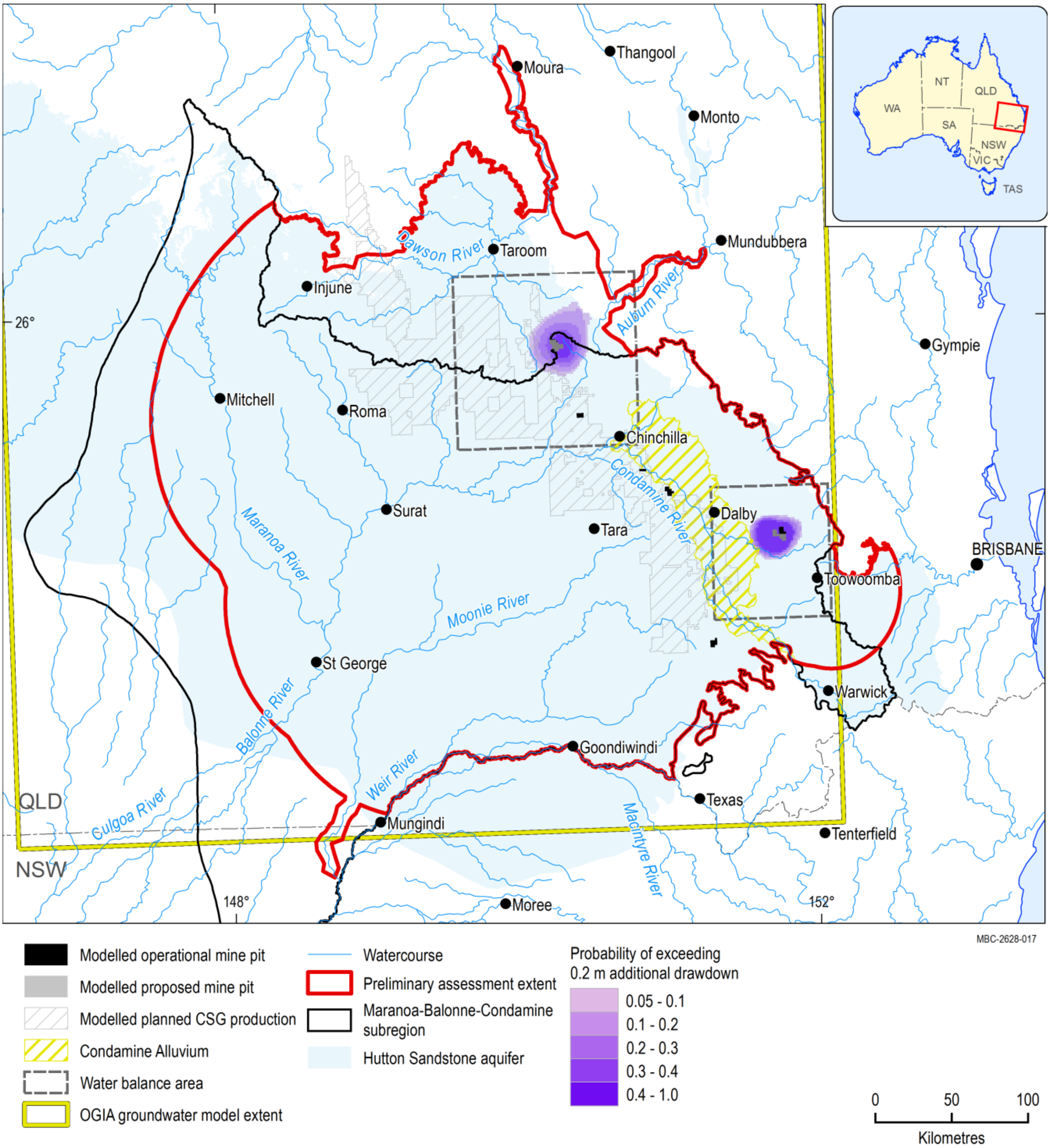

Figure 24 Probability of exceeding 0.2 m additional groundwater drawdown for Model layer 12 – Hutton / Marburg Sandstone in the Maranoa-Balonne-Condamine subregion

The drawdown contours show the 0.05 probability, or 95th percentile of the 200 uncertainty runs, of exceeding 0.2 m and 5 m additional drawdown after 90 years (2013–2102).
In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled.
OGIA = Office of Groundwater Impact Assessment
Data: Office of Groundwater Impact Assessment (Dataset 2, Dataset 3), Bioregional Assessment Programme (Dataset 7)

Table 12 Summary of additional groundwater drawdown in the vicinity of the two additional coal mines for the Maranoa-Balonne-Condamine subregion

Additional groundwater drawdown predicted by the regional-scale Office of Groundwater Impact Assessment (OGIA) model associated with each coal mine is summarised by: 0.2 m – estimate of the extent of cumulative groundwater drawdown in excess of 0.2 m (p=0.05) in the vicinity of each coal mine; and 5 m – estimate of the extent of cumulative groundwater drawdown in excess of 5 m (p=0.05) in the vicinity of each coal mine.

Model layer – Formation	New Acland Stage 3	The Range
Model layer 1 – Alluvium (Condamine) and Main Range Volcanics	0.2 m: 20 to 30 km 5 m: 10 to 15 km	Not within model layer extent
Model layer 3 – Bungil Formation and Mooga Sandstone	Not within model layer extent	Not within model layer extent
Model layer 5 – Gubberamunda Sandstone	Not within model layer extent	Not within model layer extent
Model layer 8 – Lower Springbok Sandstone	Not within model layer extent	Not within model layer extent
Model layer 10 – Walloon Coal Measures	0.2 m: 30 to 40 km 5 m: 15 km	0.2 m: 50 to 60 km 5 m: 15 km
Model layer 12 – Hutton / Marburg Sandstone	0.2 m: 30 to 40 km 5 m: none	0.2 m: 50 to 60 km 5 m: none

Additional drawdown at economic bores

Hydrological changes due to additional coal resource development are presented as the maximum additional drawdown (*dmax*) and time to maximum drawdown (*tmax*) at the economic bores within two water balance areas in the Maranoa-Balonne-Condamine subregion. Two water balance areas are defined around the proposed open-cut coal mines (The Range and New Acland Stage 3 Coal Mine) that encompass all model grid cells where additional groundwater drawdown is greater than the minimum detectable difference (0.02 m) for the groundwater model. The New Acland Coal Mine water balance area contains 9213 bores and The Range water balance area contains 411 bores. The distribution of the 5th, 50th and 95th percentile values of *dmax* and *tmax* at the economic bores in affected aquifers (or model layers) are shown in Figure 25 and Figure 26 for the two water balance areas.

In the New Acland Coal Mine water balance area outside of the modelled pits, additional groundwater drawdown in excess of 0.2 m (p=0.05) is predicted at 98 bores (up to 65 m additional groundwater drawdown) in Model Layer 1 – Alluvium (Condamine) and Main Range Volcanics, 237 bores (up to 37 m additional groundwater drawdown) in Model layer 10 – Walloon Coal Measures and 108 bores (up to 2.9 m additional groundwater drawdown) in Model layer 12 – Hutton / Marburg Sandstone (Figure 25). Model Layer 1 – Alluvium (Condamine) and Main Range Volcanics includes 30 bores and Model layer 10 – Walloon Coal Measures includes 49 bores with 95th percentiles values of *dmax* greater than 5 m. Baseline groundwater drawdown (p=0.05) at these bores ranges from 0 to 45 m in Model Layer 1 – Alluvium (Condamine) and Main Range Volcanics and 0 to 19 m in Model layer 10 – Walloon Coal Measures.

Additional groundwater drawdown in excess of 0.2 m (p=0.05) is not predicted in Model Layer 1 – Alluvium (Condamine) and Main Range Volcanics in The Range water balance area (Figure 22). The Range water balance area (outside of the modelled pits) includes 95th percentile values of *dmax* in excess of 0.2 m at 29 bores in Model layer 10 – Walloon Coal Measures (0 to 14 m additional groundwater drawdown) and at 29 bores in Model layer 12 – Hutton / Marburg Sandstone (0 to 0.7 m additional groundwater drawdown) (Figure 26). Model layer 10 – Walloon Coal Measures includes 7 bores with 95th percentiles values of *dmax* between 5 and 14 m additional groundwater drawdown and baseline groundwater drawdown (p=0.05) of 0.7 to 2 m.

Overall, 86 of approximately 19,000 bores are predicted to experience hydrological changes in excess of a 95th percentile value of 5 m additional groundwater drawdown in the Maranoa-Balonne-Condamine subregion. The median time to reach maximum drawdown difference (*tmax*) is greater for small additional hydrological changes and less for larger changes in each model layer. This is because the larger values of *dmax* occur in bores close to the mines or within the modelled pits and the drawdown in these bores occurs in the years that immediately follow the mining activity. Smaller values of *dmax* are observed in bores located further from the mines and occur in later years when the groundwater drawdown propagates to these bores. This is consistent with groundwater responses to hydrological change.

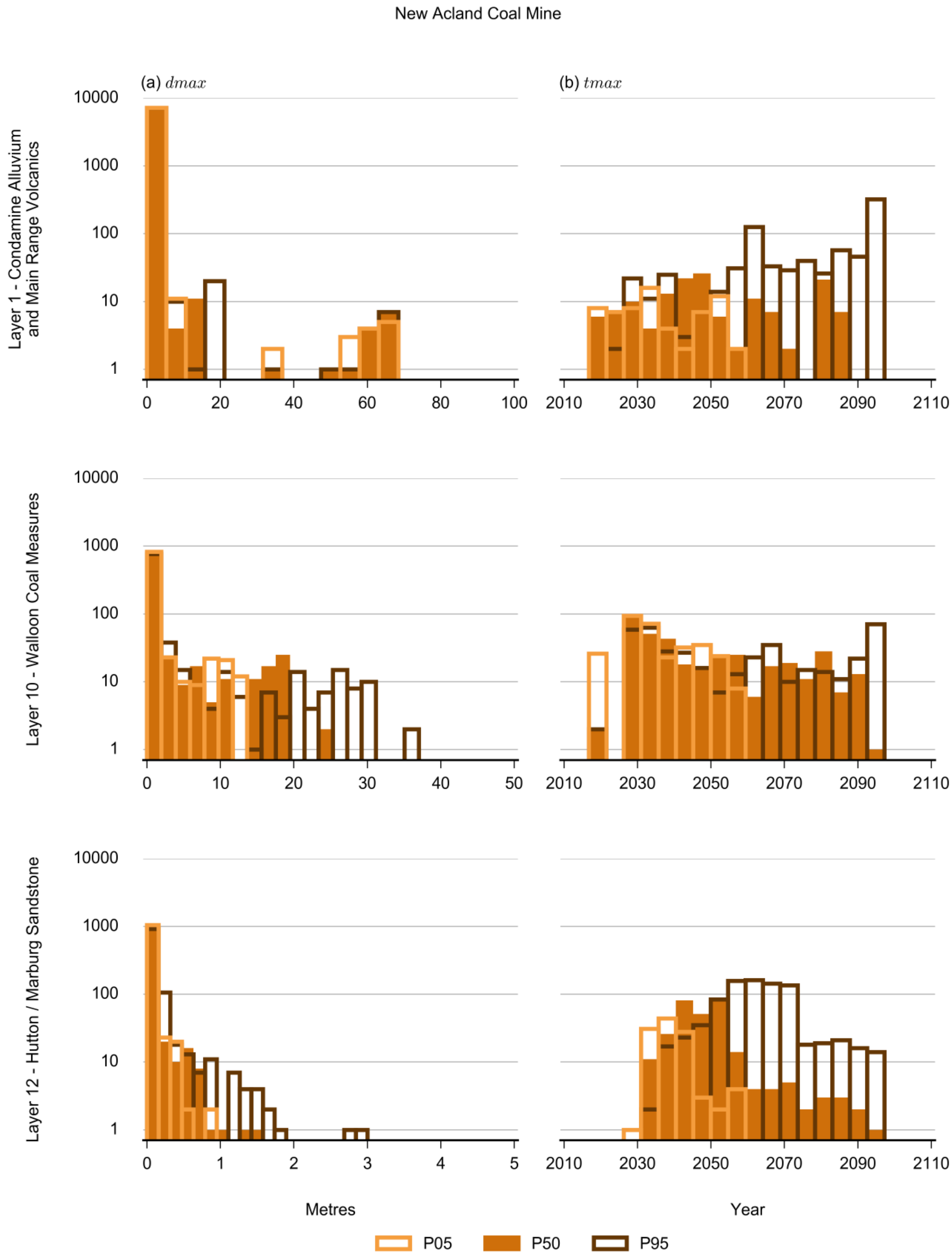

Figure 25 Histograms of 5th (P05), median (P50) and 95th (P95) percentile values of (a) maximum additional groundwater drawdown (*dmax*) and (b) corresponding time (*tmax*) for economic bores in model layers 1, 10 and 12 for New Acland Coal Mine water balance area

In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled. The number of economic bores in each category is shown using a logarithmic scale on the y-axis. The modelled time period is 90-years from 2012 to 2102.
Data: Bioregional Assessment Programme (Dataset 1)

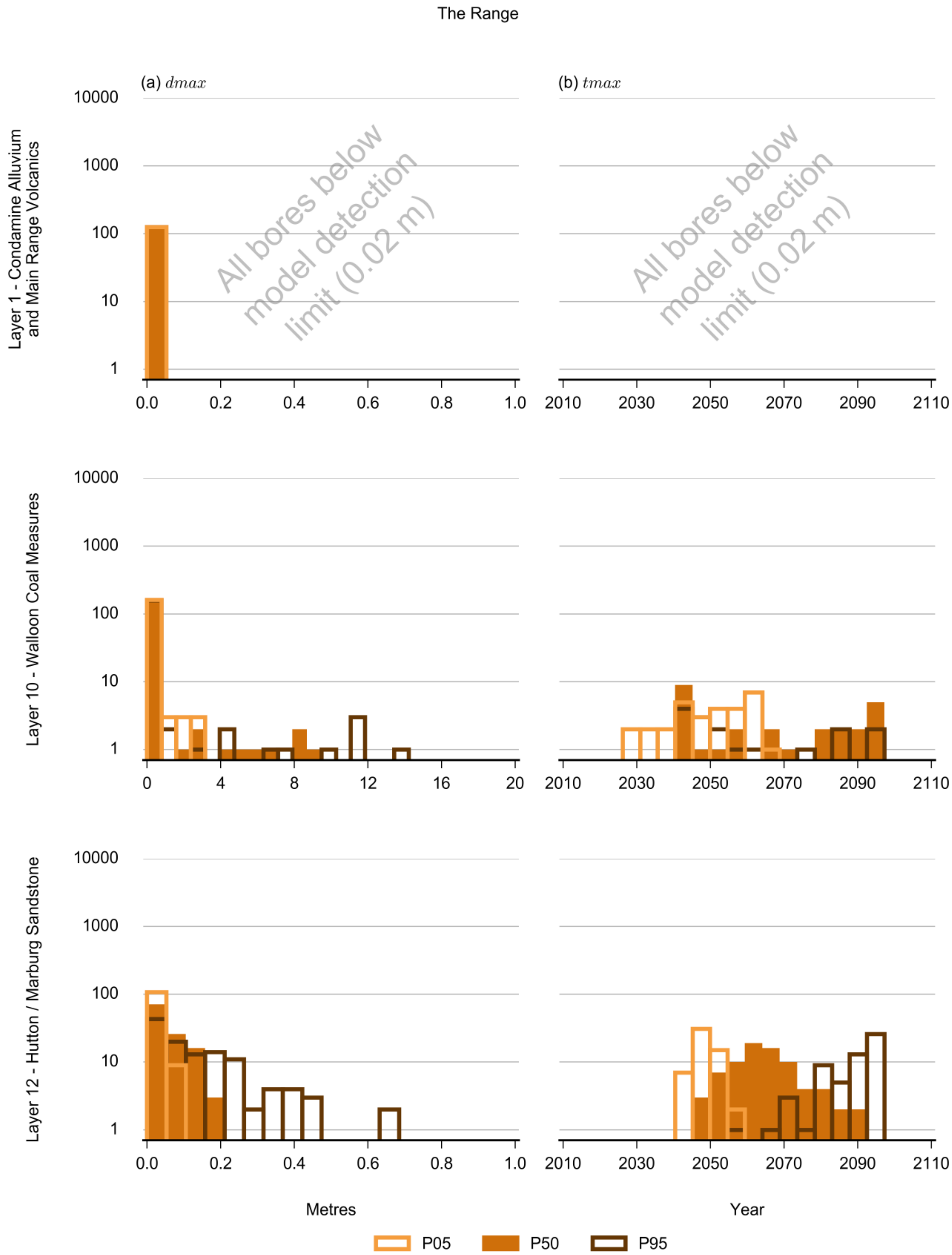

Figure 26 Histograms of 5th (P05), median (P50) and 95th (P95) percentile values of (a) maximum additional groundwater drawdown (*dmax*) and (b) corresponding time (*tmax*) for economic bores in model layers 1, 10, 12 for The Range water balance area

In this figure, results are presented for only that part of the coal resource development pathway (CRDP) that can be modelled. The number of economic bores in each category is shown using a logarithmic scale on the y-axis. The modelled time period is 90-years from 2012 to 2102.

Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.8.3 Qualitative uncertainty analysis

The major assumptions and model choices underpinning groundwater modelling in the Maranoa-Balonne-Condamine subregion are listed in Table 13. The goal of the table is to provide a non-technical audience with a systematic overview of the model assumptions, their justification and effect on predictions, as judged by the modelling team. This table is aimed to assist in an open and transparent review of the modelling. Each assumption is scored on four attributes using three levels: high, medium and low. Beneath the table, each of the assumptions are discussed in detail, including the rationale for the scoring.

The data column is the degree to which the question ‘if more or different data were available, would this assumption/choice still have been made?’ would be answered positively. A ‘low’ score means that the assumption is not influenced by data availability while a ‘high’ score would indicate that this choice would be revisited if more data were available. Closely related is the resources attribute. This column captures the extent to which resources available for the modelling, such as computing resources, personnel and time, influenced this assumption or model choice. Again, a ‘low’ score indicates the same assumption would have been made with unlimited resources, while a ‘high’ value indicates the assumption is driven by resource constraints. The third attribute deals with the technical and computational issues. ‘High’ is assigned to assumptions and model choices that are predominantly driven by computational or technical limitations of the model code. These include issues related to spatial and temporal resolution of the models. The final, and most important column, is the effect of the assumption or model choice on the predictions. This is a qualitative assessment by the modelling team of the extent to which a model choice will affect model predictions, with ‘low’ indicating a minimal effect and ‘high’ a large effect. The precautionary principle is applied for assumptions with a large potential impact on model predictions; that is, the hydrological change is overestimated, rather than underestimated.

Beneath the table, each of the assumptions is discussed in detail, including the rationale for the scoring. The goal of the table is to provide a non-technical audience with a systematic overview of the model assumptions, their justification and effect on predictions, as judged by the modelling team.

Table 13 Qualitative uncertainty analysis for the Maranoa-Balonne-Condamine subregion

In this table, each assumption is scored on four attributes using three levels: high, medium and low. For example, the data column is the degree to which the question 'if more or different data were available, would this assumption/choice still have been made?' would be answered positively. In other words, a 'low' score means that the assumption is not influenced by data availability while a 'high' score would indicate that this choice would be revisited if more data were available.

Assumption / Model choice	Data	Resources	Technical	Effect on predictions
Model horizontal and vertical discretisation	medium	high	high	medium
Model code and solver	low	low	high	low
Model boundary conditions	medium	low	low	low
Surface water – groundwater interactions	high	high	medium	low
Assume constant rate non-P&G extractions	high	low	low	low
Mine pit dewatering represented by MODFLOW drain cells	medium	high	medium	high
CSG activities simulated by MODFLOW evapotranspiration cells	low	medium	high	medium
Spatial interpolation of hydraulic conductivity, recharge and storage values	medium	low	low	low
Quantitative uncertainty analysis using 200 calibration-constrained parameter sets	medium	high	low	medium

CSG = coal seam gas, P&G = petroleum & gas

Model horizontal and vertical discretisation

The OGIA model is conceptualised with 19 layers consisting of 1.5 km x 1.5 km grid cells to represent all major aquifers and aquitards as described in detail in Section 2.6.2.3.3. The vertical and horizontal discretisation is partly driven by technical limitations as a higher resolution model would have more grid cells, which would make model runtimes and storage requirements exceedingly difficult.

Horizontal discretisation affects predictions, particularly where large hydraulic gradients are to be expected. Model predictions are most likely to be affected by horizontal discretisation in the immediate vicinity of coal mines where hydraulic gradients are steepest. Local-scale modelling is the only way to resolve this issue. Relatively simple representations of the Main Range Volcanics and Condamine Alluvium have been adopted in the model with each unit represented by a single layer for each unit. The integrated approach that OGIA used to model groundwater levels in the Condamine Alluvium using the more detailed Condamine Model is an example of using a more detailed local-scale model to make predictions at an appropriate scale.

Vertical discretisation is driven by the hydrostratigraphic interpretation of the geological basin at a regional scale and available modelling resources. While more detailed interpretations may be possible at a local scale, this stratigraphic interpretation is justified at the regional scale and sufficient data are available to create the top and bottom surfaces for each hydrostratigraphic unit. The Walloon Coal Measures are represented in the OGIA model using three model layers: an upper and lower layer representing generally low permeability mudstone and a composite middle representing all productive coal seams and inter-bedded low permeability sediments. While an increased vertical resolution allows for a more accurate representation of hydraulic properties, especially storage values, there are insufficient data to justify parameterising and constraining a higher vertical resolution at the regional scale. This will affect model predictions, but is compensated for by the calibration-constrained hydraulic conductivity parameters (*Kh* and *Kv*) that vary over several orders of magnitude in each layer of the OGIA model.

Model code and solver

MODFLOW is one of the industry standard codes for solving the finite difference groundwater flow equations and has a large number of different modules available for simulating different groundwater flow processes. But MODFLOW and other similar groundwater flow models are only able to simulate water movement and hence are unable to simultaneously simulate dual-phase flow. In the short-term and at the local scale, interaction between gas and water phases is an important factor governing water flow from CSG wells. Hence, the model has limitations in accurately estimating the short-term well yields and pressure recovery.

Model boundary conditions

The no flow boundary conditions to the north-east and north-west of the model domain coincide with the Surat and Bowen geological basin boundaries. There is no evidence of groundwater flow across these boundaries, meaning that the no flow boundaries are appropriate in this part of the model. MODFLOW general head boundary cells are used to simulate groundwater flow across the Surat and Clarence-Moreton basin boundaries to match hydraulic gradients derived from observed groundwater levels. Parameterisation of this boundary condition is limited by analysis of available groundwater level data. However, the OGIA model boundaries are sufficiently distant from the modelled CSG and coal mine areas, which means that these boundary conditions are unlikely to affect model predictions.

Surface water – groundwater interactions

Surface water – groundwater interactions in the OGIA model are simulated using MODFLOW drain and river packages. It is assumed that all surface watercourses act as groundwater discharge boundaries, meaning that groundwater only flows from the aquifer into the watercourse and that groundwater does not recharge the aquifer from the watercourse. This conceptualisation is consistent with previous studies of groundwater fluxes in the alluvial systems overlying the Great Artesian Basin (GAB) (Hillier, 2010). Groundwater is recharged in the GAB aquifer outcrop areas, with some groundwater discharging to watercourses via the alluvium, particularly in wetter years to sustain baseflows (QWC, 2012). This is a conservative approach to predicting groundwater drawdown, as it means recharge from surface watercourses cannot affect predicted groundwater level drawdown due to licensed extractions or for petroleum and gas (P&G) extractions.

This approach is not appropriate for the Condamine Alluvium, which is an important water source for irrigation, stock and domestic and town water supplies. Instead, OGIA used an integrated modelling approach for the Condamine Alluvium. Groundwater fluxes between the Walloon Coal Measures and the Condamine Alluvium model layers predicted by the regional model are set as boundary conditions for the more detailed Condamine Model to predict alluvial groundwater levels. Minimal additional groundwater drawdown less than 1.0 m ($p=0.05$) is predicted in Model layer 10 – Walloon Coal Measures under the eastern edge of the Condamine Alluvium in the vicinity of the New Acland Coal Mine. This is not considered likely to cause additional groundwater drawdown in the Condamine Alluvium. For this reason, the more detailed Condamine Model is not used to revise surface water – groundwater interactions in the Condamine Alluvium for BA. Available data, resources and technical issues limit representation of surface water – groundwater interactions in the regional model. However, this is likely to have a minimal effect on the regional-scale model predictions, which are confined to the deeper model layers for which the OGIA model was developed.

The focus on the deep regional aquifers targeted by CSG development means that the OGIA model may not on its own be suitable for assessing hydrological changes in surficial aquifers that are important in representing impacts to surface water – groundwater interactions and groundwater-dependent ecosystems. Improved model predictions for risk and impact analysis of surface water – groundwater interactions and groundwater-dependent ecosystems in the surficial aquifers would require significant additional investment in modelling resources, but is likely to be limited by water quality and quantity data availability.

Assume constant rate non-P&G (petroleum and gas) extractions

All groundwater extractions except CSG depressurisation and mine dewatering are considered to be occurring at a constant rate for individual bores. This assumption was mainly driven by the limited availability of time series data of groundwater extractions. Information on the aquifer from which water is taken and the volumes of extraction were largely absent. Hence, the missing information is estimated from geological mapping and other information. Extraction volumes are estimated using the best available information and follow the methodology used in the preparation of the *Great Artesian Basin Water Resources Plan* and *Murray Darling Basin Plan*. In accordance with previous water resources studies, groundwater extraction is assumed to be at the full entitlement level. The trajectory modelling approach used by OGIA and BA, where reported drawdown is the difference between the baseline and the development case, means that non-P&G extraction volumes have a minimal impact on predicted cumulative impacts of coal resource development.

Mine pit dewatering represented by MODFLOW drain cells

Simulation of dewatering of the open-cut coal mines using the MODFLOW drain package is affected by drain cell elevations, which are derived from the regional-scale hydrostratigraphic interpretation of the geological basin. More accurate drain cell elevations and pit geometry are available in local-scale models, such as those used during the environmental impact assessments. However, the regional-scale hydrostratigraphic interpretation and pit geometry is justified for the 1.5 km × 1.5 km grid cells used in the regional model. While data are available to improve model predictions of mine pit dewatering at a local scale, the conservative approach used for the BA modelling is driven by limited modelling resources and technical and computation requirements that are inherent in regional-scale modelling. The predictions of cumulative drawdown impacts are considered appropriate at a regional scale. However, predicting absolute drawdown in the vicinity of the mines is beyond the capability of this representation.

Coal seam gas activities simulated by MODFLOW evapotranspiration cells

The MODFLOW EVT package used to simulate groundwater extraction associated with petroleum and gas activities, including CSG, includes historical and planned extraction rates. This dataset is revised annually using the development scenarios provided by the tenure holders to OGIA each year (OGIA, 2014). The MODFLOW EVT package sets user defined volumes of water extraction that are subject to an additional control on resulting head. This is a superior approach for representing CSG depressurisation in MODFLOW models compared to using the well or drain packages.

While the representation of CSG depressurisation as single-phase flow in MODFLOW in the OGIA model is not limited by data availability, resources or technical issues, MODFLOW is not able to simulate dual-phase flow. CSG depressurisation using MODFLOW model code over-estimates produced water volumes and hence groundwater drawdown during the initial production periods. A better method for representing CSG depressurisation using the MODFLOW code is currently unavailable. Alternative modelling approaches using dual-phase model code have greater data, resources and technical or computational requirements and would improve the accuracy of predicted drawdowns.

Spatial interpolation of hydraulic conductivity, recharge and storage values

Hydraulic conductivity, recharge and storage values are known to be heterogeneous and spatially variable. The regional model is calibrated using water levels or water pressure measurements for 1541 bores. The parameter sets – horizontal (Kh) and vertical (Kv) hydraulic conductivity, vertical anisotropy, recharge rates and specific storage (Ss) / specific yield (Sy) – are included in the model using pilot points (GHD, 2012). Pilot points are located 45 km apart, reducing to 15 km or less in areas and layers of particular interest. This approach resulted in 200 sets of horizontal and vertical parameter values that varied spatially, where the overall difference between observed and predicted water levels is within the acceptable calibration limits.

Spatial parameterisation using the pilot point approach to define calibration-constrained parameter sets for the uncertainty analysis reduces the reliance of model predictions on heterogeneous parameters that are inherently data limited. This uncertainty analysis approach means that additional estimates of parameter values do not limit model predictions. However, additional time series of groundwater levels would potentially reduce predictive uncertainty.

Quantitative uncertainty analysis using 200 calibration-constrained parameter sets

The quantitative uncertainty analysis numerically evaluates the uncertainty in the hydraulic conductivity fields. However, this does not account for uncertainty in other hydraulic properties and boundary conditions. While it is technically possible to include these parameters, the number of model runs and data required are prohibitive in the context of a regional-scale model. The effect of the individual components on model predictions is discussed in 2.6.2.8.1. The existing uncertainty analysis accounts for the potential effects of hydraulic conductivity, recharge and storage values on model predictions, but not model conceptualisation or the parameters used to specify drain and river boundary conditions.

The 200 calibration-constrained parameter sets obtained from OGIA are used for the quantitative uncertainty analysis. These parameter sets are calibrated to pre 1995 groundwater levels that represent a period before significant coal seam gas extraction (CSG) and open-cut coal mine development affected the regional groundwater levels. For this reason, the OGIA model was not recalibrated when the open-cut coal mine boundary conditions were added for the BA groundwater modelling in the Maranoa-Balonne-Condamine subregion. Model calibration with additional groundwater level or flux observations and a finer resolution model grid in the vicinity of the coal mines would improve model predictions, but is not feasible in the existing regional-scale groundwater model.

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Datasets

Dataset 1 Bioregional Assessment Programme (2015) MBC Groundwater model uncertainty plots. Bioregional Assessment Derived Dataset. Viewed 12 April 2016, http://data.bioregionalassessments.gov.au/dataset/44f36874-d053-4cfb-9ccd-d5407e3b1b18.

Dataset 2 Office of Groundwater Impact Assessment (2012) MBC Groundwater model layer boundaries. Bioregional Assessment Source Dataset. Viewed 14 April 2016, http://data.bioregionalassessments.gov.au/dataset/32b986d0-c3d0-4a01-a5a9-6fffde638e11.

Dataset 3 Office of Groundwater Impact Assessment (2015) Coal Seam Gas company development proposals. Bioregional Assessment Source Dataset. Viewed 22 April 2016, http://data.bioregionalassessments.gov.au/dataset/297b5b8b-5138-4de9-acf3-c9301428052a.

Dataset 4 Office of Groundwater Impact Assessment (2012) Baseline drawdown Layer 1 - Condamine Alluvium. Bioregional Assessment Source Dataset. Viewed 22 April 2016, http://data.bioregionalassessments.gov.au/dataset/49b2cbac-c570-461d-b6e6-8e2e584aeaea.

Dataset 5 Geoscience Australia (2012) Surface Geology of Australia, 1:1 000 000 scale, 2012 edition. Bioregional Assessment Source Dataset. Viewed 22 April 2016, http://data.bioregionalassessments.gov.au/dataset/8284767e-b5b1-4d8b-b8e6-b334fa972611.

Dataset 6 Geoscience Australia (2015) Great Artesian Basin - Hydrogeology and Extent Boundary. Bioregional Assessment Source Dataset. Viewed 22 April 2016, http://data.bioregionalassessments.gov.au/dataset/020957ea-4877-4009-872c-3cacfb6f8ded.

Dataset 7 Bioregional Assessment Programme (2016) MBC Groundwater model uncertainty analysis. Bioregional Assessment Derived Dataset. Viewed 22 April 2016, http://data.bioregionalassessments.gov.au/dataset/484c800e-55e0-465a-9243-c440311c51f3.

2.6.2.9 Limitations

Summary

The representations of surface water – groundwater interactions, mine pit dewatering, coal seam gas (CSG) activities and horizontal and vertical discretisation in the regional model are identified as having the greatest potential effect on model predictions in the qualitative uncertainty analysis. The revised Office of Groundwater Impact Assessment (OGIA) model released for public comment in early 2016 has addressed many of the model data and resource availability and technical issues. The consistency between OGIA 2012 and revised OGIA 2016 model predictions of hydrological change lends confidence to the bioregional assessment (BA) model predictions. The main opportunities to reduce predictive uncertainty in the regional model for this BA are related to the representation of hydrological changes in surficial aquifers that affect surface water – groundwater interactions and groundwater-dependent ecosystems.

The regional groundwater model was developed with the single purpose 'to provide a suitable tool for assessing the impacts of CSG development on water levels in the aquifers present within the Surat cumulative management area'. It is 'therefore on its own not necessarily suitable for predicting responses to arbitrary changes in hydrological conditions, developing sustainable water resource management policies, assessing impacts on groundwater-dependent ecosystems or quantifying surface water – groundwater interactions' (GHD, 2012, p. 50). However, it has the best available representation of CSG development in the Surat cumulative management area and is considered fit for purpose for BA groundwater modelling, with the exception of criteria related to the representation of water fluxes in surficial aquifers.

Hydrological changes arising from coal resource development for two possible futures – the baseline and the coal resource development pathway (CRDP) – are assessed using a probabilistic approach to inform the assessment of direct impacts on groundwater-dependent assets, such as groundwater-dependent ecosystems and economic bores. The focus on the deep regional aquifers targeted by CSG development, means that the conceptual model of causal pathways that describes the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water and water-dependent assets will inform the assessment of indirect impacts.

Maximum baseline groundwater drawdown associated with CSG production (in excess of 700 m) is predicted near the towns of Chinchilla and Roma. Baseline groundwater drawdown associated with CSG production in the vicinity of the coal mines is generally less than 10 m. Hydrological changes in the vicinity of the five baseline coal mines are generally within 5 to 10 km (maximum 15 to 20 km) of the modelled pits. Additional groundwater drawdown in the vicinity of proposed coal mines is generally within 20 to 40 km (maximum 50 to 60 km) of the proposed pits. Overall, 86 of the 19,000 economic bores are predicted to experience more than 5 m additional groundwater drawdown in the Maranoa-Balonne-Condamine subregion.

2.6.2.9.1 Data gaps and opportunities to reduce predictive uncertainty

Two assumptions or model choices that have a large potential impact on model predictions: 'Surface water – groundwater interactions' and 'Mine pit dewatering represented by MODFLOW drain cells' are identified in the qualitative uncertainty analysis. The representation of hydrological changes in surficial aquifers that affect surface water – groundwater interactions and groundwater-dependent ecosystems are influenced by model assumptions and the availability of water quality and quantity data. Assumptions and model choices related to 'Mine pit dewatering represented by MODFLOW drain cells' can also have a large potential impact on model predictions. Data and resources that limit improved model predictions are related to the use of regional-scale hydrostratigraphic interpretation and pit geometry, which are appropriate for the 1.5 km × 1.5 km grid cells used in the regional model, but mean that model predictions are not comparable to those made using local-scale groundwater models, such as those used during the environmental impact assessments.

'Model horizontal and vertical discretisation', 'CSG activities simulated by MODFLOW evapotranspiration cells' and 'Quantitative uncertainty analysis using 200 calibration constrained parameter sets' have a medium potential impact on model predictions. The revised OGIA model developed for the Surat Underground Water Impact Report (UWIR) and released for public comment in early 2016 (OGIA, 2016) has addressed several of the assumptions and model choices identified in the qualitative uncertainty analysis, including:

- reinterpretation of geological logs for over 7700 water bores, including surficial aquifers
- interpretation of geologic formation contacts from geophysical logs for over 4800 petroleum and gas wells and water bores
- estimated displacements associated with 17 major fault systems
- initial parameter distributions derived from lithological data and hydraulic parameter estimates
- revised estimates of natural groundwater recharge
- hydrostratigraphy represented by 32 model layers, including 3 to 6 layers to represent target coal seams
- MODFLOW USG model code using dual-porosity functionality in target coal seams to approximate water and gas flow in and near CSG wells, where CSG extraction is represented using gradually descending MODFLOW Drain cells
- model calibration using water levels from 12,000 bores (OGIA 2012 model used 1500 bores).

The OGIA 2016 model has addressed many of the model data and resource availability and technical issues, which has reduced model prediction uncertainty of areas impacted by CSG development. However, the patterns of long-term drawdown impacts are broadly consistent between the OGIA 2012 model used for BA and the revised OGIA 2016 model, lending confidence to the BA model predictions and indicating that these improvements to the regional model have a moderate effect on model predictions. Changes to the representation of hydrological changes in surficial aquifers that affect surface water – groundwater interactions and groundwater-dependent ecosystems provide the greatest opportunities to reduce predictive uncertainty in the regional model.

2.6.2.9.2 Modelling limitations

The report for the Queensland Water Commission (GHD, 2012) states that the 2012 Office of Groundwater Impact Assessment (OGIA) model was developed

> 'to provide a suitable tool for assessing the impacts of CSG activities on water levels in the aquifers present within the Surat CMA. The modelling work was therefore undertaken with this single purpose in mind. Hence, according to the definitions presented in the MDBC modelling guideline (Middlemis et al., 2000), the regional scale model developed is considered to be an 'impact assessment model'. The model is therefore not considered to be an 'aquifer simulator' and is therefore on its own not necessarily suitable for:
>
> - Predicting responses to arbitrary changes in hydrological conditions;
> - Developing sustainable water resource management policies;
> - Assessing impacts on groundwater dependent ecosystems; or
> - Quantifying surface water – groundwater interactions.
>
> In particular the regional scale of the model and hence the relatively coarse model grid is likely to represent a significant limitation to use of the model for these purposes' (GHD, 2012, p. 50).

The first generation OGIA model built in 2012 has the best available representation of CSG development in the Surat cumulative management area (CMA) for cumulative groundwater impact assessment purposes. It is considered a fit-for-purpose regional-scale groundwater model for the bioregional assessment of the Maranoa-Balonne-Condamine subregion, with the exception of criteria related to integration with surface water numerical modelling and receptor impact modelling that are related to the representation of water fluxes in surficial aquifers, as discussed in Section 2.6.2.1.

The representation of surface water – groundwater interactions, mine pit dewatering, CSG activities and horizontal and vertical discretisation are identified as having the greatest potential effect on model predictions in the qualitative uncertainty analysis. Drain cell conductance, which represents mine pit dewatering, has a major effect on modelled drawdown and water balance. Higher drain cell conductance values will increase the slope of modelled groundwater drawdown above the drain cell elevation in the surrounding model cells. However, it is not considered in the formal uncertainty analysis. The MODFLOW EVT package is considered a superior approach for representing CSG depressurisation in MODFLOW models compared to using the well or drain packages. However, while alternative modelling approaches using dual-phase model code would improve the accuracy of predicted drawdowns they have greater data, resources and technical or computational requirements. Horizontal discretisation affects model predictions, particularly where large hydraulic gradients are to be expected, such as near coal mines where hydraulic gradients are steepest. Local-scale modelling is the only way to resolve this issue. The integrated approach that OGIA used to model groundwater levels in the Condamine Alluvium is an example of using a more detailed local-scale model to make predictions at an appropriate scale. While an increased vertical discretisation allows for a more accurate representation of hydraulic properties, especially storage values, there are insufficient data to justify parameterising and constraining a higher vertical resolution at the regional scale.

The quantitative uncertainty analysis considered hydraulic conductivity, recharge and storage values, but did not consider the parameters used to specify boundary conditions such as drain and river boundary conductance and the lateral head dependent boundary conditions. Model conceptualisation is not considered as part of the formal uncertainty analysis. The calibration-constrained uncertainty analysis is used to quantify the effect of horizontal hydraulic conductivity, vertical anisotropy, modelled watertable recharge and specific storage/specific yield on model predictions. These parameters are not re-calibrated after the boundary conditions that represent the open-cut coal mines are added into the model. However, this is not likely to affect modelled predictions as the pre 1995 groundwater levels used for model calibration represent a period before significant CSG extraction and open-cut coal mine development affected the regional groundwater levels. Model calibration with additional groundwater level or flux observations and a finer resolution model grid in the vicinity of the coal mines would improve model predictions, but is not feasible in the existing regional-scale groundwater model.

2.6.2.9.3 Conclusions

The review of existing groundwater models concluded that the first generation OGIA model built in 2012 meets the fit-for-purpose criteria for groundwater modelling in BA, with the exception of criteria related to the representation of water fluxes in surficial aquifers. The primary purpose of the OGIA model is to probabilistically predict the regional water pressure and water level changes in aquifers within the Surat CMA in response to the depressurisation of the coal seams for CSG production. The OGIA model is re-run annually based on the latest available industry development plans and has been revised for the BA to also simulate water-related impacts of coal mine developments in the Maranoa-Balonne-Condamine subregion.

Hydrological changes arising from coal resource development for two possible futures – the baseline and the CRDP – are assessed using a probabilistic approach. Probabilistic estimates of the hydrological changes associated with coal resource development in the Maranoa-Balonne-Condamine subregion can inform the assessment of direct impacts on groundwater-dependent assets, such as groundwater-dependent ecosystems (ecological assets), or groundwater bores used for stock, irrigation and domestic purposes (economic assets). The focus on the deep regional aquifers targeted by CSG development, means that integration of the OGIA model with a surface water numerical model and receptor impact modelling is not possible at this time in the Maranoa-Balonne-Condamine subregion. Instead, the conceptual model of causal pathways that describes the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water and water-dependent assets will inform the assessment of indirect impacts.

The OGIA model uses calibration-constrained uncertainty analysis, which is also known as Null-space Monte Carlo Analysis. This approach provides an efficient method to explore the non-uniqueness of model parameters and resulting model prediction uncertainty. The formal uncertainty analysis considered hydraulic conductivity, recharge and storage values, but did not consider model conceptualisation or the parameters used to specify drain and river boundary conditions. The 200 calibration-constrained parameter sets are defined spatially using pilot points in each model layer, which gives spatial coherence to the model parameter values that is consistent with the model conceptualisation and uses regularisation to solve the problem mathematically.

Model predictions of baseline groundwater drawdown associated with coal resource development are presented as maps of the 95th percentile of baseline groundwater drawdown. The baseline future includes five baseline open-cut coal mines and the five baseline CSG projects that are reported in the 2014 Annual Report for the Surat CMA (OGIA, 2014). Maximum baseline groundwater drawdown associated with CSG production (in excess of 700 m drawdown in the productive Walloon Coal Measures model layer) is predicted near the towns of Chinchilla and Roma. Hydrological changes in excess of 0.2 m baseline groundwater drawdown in the vicinity of the five baseline coal mines are generally within 5 to 10 km (maximum 15 to 20 km) of the modelled pits. Baseline groundwater drawdown associated with CSG production in the vicinity of the coal mines is generally less than 10 m (maximum 20–40 m in the Walloon Coal Measures model layer).

Model predictions of additional groundwater drawdown under the CRDP future are presented as maps of the probability of exceeding additional groundwater drawdown thresholds for each model layer and histograms of maximum additional drawdown (*dmax*) and time to maximum drawdown (*tmax*) at the economic bores within the two water balance areas. The CRDP future includes the baseline coal resource developments plus the two proposed open-cut coal mines. Additional groundwater drawdown in the vicinity of the proposed coal mines in excess of 0.2 m (probability, p=0.05) is generally within 20 to 40 km (maximum 50 to 60 km in the Walloon Coal Measures and Hutton / Marburg Sandstone model layers) of the proposed pits. Additional groundwater drawdown in the vicinity of proposed coal mines in excess of 5 m (p=0.05) is generally less than 10 km (maximum 10 to 15 km in the Walloon Coal Measures model layer) of the proposed pits. Overall, 86 of approximately 19,000 bores are predicted to experience hydrological changes in excess of a 95th percentile value of 5 m additional groundwater drawdown in the Maranoa-Balonne-Condamine subregion outside of the proposed pit extents.

The quantitative uncertainty analysis considered hydraulic conductivity, recharge and storage values, but not model conceptualisation or the parameters used to specify drain and river boundary conditions. The representation of hydrological changes in surficial aquifers that affect surface water – groundwater interactions and groundwater-dependent ecosystems are influenced by model assumptions and the availability of water quality and quantity data. Assumptions and model choices related to mine pit dewatering are related to the use of regional-scale hydrostratigraphic interpretation and pit geometry. The revised OGIA model developed for the Surat Underground Water Impact Report (UWIR) and released for public comment in early 2016 (OGIA, 2016) has addressed many of the model data and resource availability and technical issues discussed in the qualitative uncertainty analysis. The patterns of long-term drawdown impacts are broadly consistent between the OGIA 2012 model used for BA and the revised OGIA 2016 model, lending confidence to the BA model predictions and indicating that these improvements to the regional model have a moderate effect on model predictions. Changes to the representation of hydrological changes in surficial aquifers that affect surface water – groundwater interactions and groundwater-dependent ecosystems provide the greatest opportunities to reduce predictive uncertainty in the regional groundwater model used for this Assessment.

References

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Glossary

The register of terms and definitions used in the Bioregional Assessment Programme is available online at http://environment.data.gov.au/def/ba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies.

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with a coal seam gas (CSG) operation or coal mine. For example, activities during the production life-cycle stage in a CSG operation include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into components, which are grouped into life-cycle stages.

aquifer: rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit quantities of water to wells and springs

asset: an entity that has value to the community and, for bioregional assessment purposes, is associated with a subregion or bioregion. Technically, an asset is a store of value and may be managed and/or used to maintain and/or produce further value. Each asset will have many values associated with it and they can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

baseline coal resource development: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012

bioregion: a geographic land area within which coal seam gas (CSG) and/or coal mining developments are taking place, or could take place, and for which bioregional assessments (BAs) are conducted

bioregional assessment: a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion, with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and coal mining development on water resources. The central purpose of bioregional assessments is to analyse the impacts and risks associated with changes to water-dependent assets that arise in response to current and future pathways of coal seam gas and coal mining development.

bore: a narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole or piezometer.

causal pathway: for the purposes of bioregional assessments, the logical chain of events either planned or unplanned that link coal resource development and potential impacts on water resources and water-dependent assets

conceptual model: abstraction or simplification of reality context: the circumstances that form the setting for an event, statement or idea

dataset: a collection of data in files, databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file). In the BA Repository, datasets are guaranteed to have a metadata record in the Metadata Catalogue and to have their components (files, database interface) delivered via the Data Store. In semantic web terms, a BA dataset is defined as a subclass of DCAT Dataset and PROMS Entity and is described in the BA Ontology as a scope note in term record.

direct impact: for the purposes of bioregional assessments, a change in water resources and water-dependent assets resulting from coal seam gas and coal mining developments without intervening agents or pathways

ecosystem: a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit. Note: ecosystems include those that are human-influenced such as rural and urban ecosystems.

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), change in the quantity or quality of surface water or groundwater. An effect is a specific type of an impact (any change resulting from prior events).

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels

formation: rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time

groundwater: water occurring naturally below ground level (whether in an aquifer or other low permeability material), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

groundwater-dependent ecosystem: ecosystems that rely on groundwater - typically the natural discharge of groundwater - for their existence and health

groundwater recharge: replenishment of groundwater by natural infiltration of surface water (precipitation, runoff), or artificially via infiltration lakes or injection

hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock

impact: a change resulting from prior events, at any stage in a chain of events or a causal pathway. An impact might be equivalent to an effect (change in the quality or quantity of surface water or groundwater), or it might be a change resulting from those effects (for example, ecological changes that result from hydrological changes).

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

indirect impact: for the purposes of bioregional assessments, a change in water resources and water-dependent assets resulting from coal seam gas and coal mining developments with one or more intervening agents or pathways

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass

receptor: a point in the landscape where water-related impacts on assets are assessed

recharge: see groundwater recharge

source dataset: a pre-existing dataset sourced from outside the Bioregional Assessment Programme. This includes data sourced from the Programme partner organisations.

stratigraphy: stratified (layered) rocks

subregion: an identified area wholly contained within a bioregion that enables convenient presentation of outputs of a bioregional assessment (BA)

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs

uncertainty: the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence, or likelihood. For the purposes of bioregional assessments, uncertainty includes: the variation caused by natural fluctuations or heterogeneity; the incomplete knowledge or understanding of the system under consideration; and the simplification or abstraction of the system in the conceptual and numerical models.

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development

watertable: the upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating or recovering various natural resources, such as hydrocarbons (oil and gas) or water. As part of the drilling and construction process the well can be encased by materials such as steel and cement, or it may be uncased. Wells are sometimes known as a ‘wellbore’.

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