Australian Government

BIOREGIONAL ASSESSMENTS

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

Groundwater numerical modelling for the Clarence-Moreton bioregion

Product 2.6.2 from the Clarence-Moreton Bioregional Assessment

20 October 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

The Office of Water Science, within the Australian Government Department of the Environment and Energy, is strengthening the regulation of coal seam gas and large coal mining development by ensuring that future decisions are informed by substantially improved science and independent expert advice about the potential water related impacts of those developments. For more information, visit http://www.environment.gov.au/coal-seam-gas-mining/.

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Authorship is listed in relative order of contribution.

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Cover photograph

Rainforest waterfall in Border Ranges National Park, NSW, 2008

Credit: Liese Coulter, CSIRO

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Department of the Environment and Energy
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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 provides the modelled hydrological changes to groundwater in response to likely coal resource development in the Clarence-Moreton bioregion after December 2012. The methods are summarised and existing models are reviewed, followed by details regarding the model development, parameterisation, and sensitivity analysis. The product concludes with probabilistic predictions of hydrological change, including uncertainty analysis and a discussion of model limitations.

This bioregional assessment (BA) considers two potential futures:

- baseline coal resource development (baseline): a future that includes all coal mines and 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 BA. This change is due to the additional coal resource development – all coal mines and CSG fields, including expansions of baseline operations, which are expected to begin commercial production after December 2012.

The conceptual model for the Clarence-Moreton bioregion in companion product 2.3 (Conceptual modelling for the Clarence-Moreton bioregion) indicates that no new coal mines are expected in the foreseeable future and CSG development is restricted to the Richmond river basin of north-eastern NSW. There is only one additional coal resource development in the Richmond river basin, the West Casino Gas Project (Metgasco Limited) near Casino, NSW. The Clarence-Moreton bioregion baseline includes only one operational mine, namely, the Jeebropilly Mine that is located in the Bremer river basin. As the only baseline coal mine is very remote from the West Casino Gas Project and geological evidence suggests that it is not hydraulically connected to the Richmond river basin, the conceptual hydrogeological model only focused on the geological, hydrogeological and hydrological characteristics of the Richmond river basin.

A recent decision by Metgasco (16 December 2015) to sell back their petroleum exploration licences (PELs) to the NSW Government, as well as withdraw their petroleum production license application (PPLA), effectively means that future development of any CSG resources in the Clarence-Moreton bioregion is highly uncertain. However, as per companion submethodology M04 for developing a coal resource development pathway, once the CRDP is determined, it is not changed for BA purposes, even in cases such as this where Metgasco have discontinued their operations in the Clarence-Moreton bioregion.

Groundwater modelling in the Clarence-Moreton bioregion was guided by the criteria reported in companion submethodology M07 (as listed in Table 1) for groundwater modelling. A regional numerical MODFLOW groundwater model was developed to assess the potential impacts of CSG development on water-dependent assets within and surrounding the area of the West Casino Gas Project. Hydrostratigraphic units in the Richmond river basin were represented by six layers in the MODFLOW model, including layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock), layer 2 (Grafton Formation), layer 3 (Bungawalbin Member), layer 4 (Kangaroo Creek Sandstone Member), layer 5 (Maclean sandstone of the Walloon Coal Measures) and layer 6 (coal seams of the Walloon Coal Measures). The groundwater model provided drawdown estimates to assess the direct impacts on groundwater-dependent assets. The direct impact of CSG extraction was reported as the maximum difference in groundwater levels between the baseline and CRDP, along with the time at which it was realised. In addition, the model provided estimates of the exchange flux between surface water and groundwater, which provided input into the surface water model (Australian Water Resources Assessment (AWRA) landscape model (AWRA-L)) to assess the indirect impacts on surface-water-dependent assets. Baseflow change due to the West Casino Gas Project was reported at 16 virtual gauge locations.

CSG extraction wells within the Walloon Coal Measures were simulated in the numerical groundwater model using the MODFLOW Drain package, with a variable conductance that aimed at matching the previously estimated volumes of the extracted water while achieving the target pressure heads. All coal seams were amalgamated into a single layer for the purpose of simulation due to the lack of information regarding the internal structure of the Walloon Coal Measures, in addition to reducing model execution time.

Three types of observed data were used to constrain the uncertainty analysis; namely, historical groundwater levels, water production forecasts and baseflow estimates. Groundwater level records from 188 groundwater bores were used to constrain the simulated baseline heads and 712 water level measurements from 30 monitoring groundwater bores were used to constrain the transient simulations during the period between 1983 and 2013. Upper and lower limits were imposed based on the independently generated forecasts provided by Metgasco to constrain the simulated water production. The observed baseflow in the Richmond River at the Casino gauging station that was derived from historical hydrograph time series from 1983 to 2013 was also used to constrain the pre-production analyses.

A total of 38 parameters were varied during the sensitivity and uncertainty analyses yielding 10,000 parameter combinations, which resulted in 3,877 successful evaluations that could be achieved within the operational constraints of the project. Recharge, drainage conductance of non-CSG drain cells and riverbed conductance were found to be the three most sensitive parameters influencing head observations in layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock). The drawdown impact on existing groundwater bores in layer 3 (Bungawalbin Member) was dominated by the vertical hydraulic conductivity ratio of layer 3, followed by the hydraulic conductivity of layers 3 and 4 (Kangaroo Creek Sandstone). The drain conductance of the CSG wells and the storage coefficient and hydraulic conductivity of layer 6 (coal seams of the Walloon Coal Measures) controlled the amount of water that could potentially be produced due to the depressurisation process.

In the Clarence-Moreton bioregion, predictions of drawdown due to the West Casino Gas Project – referred to as additional drawdown, and year of maximum change are made at 1462 model nodes. The median predicted changes in groundwater levels due to the West Casino Gas Project were less than 0.01 m across all model nodes, with the 95th percentile of additional drawdown not exceeding 1 m. For most of the model nodes, the year of maximum change is at or beyond 2102, although a considerable number of model nodes in layers 1 to 4 have median predicted year of maximum change in the decades following cessation of active depressurisation. The 95th percentile of additional drawdown at mode nodes located in the Walloon Coal Measures (layer 6), the target coal seam layer of the CSG extraction, was also less than 1 m. This was due to the model nodes in layer 6 being located close to the model boundary and outside the West Casino Gas Project extents. The additional drawdown in the Walloon Coal Measures should be larger at locations that are nearby the CSG wells within the West Casino Gas Project extents. However, there are no model nodes in the West Casino Gas Project area for model layer 6 (Walloon Coal Measures), so no model predictions were made there for this assessment.

The absolute surface water – groundwater flux, including both leakage and baseflow, was most sensitive to the riverbed conductance followed by the drainage conductance of the non-CSG drainage boundary at the top of the model and the recharge multipliers of recharge in the alluvium and volcanics. However, the drainage conductance of the CSG drain cells is the second-most influential parameter after the riverbed conductance for the change of the exchange flux due to the West Casino Gas Project at most reporting gauges. The median predicted change in surface water – groundwater flux at the reported locations does not exceed 0.01 GL/year.

Overall, the extracted water volume, which mainly depends on the scale of development and the hydraulic properties of target coal seams, is the major controlling factor for forecast impact. In the current study, the influence of hydraulic properties has been taken into account by assigning them a wide value range in order to avoid underestimation during uncertainty analysis. The minor forecast impact likely reflects the relatively small number of wells assumed for the West Casino Gas Project.

Although the current model has shown that the overall potential impact of the West Casino Gas Project is very minor, it is worth highlighting the implications of the limiting assumptions. The groundwater model described in this product is designed for the specific purpose of delivering a probabilistic assessment of the impact of the West Casino Gas Project on water resources in the Clarence-Moreton bioregion. In its current form, the model is neither suited to address any other water management questions nor provide deterministic predictions of hydrological change for this bioregion. Any evaluation or further use of the model requires a formal re-evaluation of the suitability of the conceptual model and underpinning assumptions.

The impact and risk analysis (product 3-4) will not be conducted in the Clarence-Moreton bioregion due to the limited potential for impacts of the additional coal resource development in the bioregion. However, an outcome synthesis (product 5) will be developed for the Clarence-Moreton bioregion to summarise the key findings of this assessment.

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Figures

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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: Dirk Mallants (CSIRO) and Peter Cook (NCGRT).

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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.

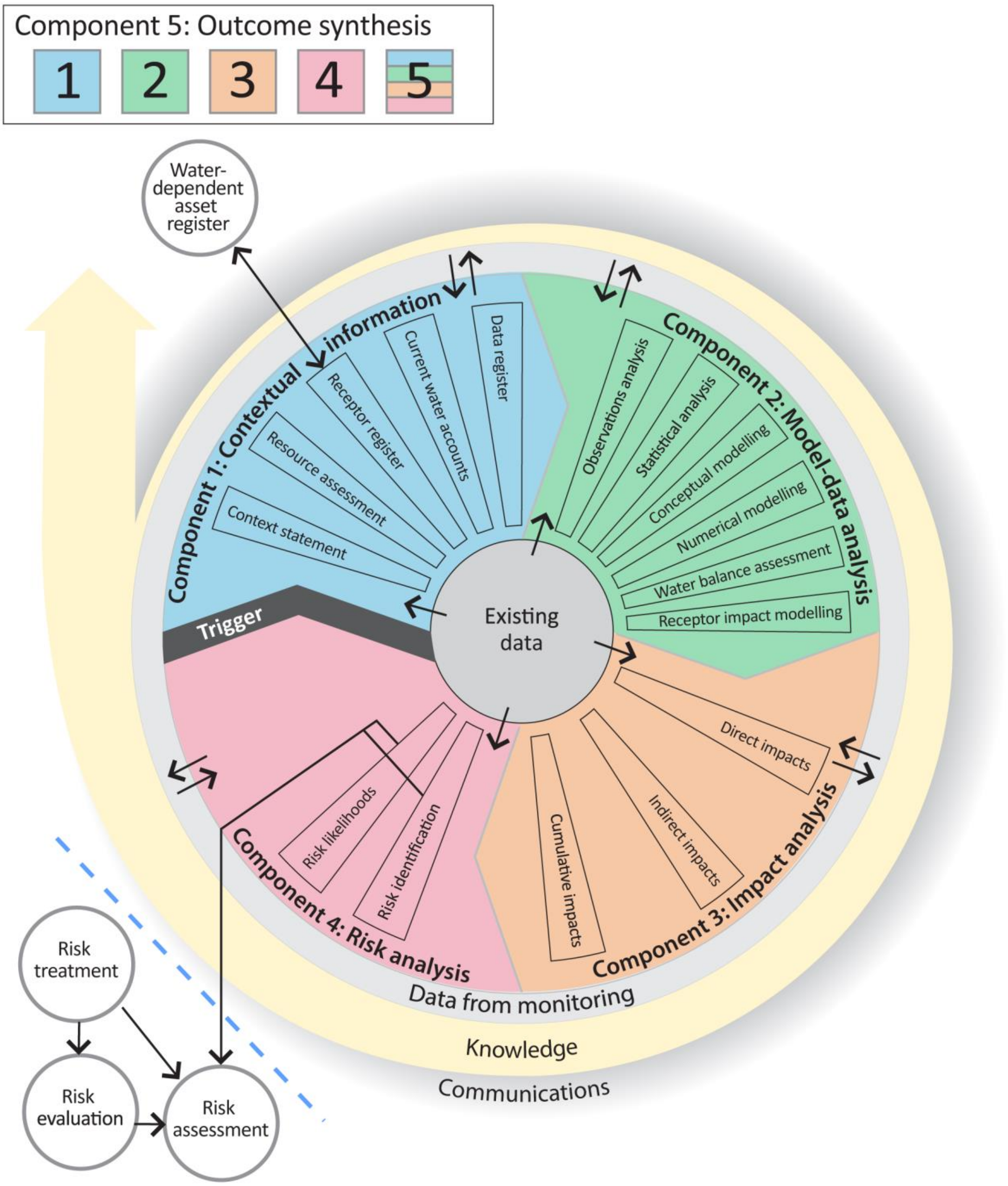

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

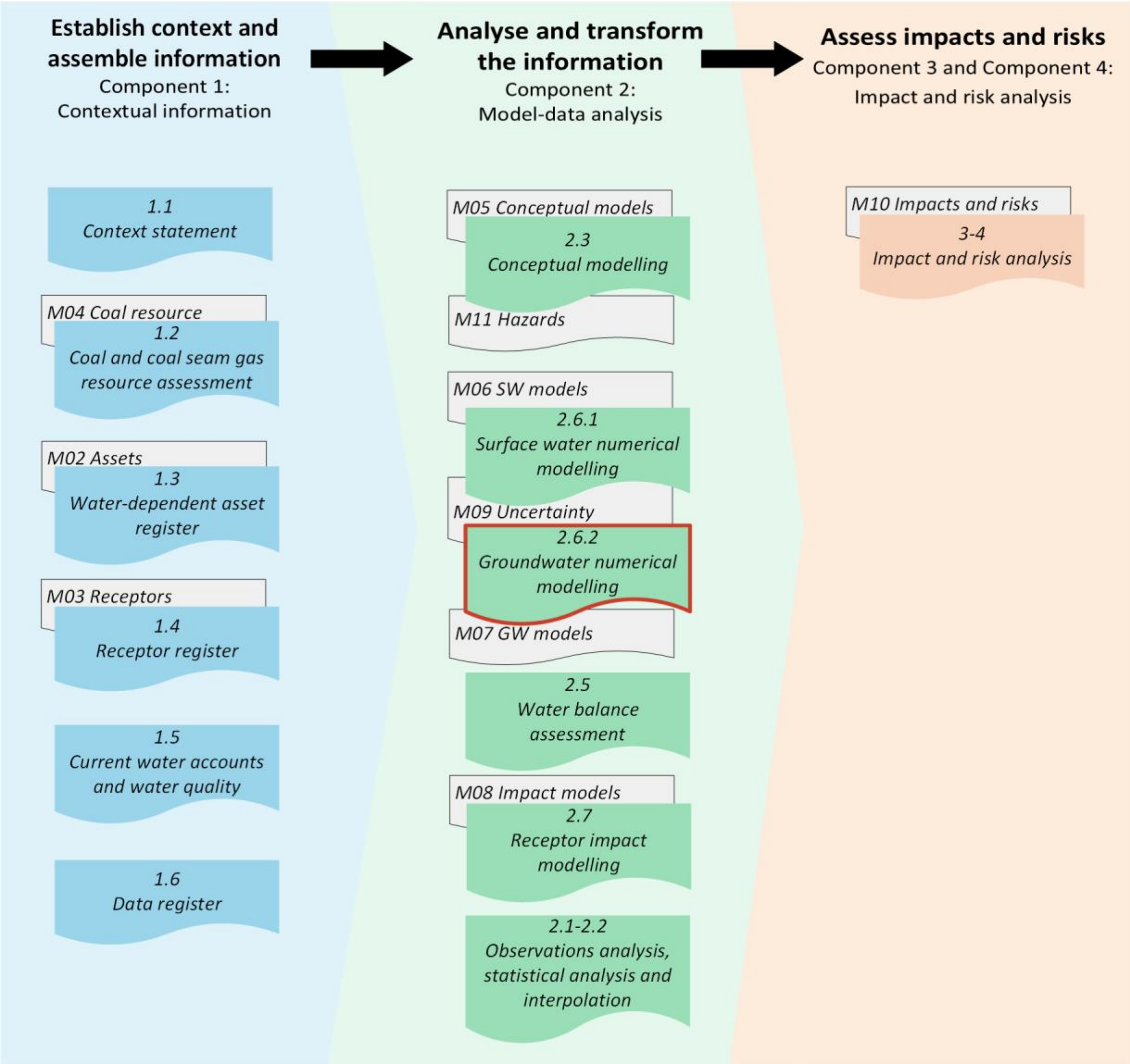

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Clarence-Moreton bioregion

For the Clarence-Moreton 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), product 2.6.1 (surface water numerical 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 Clarence-Moreton bioregion	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 Clarence-Moreton bioregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2	PDF, HTML
	2.3	Conceptual modelling	2.5.2.3, 4.3	PDF, HTML
	2.5	Water balance assessment	2.5.2.4	PDF, HTML
	2.6.1	Surface water numerical modelling	4.4	PDF, HTML
	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 Clarence-Moreton bioregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	Not produced
Component 5: Outcome synthesis for the Clarence-Moreton bioregion	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 Clarence-Moreton 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).

About this technical product

The following notes are relevant only for this technical product.

- All material in the current product are 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 Clarence-Moreton 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 31 March 2017, 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 31 March 2017, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

2.6.2 Groundwater numerical modelling for the Clarence-Moreton bioregion

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 Clarence-Moreton bioregion.

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 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. Similarly, potential hydrological changes are estimated for surface water in product 2.6.1 (surface water numerical modelling).

The hydrological results from both product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling) are used to assess water balances, reported in product 2.5 (water balance assessment).

2.6.2.1 Methods

Summary

A regional numerical MODFLOW groundwater model was developed to assess the impacts of the additional coal resource development on water-dependent assets within and surrounding the extents of the additional coal resource development in the Clarence-Moreton bioregion. The impact is quantified as the change in predefined hydrological response variables, namely, drawdown due to additional coal resource development (additional drawdown), year of maximum change, and surface water – groundwater flux at a number of locations. The changes in these variables are presented probabilistically using a formal uncertainty analysis method. The groundwater model was coupled with the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) to assess the indirect impacts of the additional coal resource development on hydrological variables associated with surface water systems through baseflow changes as a result of coal seam gas (CSG) extraction.

2.6.2.1.1 Background and context

The groundwater modelling in bioregional assessments has a very specific objective: to probabilistically evaluate potential drawdown and changes in surface water – groundwater flux relevant to the surface water modelling in the coal resource development pathway (CRDP) relative to the baseline at specified locations in the landscape.

The modelling is focused 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 of fluxes. The main rationale for this approach is that 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 the 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 on 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 based on user-defined probability distributions of input parameters. 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 surface water and groundwater models. The range of parameters reflects both the natural variability of the system and the uncertainty in the understanding of the system as of March 2016. 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. When no relevant observations are available, the prior parameter combinations are not constrained. 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 in the understanding of the system in the parameterisation of the numerical models. It is, therefore, inevitable that there will be a number of assumptions and model choices necessary to create the models. This is often referred to as structural or conceptual model uncertainty. 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.

A precautionary approach is adopted in making modelling choices and assumptions to reduce the likelihood of under estimating the hydrological changes due to coal resource development. However, an overly conservative estimate of impact is not desirable either. If there are sound reasons to believe that predicted hydrological changes are unrealistically high (e.g. in comparison to earlier modelling efforts in the bioregion) the assumptions may need to be revisited.

The effect on predictions is crucial in justifying assumptions. In a conservative numerical modelling analysis the precautionary principle is adopted: impacts are over estimated rather than under estimated. Wherever possible, this precautionary principle is adopted and if it can be shown that an assumption over estimates – not under estimates – impacts, the assumption is considered appropriate for the specific purpose of this modelling. This approach is also adopted by the US Environmental Protection Agency (US Environmental Protection Agency, 2004).

The stochastic approach to modelling uncertainty also 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.

In the reporting of the groundwater modelling a choice is made only to present the predictions of the model, the drawdown caused by coal resource development. Only for these predictions is it ensured that all the model assumptions are valid and conservative. In addition to that, the parameter distributions are tailored to these predictions. This means that this product will not present simulated historical groundwater levels or potentiometric surfaces.

In traditional groundwater modelling (i.e. deterministic simulation of current and future aquifer states over the entire model domain), this information, together with calibration results, are used to build confidence in the model predictions. This is based on the premise that a model that can accurately reproduce historical states, such as groundwater levels, will be able to make accurate predictions. The work by, among others, Moore and Doherty (2005), Doherty and Welter (2010), and White et al. (2014) have shown that this premise is not universally valid and very dependent on the type and nature of the observations and the type and nature of the predictions. In extremis, matching historical observations can lead to an increase in predictive uncertainty. In order to safeguard the analysis from these pitfalls, while still ensuring the model is consistent with available relevant observations, the sensitivity analysis is focused on identifying the parameters the predictions are sensitive to and, should observations be available, identifying which parameters can be constrained by observations. In the uncertainty analysis a set of rules or objective functions are defined, if relevant observations are available, that need to be satisfied before a particular parameter combination is considered suitable to make predictions. An example of such a rule is that the mismatch between simulated and observed groundwater levels is less than a predefined threshold or that the surface water – groundwater flux is within a specified range.

This approach to modelling is a departure from the traditional approach focused on deterministic aquifer simulation reflected in the *Australian groundwater modelling guidelines* (Barnett et al., 2012). The report structure therefore does not adhere fully to the reporting structure recommended in the guidelines. This product starts with an overview of the groundwater modelling methods as applied to the Clarence-Moreton bioregion (Section 2.6.2.1.2), in which a high-level overview is provided of the conceptualisation, modelling approach, interaction with the surface water model and uncertainty analysis in relation to the other companion documents for this region and the submethodologies. The methods section is followed with a review of the existing groundwater models (Section 2.6.2.2). Section 2.6.2.3 to Section 2.6.2.6 describe the development of the model, boundary conditions, implementation of the coal resource development pathway (CRDP) and the parameterisation of the model. In these sections, model choices and assumptions are briefly discussed. The available observations, as well as the type and location of the predictions, are presented in Section 2.6.2.7. This section also includes the sensitivity analysis of the model parameters to observations and predictions. The probabilistic estimates of drawdown are presented in Section 2.6.2.8. This section also provides an in-depth formal discussion of the justification of assumptions and their effect on predictions. The final section, 2.6.2.9, does not only contain the conclusions of the model, but also the limitations and opportunities to reduce predictive uncertainty.

2.6.2.1.2 Groundwater numerical modelling

The focus of the numerical modelling for the Clarence-Moreton Bioregional Assessment is the coal seam gas (CSG) development in the Walloon Coal Measures in the Richmond river basin (Figure 3). The Richmond river basin overlies a sedimentary basin with an alternating sequence of aquifers and aquitards (Figure 4) in which the alluvial deposits of the Richmond River and its tributaries are incised. The Walloon Coal Measures outcrop in the west of the study area. In the proposed CSG development area close to Casino, the Walloon Coal Measures are overlain by hundreds of metres of younger sedimentary bedrock, including several hydrostratigraphic units that are considered to be aquitards (Raiber et al., 2016). In the northern part of the Richmond river basin, the Lamington Volcanics form a topographic high, and these high-elevation basalts are associated with very high groundwater recharge rates.

The Richmond River system is perennial, with the exception of some smaller tributaries in the west such as Shannon Brook. Unlike the perennial streams, these smaller tributaries in the western part of the Richmond river basin are not incised into the Lamington Volcanics, and flow in Shannon Brook, for instance, is observed 94% of the year. Downstream from Casino, the Richmond River is tidally influenced.

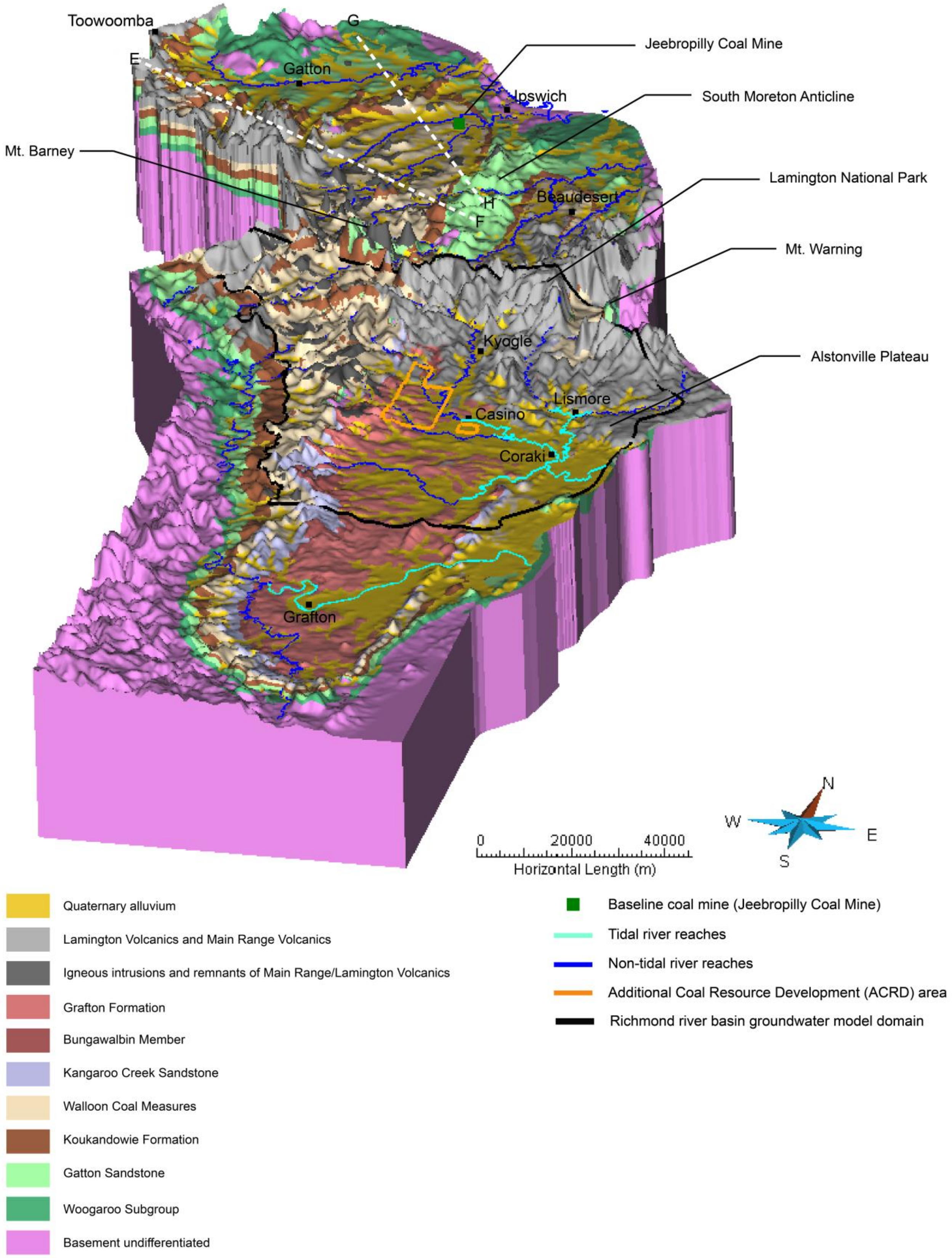

Figure 3 Three-dimensional geological model of the Clarence-Moreton bioregion

Viewed from the south-east; the vertical extent is from –2500 to +1400 m Australian Height Datum (AHD); the north–south extent is 320 km; the maximum east–west extent is 140 km; the vertical exaggeration is 10

Source: Raiber et al. (2016)

The main causal pathway group identified in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016) considered in the numerical groundwater modelling is the 'Subsurface depressurisation and dewatering' causal pathway group. Dewatering applies to coal mines and, given that no coal mines are being modelled in the baseline or CRDP, it will not be discussed further in relation to the Clarence-Moreton bioregion. Subsurface depressurisation of the Walloon Coal Measures near Casino, may lead to drawdowns in the Walloon Coal Measures and overlying aquifers including the alluvial aquifers. A change in groundwater pressures and levels in the alluvium may result in changes to surface water – groundwater interactions and thus a reduction of streamflow in the Richmond River or its tributaries.

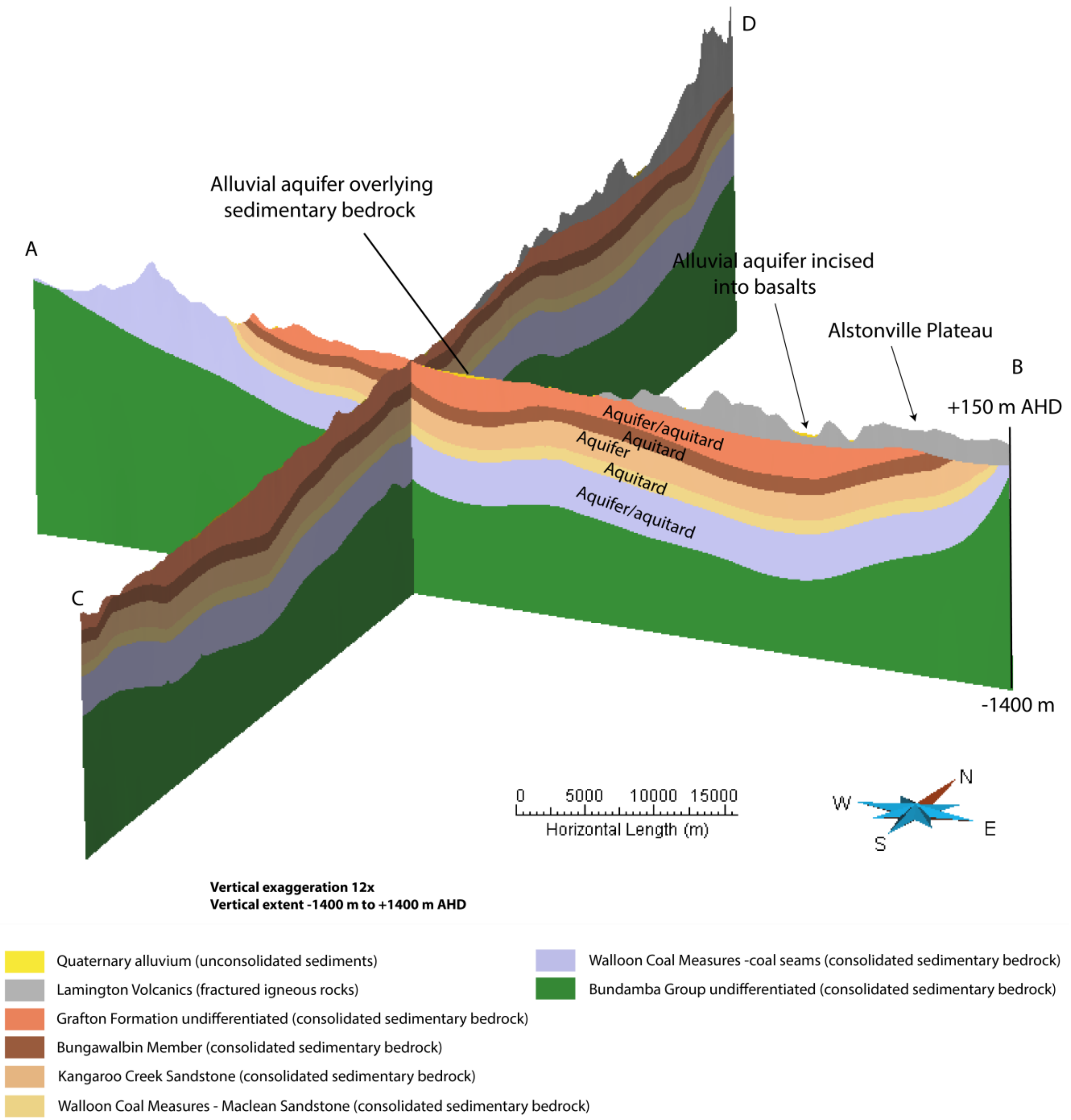

Figure 4 Fence diagram through the Richmond river basin showing geometric and thickness relationships between alluvial, volcanic and sedimentary bedrock hydrostratigraphic units

Different model types and model codes have been adopted in bioregional assessments (BAs) depending on the specific requirements of each subregion or bioregion. The companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016) stipulates that a groundwater model must deliver spatially explicit outputs that can evaluate the direct/indirect impacts on groundwater resources as well as providing input to other BA modelling tasks, including surface water modelling, uncertainty analysis and receptor impact modelling. A formal assessment of the modelling approach adopted in the Clarence-Moreton bioregion was conducted according to the five fit-for-purpose criteria listed in Table 3.

Table 3 Assessment of groundwater numerical modelling approach in the Clarence-Moreton bioregion

Fit-for-purpose assessment criteria	Components	Criteria met
1. Prediction of hydrological response variables	Probabilistic estimates of hydrological change at mode nodes	Yes
	Integration with receptor impact modelling	No
	Linkage with surface water numerical models	Yes
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
	Transparent description of conceptual model and traceable process for deriving model parameter/data	Yes

2.6.2.1.2.1 Prediction of hydrological response variables

The objective of groundwater modelling that is undertaken as part of a BA is to probabilistically assess the impacts of additional coal resource development at model nodes associated with water-dependent assets. The impact is quantified by the change in some predefined hydrological response variables such as fluxes, hydraulic heads or variables depending on fluxes or hydraulic heads. Hydrological response variables need to be decided upon prior to the sensitivity analysis, for example, drawdown at model node (x, y, z) at time t. The hydrological response variables adopted in the current assessment include additional drawdown (*dmax,* maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to the additional coal resource development), year of maximum change (*tmax*) and leakage/baseflow changes at a number of model nodes.

In order to quantify the uncertainties associated with model predictions, groundwater modelling in BA is run probabilistically and not deterministically. Consequently, this means that model predictions cannot be presented as unique values but as probability distributions. Mismatches in spatial and temporal scale between the regional nature of the modelling and the point-scale nature of model nodes mean that the modelling is not able to capture fine-scale complexities of impacts upon model nodes. In BA, the focus is on the impact of the additional coal resource development, which is attributed to the difference in results between two possible futures – the baseline and the CRDP. Hence, numerical groundwater modelling results are primarily presented as the difference in groundwater drawdown between the baseline and CRDP. This approach reduces the uncertainty as the prediction is formulated as the difference between the output of two model results (Barnett et al., 2012).

The linkage between the groundwater model and the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) (Vaze et al., 2015) is depicted in Figure 5. AWRA-L was used to generate the temporal trends of diffuse recharge for the groundwater model. The river stage elevation time series for the groundwater model was derived from the runoff outputs of AWRA-L, which were coupled with rating curves derived from measured data sourced from the NSW streamflow dataset from NSW Office of Water. The groundwater model was used to generate the leakage/baseflow change at a number of gauges along the Richmond River due to the additional coal resource development. These flux changes can then be fed back into the AWRA-L model predictions to estimate changes of relevant hydrological response variables. Subsequently, changes of hydrological response variables can be used to assess the impacts on model nodes associated with surface water-dependent assets.

Although the groundwater model was able to deliver input for receptor impact modelling, receptor impact modelling was not considered in this current BA. Analysis of the potential impacts of the additional coal resource development have shown minimal hydrological changes, particularly at the uppermost aquifer where median additional drawdowns does not exceed 0.2 m. The median predicted change in surface water – groundwater flux at simulated model nodes, including both leakage and baseflow, does not exceed 0.01 GL/year as shown in companion product 2.6.1 for the Clarence-Moreton bioregion (Gilfedder et al., 2016). As a result of these minor hydrological impacts, ecological impacts are expected to be below the detectable limit and hence the decision was to not carry out receptor impact modelling in the Clarence-Moreton bioregion.

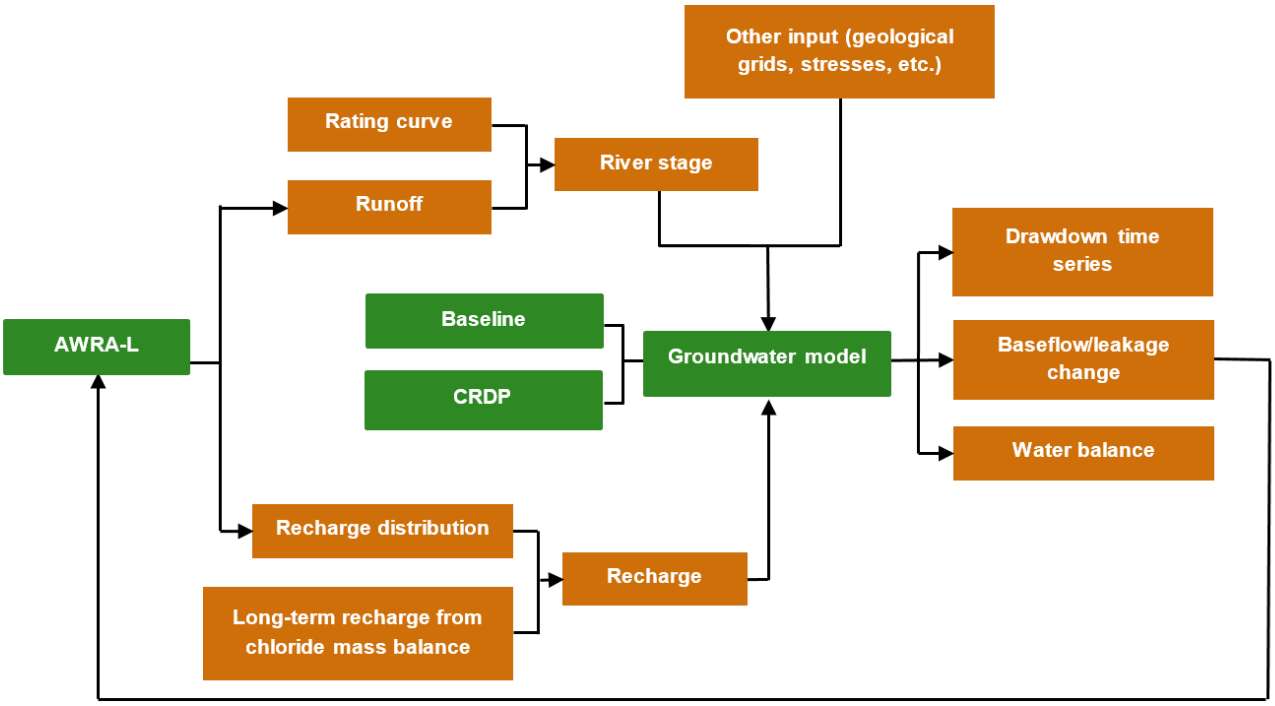

Figure 5 Model sequence for the Clarence-Moreton bioregion

AWRA-L = Australian Water Resources Assessment landscape module; baseline = baseline coal resource development; CRDP = coal resource development pathway; CRDP = baseline + additional coal resource development; green rectangles represent models; orange rectangles are input and/or output data of models

2.6.2.1.2.2 Design and construction

Following the guidelines of companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016), a numerical groundwater model was developed to assess the potential impacts of the additional coal resource development on the groundwater system of the Clarence-Moreton bioregion. As reported in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016), the additional coal resource development in this BA only includes one CSG development, the West Casino Gas Project. The groundwater model mainly focused on the Richmond river basin where the West Casino Gas Project is likely to occur. The conceptualisation and the likely causal pathways that underpinned the model are identified in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016).

The major assumptions and model choices related to model development are described in Section 2.6.2.3. The groundwater model is considered the first regional model for the area and is based on a three-dimensional geological model that was specifically developed for the current BA (see companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)). MODFLOW-NWT (Niswonger et al., 2011) was used to run the model in order to minimise the numerical instabilities that can be caused by cell drying and rewetting in the unconfined layer of the model. The effect of the assumptions and model choices on predictions are discussed in Section 2.6.2.8.

Groundwater modelling simulations were run under historical conditions for the 30-year period from 1 January 1983 to 31 December 2012. The historical climate time series was 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 was repeated to ensure that the effect of droughts and floods does not confound the comparison between time periods. Monthly stress periods were used throughout the simulation to provide monthly change of baseflow required by the surface water model. This led to a total number of 1441 stress periods from 1983 to 2102, including the first steady-state stress period.

Final outputs of predicted impacts were produced with the aid of emulators as described in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016) and M09 (as listed in Table 1) for propagation of uncertainty through models (Peeters et al., 2016). The main goal of the groundwater model was to provide realisations that can be used to train the emulators for the model nodes. Emulators are computationally efficient approximation statistical tools compared to the slower process-based groundwater model. As described in companion submethodology M09 (Peeters et al., 2016), the application of model emulation is to overcome the computational inefficiency of the original groundwater model, but still being able to capture the important groundwater flow features.

For those model nodes that are associated with groundwater-dependent assets and hence directly impacted by groundwater extraction, such as stock and domestic groundwater bores, the groundwater model directly generates the drawdown impacts. If receptor impact modelling is deemed necessary, then the groundwater model outputs will directly feed into the receptor impact model. For other model nodes that are indirectly impacted by groundwater extraction through an interaction with any of the various surface water features, a surface water model is required to simulate the impact of the additional coal resource development. Due to minimal regulation in the Richmond river basin, the rainfall-runoff model AWRA-L (Hafeez et al., 2015) was deemed adequate to model the Richmond River flows. The modelling results for these model nodes are presented in companion product 2.6.1 for the Clarence-Moreton bioregion (Gilfedder et al., 2016).

2.6.2.1.2.3 Integration with sensitivity and uncertainty analysis workflow

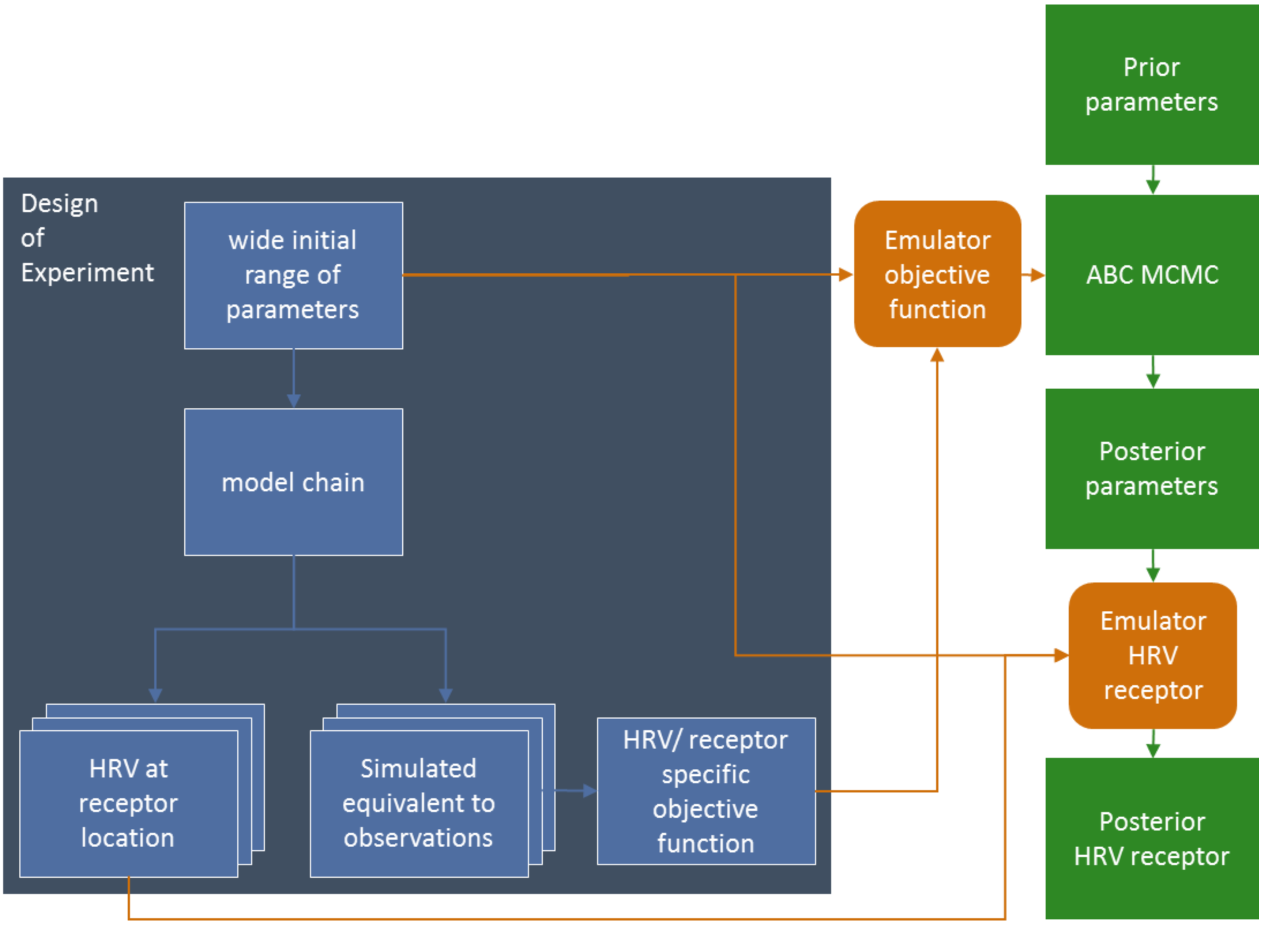

Figure 6 Uncertainty analysis workflow

ABC MCMC = Approximate Bayesian Computation Markov chain Monte Carlo; HRV = hydrological response variable

Submethodology M09 (as listed in Table 1) (Peeters et al., 2016) discusses in detail the propagation of uncertainty through numerical models in the BAs. Figure 6 summarises the uncertainty propagation workflow which consists of four major steps:

1. Design of experiment: large number of model chain evaluations with a wide range of parameter values
2. Train emulators for:
   a. each hydrological response variable at each model node
   b. objective function tailored to each hydrological response variable at each model node
3. Create posterior parameter probability distribution through Approximate Bayesian Computing Markov chain Monte Carlo
4. Sample the posterior parameter probability distribution to generate the posterior probability distribution for each hydrological response variable at each model node.

The first step is to identify the parameters of the model chain to include in the uncertainty analysis and to define a wide range that represents the plausible range of the parameters. A large number of model chain evaluations are carried out, sampling extensively from this parameter range. For each evaluation the corresponding simulated change in hydrological response variables at the model nodes is stored, together with the simulated equivalents to the observations. The latter are summarised into objective functions, tailored to each hydrological response variable.

This information forms the basis for the subsequent uncertainty analysis. In the uncertainty analysis, the prior parameter distributions, the most likely range of the parameter values based on data and expert knowledge, is constrained with the available relevant data using the Approximate Bayesian Computation methodology. This results in a posterior parameter distribution, tailored to a specific hydrological response variable, which subsequently can be sampled to generate a probability distribution at each model node.

This type of uncertainty analysis requires a very large number of model evaluations, which is practically not feasible. This is the main reason that the original model chain in the uncertainty analysis is replaced by emulators, statistical functions that closely mimic the effect of parameter values on predictions. These emulators take little time to evaluate and are straightforward to integrate into the uncertainty analysis workflow.

In order for the model chain to be amenable for incorporation into this uncertainty analysis it needs to be scripted so that parameter values can be changed in an automated fashion, be able to be evaluated from a command line on high performance computers and, most importantly, be numerically stable so that the model converges for a wide range of parameter values.

The two models in the model chain for the Clarence-Moreton bioregion have text files as input files and can be executed from the command line. The robustness of each model is tested through a stress-test in which a selection of extreme parameter combinations is evaluated. While this does not guarantee that all model evaluations will converge, it provides confidence that the majority of parameter combinations will.

Section 2.6.2.7 and Section 2.6.2.8 provide details of the implementation of this uncertainty propagation workflow for the MODFLOW model. The uncertainty analysis for AWRA-L is in Section 2.6.1.5 and Section 2.6.1.6 of companion product 2.6.1 for the Clarence-Moreton bioregion (Gilfedder et al., 2016). These sections also have a qualitative uncertainty analysis that provides a structured discussion of the assumptions and model choices not included in the numerical uncertainty analysis and the perceived effect on the predictions.

2.6.2.1.2.4 Water balance components

The water balance was reported for a defined control volume in BA that includes all hydrologically connected changes predicted by the surface water and groundwater models. The water balance components (e.g. recharge, evapotranspiration, baseflow, licensed extractions, upward flow from deeper groundwater and change in storage) were compared with estimates 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). Companion product 2.5 for the Clarence-Moreton bioregion (Cui et al., 2016) compares model estimates of water extraction from CSG with available local and regional estimates. Parameters associated with water balance components are discussed in Section 2.6.2.4 and Section 2.6.2.5.

2.6.2.1.2.5 Transparent and reproducible model outputs

The BA requirement that model results must be reproducible 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 at www.bioregionalassessments.gov.au; 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 current model described in this product is designed specifically for delivering a probabilistic assessment of the impacts of the additional coal resource development in the Clarence-Moreton bioregion. In its current form, the model is neither suited to address any other water management questions nor provide deterministic predictions in this bioregion. The validity of all assumptions in this product should be re-assessed for any other application of the current model.

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2.6.2.2 Review of existing models

Summary

A thorough search revealed that three groundwater models exist, which cover various parts of the preliminary assessment extent (PAE) in the Clarence-Moreton bioregion. They are: the Arrow model, the Alstonville model and the Metgasco Limited model. The Arrow model covers part of the Queensland side of the Clarence-Moreton PAE, while the other two models cover parts of the NSW side of the Clarence-Moreton PAE. The Arrow model (Arrow Energy Pty Ltd, 2012) is a flat-layer model aimed at quantifying potential drawdown in water heads resulting from three production test bores planned between Beaudesert and Kooralbyn. The model estimated maximal drawdown impacts over 2 m and 5 m in the alluvial aquifer and the Walloon Coal Measures, respectively. The Alstonville model, developed by the NSW Department of Sustainable Natural Resources (Bilge, 2003), comprises only two layers and was mainly developed for educational purposes. The Metgasco model was developed by Parsons Brinckerhoff (2013) to help design and optimise a monitoring network within Metgasco's Petroleum Exploration Licences (PEL 13 and PEL 16). The Metgasco model is more comprehensive than the other two models. However, all three models are deemed to be basic; they are not suitable for direct usage in the Clarence-Moreton Bioregional Assessment due to their limited model domains and the lack of features such as temporally varying boundaries and non-coal-seam-gas groundwater bores in the Metgasco model.

2.6.2.2.1 Arrow Energy groundwater model

Arrow Energy Pty Ltd (2012) developed a groundwater model to investigate the potential impacts of water extraction on associated aquifers during its production testing of three wells in Authority to Prospect (ATP) 644 (Figure 7). The Groundwater Vistas interface was used to build the MODFLOW-2000 model (Harbaugh et al., 2000). This simple local-scale model comprises two hydrogeological units: the alluvial aquifer and the Walloon Coal Measures. These two units were divided into eight flat layers with uniform elevations in each layer. The total extracted volumes of water from the three numerical wells were approximately 0.69 ML, 0.55 ML and 0.54 ML over a period of nine months. The production test bores are located about 6 km to the north-west of Laravale.

The model, which covered an area of approximately 30 km^2, was discretised into 80 rows and 80 columns. Grid sizes were refined to 10 m in the vicinity of the production test wells from 100 m along the model boundaries. A general-head boundary was applied to the uppermost layer of the model, whereas all other boundaries were considered to be impermeable. The hydraulic conductivity, specific storage and specific yield were kept uniform as homogeneity was assumed within the alluvial aquifer and Walloon Coal Measures. These parameters were calibrated to observed groundwater levels in the three production test bores over 224 days. The transient model includes a 224-day production test period and a 3-year water level recovery period.

Based on the calibrated optimal parameters, the modelling results suggested that the drawdown impacts within the unconfined alluvial aquifer were less than the bore trigger threshold (for unconfined aquifers) of 2 m. At the end of the production test, the impact zone where noticeable drawdowns occurred in the confined Walloon Coal Measures was restricted to a radius of about 550 m from the production test wells. However, these drawdowns were reduced to below the bore trigger threshold at the end of the 3-year recovery period.

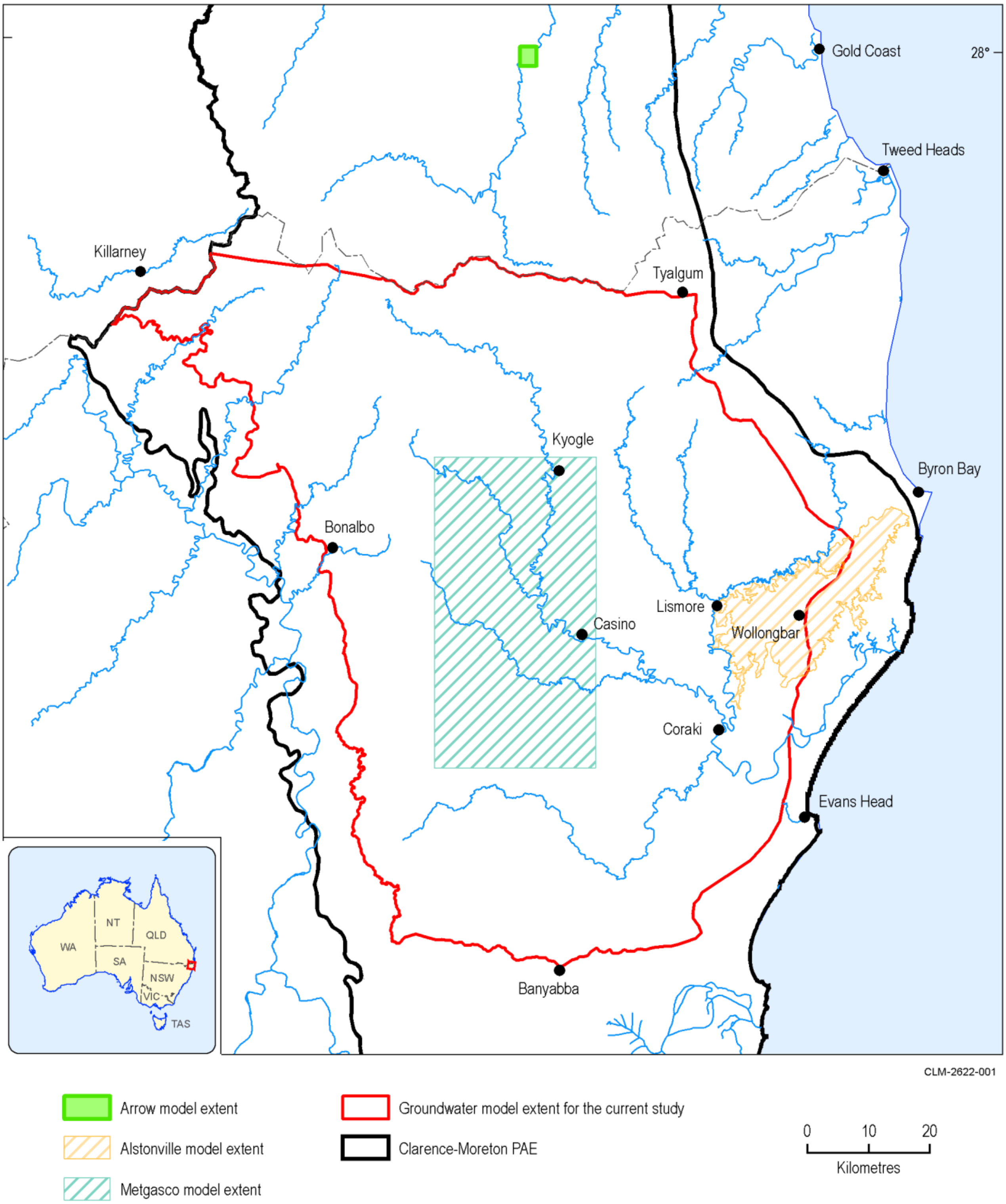

Figure 7 Extents of existing groundwater models and their spatial relationships to the extents of the groundwater model developed by the Assessment team

PAE = preliminary assessment extent
Data: Bioregional Assessment Programme (Dataset 1)

The predictive uncertainty associated with the predictions was addressed through a Monte Carlo simulation. The model was run with 100 randomly generated parameter realisations sampled from alluvial hydraulic conductivities that range from 0.01 to 1 m/day. The results showed that there is a 25% probability that the impact zone would extend to beyond 200 m from the production test bores, while 75% of the realisations showed that the impact zone would be limited to 50 m from the production test bores. The impact zone was defined as the area where drawdown is more than 5 m; this is the trigger threshold for consolidated aquifers specified in the Queensland Water Act 2000.

2.6.2.2.2 Alstonville plateau groundwater model

A two-layered MODFLOW model (Harbaugh et al., 2000) for the Alstonville plateau was developed by the NSW Department of Sustainable Natural Resources (Bilge, 2003). Bilge (2003) stated that the model was based on very limited data and hence was only suited for educational purposes. The model covers an area of 445 km^2 that lies within the Alstonville Groundwater Management Area and only contains the basalt aquifers that were represented by a shallow unconfined upper aquifer (layer 1) and an unconfined/confined lower aquifer (layer 2). A grid spacing of 300 m was used to discretise the model, whose extents are shown in Figure 7.

A monthly stress period was implemented during the simulation period. The initial heads in the upper layer were assumed at a depth 10 m below the ground level due to a lack of historical data and a very irregular topography. The initial water level of the lower layer was interpolated using the first measured value on or after 1 July 1987. A constant-head boundary was used along the western side of the plateau. All other boundaries were assumed to be impermeable. Three rainfall zones were defined depending on rainfall patterns and magnitudes. Across all three zones, it was assumed that 8% of rainfall infiltrates into the aquifers as recharge, although a large part of it would discharge to the local surface water features.

The model was calibrated to data derived from two bores in the lower aquifer with observations from 1 July 1987 to 31 June 2001. The calibration was conducted via a trial-and-error manual approach. Parameters that were adjusted during the calibration include groundwater usage, hydraulic conductivity, specific storage for the lower aquifer and the constant heads along the western boundary. With the calibrated parameter set, the model was able to match the major trends observed in the hydrographs derived from the two calibration bores.

Based on the calibrated model, an annual mean storage loss of 459 ML/year throughout the simulation period was observed with a long-term rising trend from 1987 to 2001. The lower aquifer receives 1637 ML/year from the upper aquifer, while 306 ML/year flows back into the upper aquifer. Additionally, the modelling report suggests that data gaps need to be filled by installing new monitoring bores, running pumping tests and metering groundwater usage.

2.6.2.2.3 Metgasco groundwater model

A subregional groundwater model was developed by Parsons Brinckerhoff, which was commissioned by Metgasco (Parsons Brinckerhoff, 2013). The model aids the design and optimisation of a monitoring network within Metgasco's Petroleum Exploration Licences (PEL 13 and PEL 16) by providing preliminary estimates of drawdown resulting from the proposed coal seam gas (CSG) development scheme. The model covers an area of 1250 km^2 west of Casino (Figure 7) and was designed as a 'Class 1' model in terms of confidence levels in accordance with the *Australian groundwater modelling guidelines* (Barnett et al., 2012). Three development pathways were modelled: firstly, a baseline model; secondly, a model with a conductive fault; and thirdly, a model with a low-permeable fault. The Drain package of MODFLOW (Harbaugh et al., 2000) was used to simulate 90 CSG wells based on the proposed development plan.

Eleven layers were used to represent nine hydrostratigraphic units, where the Maclean Sandstone Member was divided into three layers and the Walloon Coal Measures constituted the bottom layer. The model was discretised into 182 columns and 389 rows with a grid spacing that varies from 100 m within the proposed petroleum production lease (PPL) to 225 m outside it. General-head boundaries were assigned to the western and eastern sides of the model domain. The MODFLOW Drain package was used to simulate rivers and streams. Zones were used to distinguish different outcropping hydrogeological units in the top layer. Hydraulic conductivity of the confined bedrock formations was estimated from a depth-dependent relationship derived from data obtained from other geologically similar sedimentary basins. A constant storativity coefficient of 10^{-5} was used across the model domain, and a specific yield of 0.1 for the unconfined layers. Recharge was assumed to be 4% of the mean annual rainfall recorded at the meteorology station at Casino Airport. Potential evapotranspiration was implemented using the MODFLOW EVT package. The potential evapotranspiration rate was assumed to be 50% of the long-term mean annual pan evaporation of 1535 mm/year at Alstonville Tropical Fruit Research Station (058131) that is 45 km to the east of the model domain and the closest available evaporation data for the model area. The assumed potential evapotranspiration rate decreases gradually to an extinction depth of 4 m. The model contains a steady-state stress period and a transient stage of 51 years that were divided into 21 stress periods.

The preliminary modelling results indicate that pressure drawdown in the target coal seams can propagate into the overlying aquifers and aquitards to a maximum of up to 5 m. Although the maximum drawdown exceeds the 2 m threshold set by the NSW aquifer interference policy (NSW DPI, 2012), the 2 m impact zone is only restricted within the PPL. The drawdown impact on the watertable was found to be less than the seasonal variations in watertable levels within the modelled area. The modelling results also indicate that a fault intersecting all the geological units has an insignificant impact on the predictions of drawdown. The assignment of a high hydraulic conductivity to the fault results in a minor drawdown increase of less than 2 m in the Kangaroo Creek Sandstone in the close vicinity of the fault. On the other hand, a fault with a low hydraulic conductivity suppresses the propagation of drawdown and tends to restrict the impact within faults blocks. The additional drawdown due to CSG extraction is unlikely to be measurable at the watertable. No formal uncertainty analysis was performed for all the predictions, although a very preliminary sensitivity analysis was carried out by altering the hydraulic conductivities of some aquifers.

Despite the existence of the three models mentioned above, none of them are deemed to be suitable for groundwater modelling for the current bioregional assessment (BA). The spatial domains covered by the Arrow model and the Alstonville model are distant from the location where the additional coal resource development, West Casino Gas Project, is likely to occur. The Metgasco model lacks some advanced features required by BA, such as transient boundaries and very simplified parameterisation, although it was developed for the West Casino Gas Project. Additionally, the Metgasco model did not simulate the potential development in the gas field south of Casino corresponding to a petroleum production lease application (PPLA9). The confidential status of this model also precludes its usage in this BA.

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Datasets

Dataset 1 Bioregional Assessment Programme (2015) CLM Groundwater Model Boundary. Bioregional Assessment Derived Dataset. Viewed 30 July 2015, http://data.bioregionalassessments.gov.au/dataset/dd691d5c-48a2-42fd-9902-4770c871b50f.

2.6.2.3 Model development

Summary

The numerical groundwater model aims at evaluating the direct and indirect impacts of additional coal resource development on water resources in the Richmond river basin of the Clarence-Moreton bioregion. The hydrogeological conceptualisation of the groundwater model is underpinned by a three-dimensional geological model of the Clarence-Moreton Basin. The numerical groundwater MODFLOW model comprises six numerical layers that represent the major types of hydrostratigraphic units in the Richmond river basin within the Clarence-Moreton bioregion. A small area of the Richmond river basin close to the Mount Barney intrusion was excluded from the northern part of the model domain. The western part of the groundwater model domain was extended to include the entire extent of the Walloon Coal Measures. The outcrop or subcrop areas of the older sedimentary bedrock units (Koukandowie Formation and the Gatton Sandstone) were excluded from the eastern and western parts of the groundwater model domain. Faults were not included in the current implementation of the Clarence-Moreton groundwater model due to the lack of information.

Groundwater recharge in the Clarence-Moreton bioregion occurs via different mechanisms, which include diffuse rainfall recharge and surface water recharge. The entire extent of the Lamington Volcanics forms a preferential recharge area with maximal hydraulic connection between the streams, and the alluvial and volcanic aquifers in the headwaters of the Richmond river basin. Diffuse recharge from precipitation seems to be the more dominant recharge process in the lower catchment. In the eastern part of the Richmond river basin, upwelling of groundwater from the sedimentary bedrock into the shallow alluvial aquifers likely occurs. The three-dimensional geological model for the Clarence-Moreton Basin suggests that groundwater flows towards the lowest point in the eastern part of the Richmond river basin, where it discharges to the alluvium and streams.

The transient stage of the groundwater model spanned a total simulation period of 120 years from 1983 to 2102. Available observations were used to constrain the model parameters during the historical period from 1983 to 2012. During the prediction period that spanned a period of 90 years from 2013 to 2102, the 95 coal seam gas (CSG) wells were gradually activated from 2018 to 2036. Monthly stress periods were adopted throughout the simulation, which led to a total of 1441 stress periods including the first steady-state simulation. The model domain was discretised into 248 rows and 184 columns. Grid spacing varied from 200 to 800 m. MODFLOW-NWT was adopted to execute the numerical model.

2.6.2.3.1 Objectives

The numerical groundwater MODFLOW (Harbaugh, 2005) model aims at evaluating the impacts of the additional coal resource development on groundwater resources in the Richmond river basin of the Clarence-Moreton bioregion. The direct impact at every model node is represented by the difference of the drawdown between the coal resource development pathway (CRDP) and baseline (described in Section 2.6.2.5) and the time at which this drawdown is realised. This direct impact is mostly associated with model nodes associated with economic assets (bores) whose locations and screened aquifers are reported in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016a).

The model also provides predictions for the exchange fluxes between aquifers and surface water features, which is considered as an indirect impact. The exchange fluxes were reported as time series at 16 virtual gauges, which were subsequently incorporated into a surface water model to assess the indirect impact on other model nodes.

2.6.2.3.2 Hydrogeological conceptual model

The hydrostratigraphy and the hydrogeological conceptual model for the Clarence-Moreton bioregion have been described in detail in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b). It describes the geological, hydrogeological, ecological and hydrological characteristics of the Richmond river basin, which was identified as the area within the Clarence-Moreton bioregion where coal seam gas (CSG) development is most likely to proceed in the foreseeable future. This section summarises the major characteristics of the conceptual model for the Richmond river basin and its implementation in a numerical groundwater model.

2.6.2.3.2.1 Hydrostratigraphy and relevant model layers

There are three major types of hydrostratigraphic units with distinct hydraulic properties in the Richmond river basin within the Clarence-Moreton bioregion:

- alluvial aquifer systems: in the Clarence-Moreton bioregion, these unconsolidated to semi-consolidated aquifers can be differentiated into upper catchment, mid-catchment and lower catchment based on geomorphological features and topographic gradient
- fractured igneous rocks: in the Richmond river basin, the fractured igneous rocks consist mostly of extrusive volcanic rocks such as the basalts of the Lamington Volcanics
- sedimentary bedrock: in the Richmond river basin, the sedimentary bedrock consists of a sequence of aquifers and aquitards with highly variable hydraulic properties. This aquifer–aquitard sequence and the vertical relationships between them are shown in Figure 8. As these units can be very heterogeneous, they can form an aquifer in a particular part of the bioregion (e.g. at the margin of the Clarence-Moreton Basin where the rocks tend to be composed of coarse-grained materials), but can also act as an aquitard elsewhere (e.g. further away from the basin margin and/or at greater depth where the permeability is typically lower). The spatial (horizontal and vertical) relationships and relative thicknesses of inferred aquifers and aquitards in the Richmond river basin are shown in Figure 9.

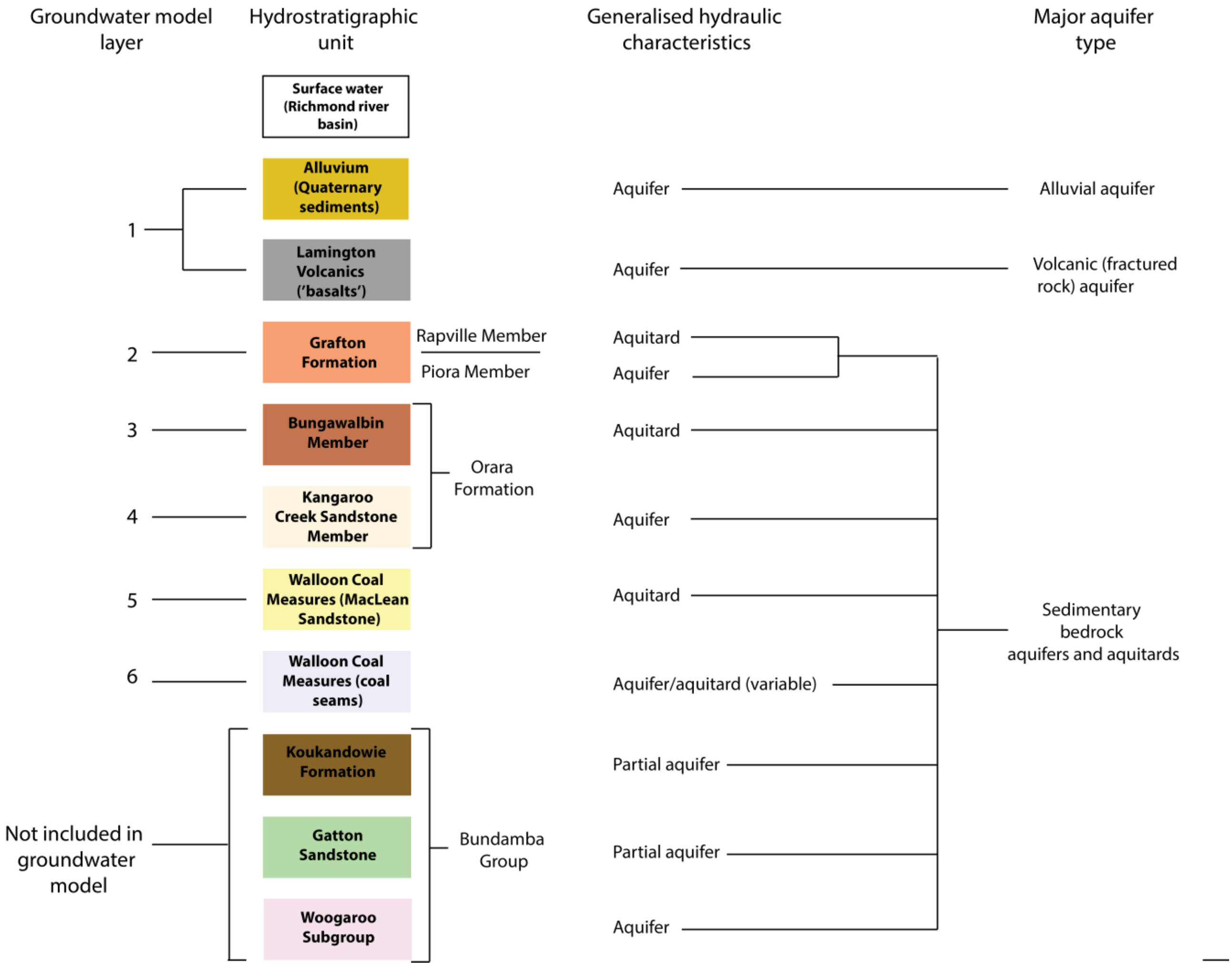

Figure 8 Simplified stratigraphy and generalised hydraulic characteristics of stratigraphic units and groundwater model layers in the Clarence-Moreton bioregion

The lowermost units (Koukandowie Formation and below) are not included in the Richmond river basin groundwater model as they are not currently utilised for groundwater extraction due to their considerable depth, their inferred low yields and the high groundwater salinity of groundwater contained within Koukandowie Formation and the Gatton Sandstone (McJannet et al., 2015).
Source: Modified from companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b)

Groundwater model layers

The seven hydrostratigraphic units above the Koukandowie Formation were simplified and represented by six layers in the numerical groundwater model (Figure 8). Some of the major characteristics of these layers are described below. More detail on the geology and hydrogeology of these layers is available in companion products 1.1, 1.2 and 2.3 for the Clarence-Moreton bioregion (Rassam et al., 2014; Raiber et al., 2014; Raiber et al., 2016b).

1. *Layer 1 – Alluvium, Lamington Volcanics and unconfined parts of other units*. The alluvium and the volcanics are the major aquifers targeted for groundwater extraction in the Clarence-Moreton bioregion. In the upper and mid catchment, the alluvial aquifer sequences are predominantly unconfined with a maximum thickness of 15 to 30 m. In the lower catchment, the alluvial aquifers can be up to 40 m thick and are more likely to be semi-confined. The Lamington Volcanics cover large surface areas in the northern part of the Richmond river basin, where they have a median thickness of 105 m and a maximum thickness of approximately 800 m. In order to reduce computation time and enhance model

stability required by stochastic groundwater modelling, the alluvium, the Lamington Volcanics and the unconfined parts of other bedrock formations were merged into a single unit. This top unit represents the uppermost unconfined layer of the numerical groundwater model, while the other layers were considered as confined units.

2. *Layer 2 – Grafton Formation*. The Grafton Formation consists of the Rapville Member and the Piora Member. As indicated by the three-dimensional geological model of the Clarence-Moreton Basin in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b), the Grafton Formation (as defined by Doig and Stanmore (2012)) has a median thickness of approximately 150 m and a maximum thickness of approximately 500 m. It consists of an upper and a lower member (Rapville and Piora members, respectively) that have different hydraulic characteristics. The Piora Member, the lower member of the Grafton Formation, is composed of medium- to coarse-grained quartzose sandstone with an extensive clay matrix (Doig and Stanmore, 2012). While sometimes described as an aquifer, its reported low bore yields of about 0.3 L/second suggest that it is more likely to be an aquitard (Parsons Brinckerhoff, 2011). The Rapville Member, the upper member of the Grafton Formation, is composed of interbedded sandstone, siltstone and mudstone, and is considered to be an aquitard or aquiclude (Doig and Stanmore, 2012). There are not enough data to identify the boundary between the two members in the model domain. Hence, they were simulated as one layer.
3. *Layer 3 – Bungawalbin Member*. The Bungawalbin Member, which is composed of mudstone and carbonaceous mudstone interbedded with fine-grained sandstone, has a median thickness of about 94 m. It has been described as an aquitard that prevents vertical groundwater leakage (Doig and Stanmore, 2012).
4. *Layer 4 – Kangaroo Creek Sandstone*. The Kangaroo Creek Sandstone Member is an aquifer composed of quartzose sandstone and conglomerate (Doig and Stanmore, 2012). The estimated median thickness of the Kangaroo Creek Sandstone using the three-dimensional geological model is about 175 m and its maximum thickness is 370 m. Yields are mostly low (less than 1 L/second), except where fractures are intercepted (McKibbin and DLWC, 1995; Parsons Brinckerhoff, 2011). However, this assessment is based on limited data from the eastern part of the basin. Doig and Stanmore (2012) indicated that the Kangaroo Creek Sandstone has poor aquifer properties below a depth of 150 m.
5. *Layer 5 – Maclean Sandstone (Walloon Coal Measures)*. The Maclean Sandstone forms the upper part of the Walloon Coal Measures. It overlies the coal-bearing strata of the Walloon Coal Measures in the Richmond river basin (Figure 8). As indicated by the three-dimensional geological model in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b), it has a median thickness of about 87 m and is described by Doig and Stanmore (2012) as an effective low-permeability top seal (aquitard) that extends over much of the basin and limits vertical leakage of gas from the coal seams to the surface.
6. *Layer 6 – Coal Seams (Walloon Coal Measures)*. The Walloon Coal Measures are typically considered as an aquitard in the Clarence-Moreton and the linked Surat basins. However, due to a spatially variable composition, their hydraulic characteristics may vary considerably. Numerous coal seams and carbonaceous coal shales have been intersected in the centre of the Logan sub-basin near Casino (Ingram and Robinson, 1996). The

Richmond Seam (one of the youngest and thickest seams in the Walloon Coal Measures) is very extensive and can be correlated over tens of kilometres based on its distinct signal that can be identified in geophysical logs (Doig and Stanmore, 2012). The coal seams are separated by interburden (e.g. mudstone, siltstone, fine-grained sandstone and shale); recent well completion reports indicate that the net coal thickness is comparatively small relative to the overall thickness of this layer as detailed in companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014). There was no differentiation between the interburden and the coal seams in this layer of the groundwater model due to the lack of data.

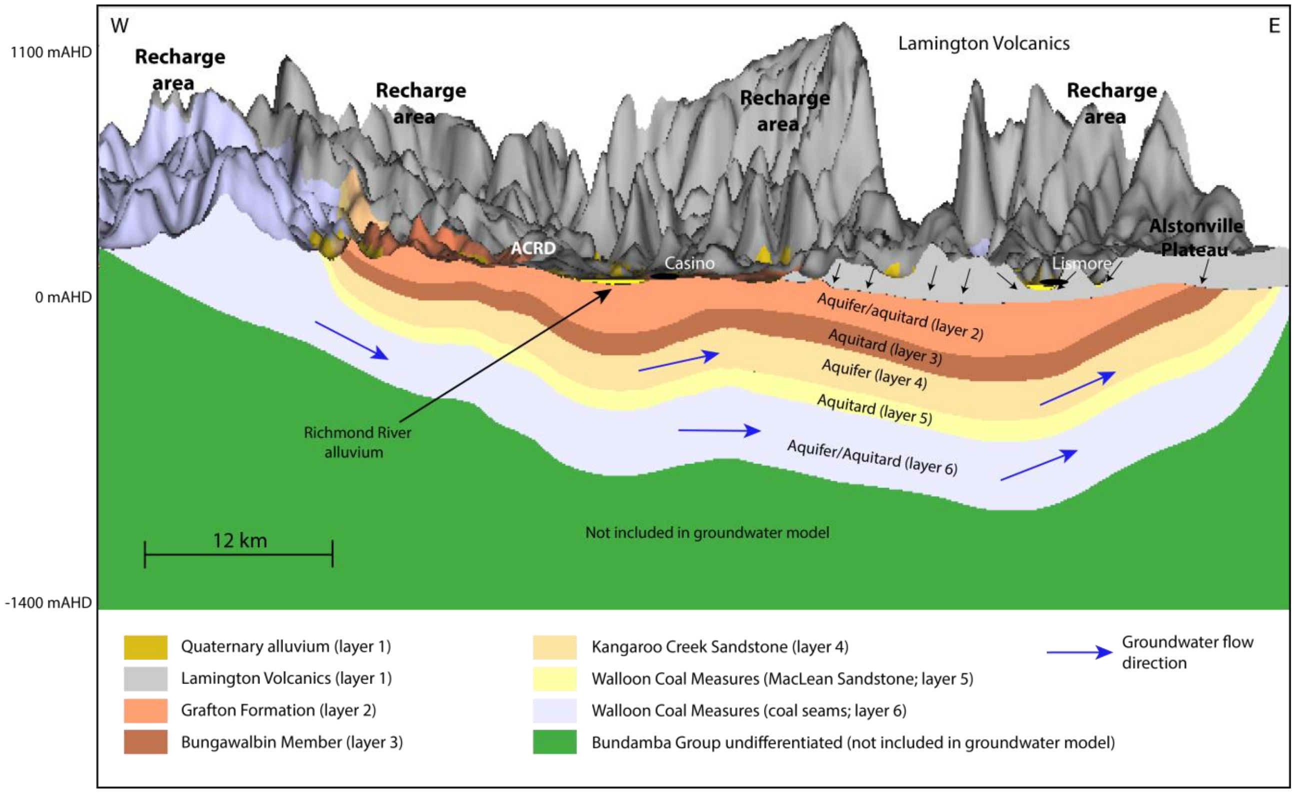

Figure 9 Example cross-section through unfaulted three-dimensional geological model of Richmond river basin, highlighting aquifer geometry, relative thicknesses of aquifers and aquitards

Groundwater model layer number is shown in brackets.
Source: Modified from companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b)

Hydrostratigraphic units not included in the groundwater model

The Koukandowie Formation and the Gatton Sandstone (both part of the Bundamba Group; refer to Figure 9), which underlie the Walloon Coal Measures, are poorly documented with no certainty as to whether they act as aquifers or aquitards throughout the Clarence-Moreton bioregion. However, the assessment of water quality in the Clarence-Moreton bioregion reported in companion product 1.5 for the Clarence-Moreton bioregion (McJannet et al., 2015), has shown that the Koukandowie Formation and the Gatton Sandstone have the highest groundwater salinity, with median electrical conductivities of 4750 and 5000 µS/cm, respectively. As they are low-yielding or partial aquifers in the Queensland part of the Clarence-Moreton bioregion (Raiber et al., 2016b), it seems more likely that these two hydrostratigraphic units are low-permeability aquifers or aquitards that are not suitable for groundwater extraction. As a result, the Koukandowie Formation and the Gatton Sandstone were excluded from the groundwater model.

2.6.2.3.2.2 Groundwater recharge and discharge

Groundwater recharge in the Clarence-Moreton bioregion occurs via different mechanisms, which include diffuse rainfall recharge and surface water recharge. The recharge assessment conducted as part of the Clarence-Moreton Bioregional Assessment for the Richmond river basin suggested that the entire extent of the Lamington Volcanics forms a preferential recharge area as presented in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b). There is a high degree of hydraulic connection between the streams, and the alluvial and volcanic aquifers in the Richmond river basin with peak-level interaction in the headwaters of the alluvial systems that decreases downstream. In the headwaters of the alluvial valleys, rapid discharge occurs from the basalts to the thin and spatially restricted alluvial deposits where flow paths are short (often in the order of hundreds of metres) and residence times are small (in the order of days to months). Unlike the upper catchment where the alluvium is exclusively underlain by highly transmissive basalts of the Lamington Volcanics, the alluvium in the mid catchment is more likely to be underlain by sedimentary bedrock units, which may constitute aquifers or aquitards with substantially lower hydraulic conductivities than the Lamington Volcanics (hydraulic conductivity data are reported in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016a)).

Higher groundwater salinities in the alluvium of the lower Richmond river basin suggest that river recharge to the alluvium is likely to have a lower influence according to companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b) compared to that in the upper catchment. Diffuse recharge from precipitation seems to be the more dominant recharge process in the lower catchment. Unlike the upper and mid catchments, the lower Richmond River alluvia are underlain mostly by low-permeability sedimentary bedrock units such as the Grafton Formation (Figure 9). There is likely to be a smaller degree of hydraulic connection across the interface between the sedimentary bedrock and the alluvium (Raiber et al., 2016b). This suggests that the relative contribution of the sedimentary bedrock discharge to the overall alluvial water balance is small during normal climate conditions. In the eastern part of the Richmond river basin where different stratigraphic units thin and pinch out at the basin margin or are displaced by faults (Figure 9), upwelling of groundwater from the sedimentary bedrock into the shallow alluvial aquifers likely occurs. While the flow directions in the sedimentary bedrock of the Richmond river basin are poorly constrained by monitoring data, the bedrock topographic gradient derived from the three-dimensional geological model in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b) suggests that groundwater flows towards the lowest point in the eastern part of the Richmond river basin, where it discharges to the alluvium and streams (Figure 9). However, while there are some elevated salinities in the alluvium that may indicate upward discharge of more-saline sedimentary bedrock groundwater, overall, most alluvial groundwater in areas where the alluvium overlies the down-gradient end of the sedimentary bedrock are fresh. This suggests that upwards leakage from the sedimentary bedrock may be overwhelmed by other sources of recharge to the alluvium, such as diffuse rainfall recharge or river recharge.

2.6.2.3.2.3 Aquifer connectivity

The hydraulic relationships between the different sedimentary bedrock units, the sedimentary bedrock and alluvial aquifers, and between the sedimentary bedrock and volcanic bedrock are much more difficult to determine compared to interactions between shallow aquifers. This is due to the complexity of the Clarence-Moreton Basin aquifer/aquitard system and the lack of groundwater observation bores in the sedimentary bedrock units. The current conceptual model for the Main Range Volcanics in Queensland assumes that there is only limited vertical connectivity across the interface between the basalts and the underlying sedimentary bedrock due to the presence of weathering horizons that have very low hydraulic conductivities as described in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b).

Most sedimentary bedrock stratigraphic units in the Clarence-Moreton bioregion are considered as poor aquifers or aquitards according to companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b). If an aquitard is an ideal regional seal, then it should limit or prevent the vertical hydraulic connection between the overlying and underlying stratigraphic units. In the case of the Walloon Coal Measures of the central part of the Richmond river basin, Doig and Stanmore (2012) suggested that the high gas saturation levels are indicative of an effective seal that prevents or limits vertical gas leakage from the Walloon Coal Measures. This seal is thought to be the Maclean Sandstone, which is located between the coal seams of the Walloon Coal Measures and the Kangaroo Creek Sandstone Member. In addition to the Maclean Sandstone, there are two other stratigraphic units that are considered as aquitards (Bungawalbin Member and Rapville Member) separating the coal seams of the Walloon Coal Measures and the shallow alluvial and volcanic aquifers. While all aquitards appear to be present and continuous throughout the potential CSG development area west of Casino, their thickness and composition can vary so their role as regional seals may be compromised by the presence of geological structures (i.e. faults). Faults can cause compartmentalisation of the hydrostratigraphic units and act as horizontal barriers to flow (e.g. Moya et al., 2015; Smerdon and Turnadge, 2015). However, both faults and fractures can also act as vertical conduits.

Although several major geological structures have been recognised within the Richmond river basin where fault displacement is known to occur, their characteristics, such as depth, dip and hydraulic conductivity, are unknown. Faults were not represented in the Clarence-Moreton groundwater model due to the lack of the above mentioned information. The Metgasco groundwater model (Parsons Brinckerhoff, 2013) simulated the impact of a very simplified high-conductance vertical fault inside the development area on impact prediction; the modelling results suggest drawdown due to additional coal resource development (additional drawdown) is less than 2 m along the fault line within the Kangaroo Creek Sandstone that is overlying the Walloon Coal Measures. The impact of faults on predictions for shallow aquifers was not discussed in the Metgasco groundwater model. In addition, there are also likely to be unknown smaller geological structures, although further work and supporting data are required to identify them.

2.6.2.3.2.4 Extent of the groundwater model domain

The extents of the groundwater model domain were primarily based on an understanding of the geology and hydrogeology outlined in companion products 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b). Overall, the groundwater model mostly follows the boundary of the Richmond river basin with deviations in some areas as follows (Figure 10):

- A small area of the Richmond river basin close to the Mount Barney intrusion was excluded from the northern part of the model domain. This was due to the very substantial geological complexity in this area and that it is more than 50 km away from the additional coal resource development area, hence, this deviation was deemed to have little or no impact on the groundwater modelling results. The only existing coal mines (operating or recently closed) within the Clarence-Moreton bioregion are located more than 120 km away from the potential CSG development area near Casino. In addition, the three-dimensional geological model of the Clarence-Moreton bioregion indicates that there is no hydraulic connection between the Bremer river basin (where the only operating coal mine is located) and the Richmond river basin, as multiple basement highs hydraulically separate the different depositional centres as described in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b).
- In order to represent recharge into the Walloon Coal Measures, the western part of the groundwater model domain was extended to include the entire extent of the Walloon Coal Measures. This meant that part of the Clarence river basin west of the Richmond river basin was included in the groundwater model.
- It was outlined in companion products 1.5 (McJannet et al., 2015), 2.1-2.2 (Raiber et al., 2016a) and 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b) that the lowermost units of the Clarence-Moreton Basin (i.e. Koukandowie Formation and below; Figure 8) are not currently utilised for groundwater extraction due to their considerable depth, their inferred low yields and the high groundwater salinity contained within Koukandowie Formation and the Gatton Sandstone. Consequently, the outcrop or subcrop areas of these older sedimentary bedrock units were excluded from the eastern and western parts of the groundwater model. Furthermore, due to their distant location from the additional coal resource development area, there are unlikely to be any impacts resulting from CSG development on water resources outside the extent of the Walloon Coal Measures.

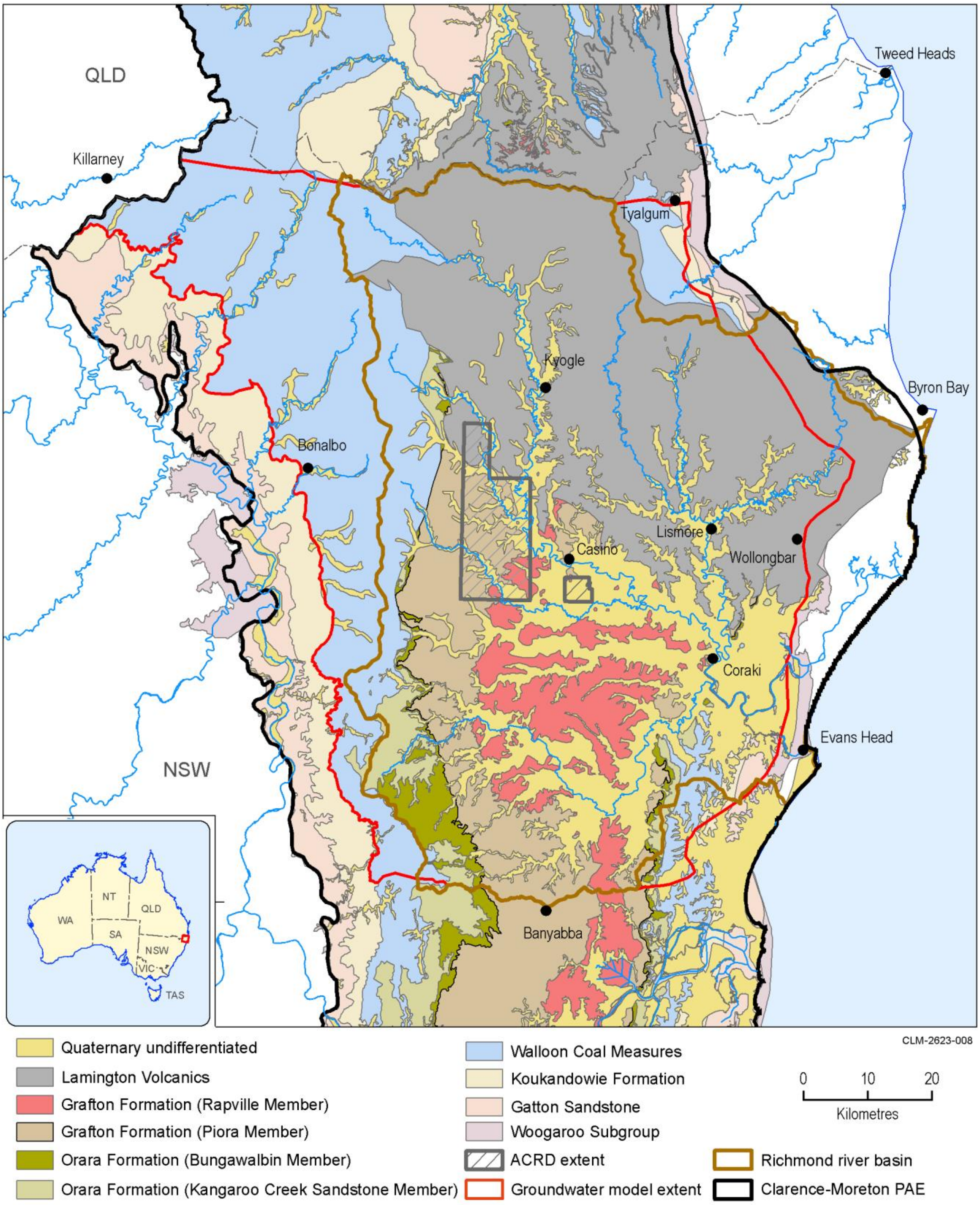

Figure 10 Groundwater model extent

This map adopts the revised stratigraphic classification proposed by Doig and Stanmore (2012).
ACRD = additional coal resource development, PAE = preliminary assessment extent
Source: (i) Surface geology map of Australia 1:1,000,000; (ii) Geological Survey of NSW (*In prep.*); (iii) Queensland and NSW geological surveys
Data: Parsons Brinckerhoff (Dataset 1); NSW Trade and Investment (Dataset 2); Bioregional Assessment Programme (Dataset 3)

The potential area of CSG development (additional coal resource development) west and south of Casino is located centrally within the Richmond river basin (Figure 10). Based on results derived from previous modelling exercises in the Surat Basin where CSG development on a much larger scale was taking place (QWC, 2012; Moore et al., 2014), it was deemed that the current groundwater model boundaries were sufficiently far from the additional coal resource development, thus ensuring that all potential impacts associated with CSG development within the Richmond river basin are captured within the model domain with minimal boundary effects. This was further confirmed by an existing preliminary modelling study (Parsons Brinckerhoff, 2013) and a simple analytical element model specifically designed for the Clarence-Moreton groundwater model.

2.6.2.3.3 Design and implementation

2.6.2.3.3.1 Modelling time and stress period setup

The transient stage of the groundwater model spanned a total simulation period of 120 years from 1983 to 2102 (Figure 11). The available observations during the historical period from 1983 to 2012 provided constraints on model parameters, such as hydraulic conductivity and boundary-related parameters. During the prediction period that spanned a period of 90 years from 2013 to 2102, the 95 CSG wells were gradually activated from 2018 to 2036 after which no additional wells were activated. These wells continued to extract water until the target water pressure (equilant to a water level of 35 m above the top of the Walloon Coal Measures) was realised. Monthly stress periods were adopted throughout the simulation to provide monthly change of baseflow required by the surface water model. This led to a total number of 1441 stress periods, including the first stress period, which represented a steady-state simulation prior to the transient modelling.

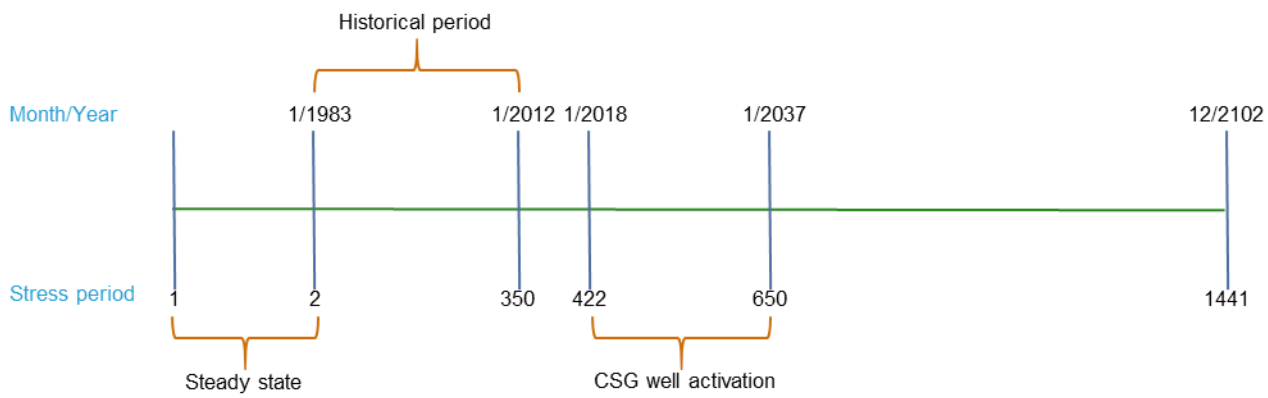

Figure 11 Time discretisation of the groundwater model

CSG = coal seam gas

2.6.2.3.3.2 Grid discretisation

The model domain shown in Figure 10 was discretised into 248 rows and 184 columns resulting in 33,352 active cells in every layer. Grid spacing varied from 200 m by 200 m inside the additional coal resource development domain to 800 m by 800 m outside the domain. The model grid is orientated in the north–south direction without any rotation.

2.6.2.3.4 Model code and solver

MODFLOW-NWT (Niswonger et al., 2011), a Newton formulation of MODFLOW-2005, was chosen to execute the model in order to avoid numerical instabilities associated with cell drying and rewetting in the uppermost layer of the model. The model area is characterised by high-relief topography that usually results in cell drying and rewetting in the unconfined parts of a groundwater model that may cause converging issues. MODFLOW-NWT was intended to solve drying and rewetting problems more efficiently and provide a more stable solution than MODFLOW-2005 by treating nonlinearities of cell drying and rewetting as a continuous function of groundwater head (Niswonger et al., 2011). The GMRES matrix solver was used for solving the linear equations generated by the groundwater model.

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2.6.2.4 Boundary and initial conditions

Summary

General-head boundaries were implemented in the northern and southern sides of the groundwater model domain where the simulated aquifers continue beyond the model extents. Furthermore, a general-head boundary was implemented in parts of the eastern side of the groundwater model domain where it intersects with the Richmond River alluvium. The conductance of the general-head boundary was allowed to vary during the sensitivity and uncertainty analyses. Other parts of the model were assigned no-flow boundaries.

The long-term average recharge was estimated using chloride mass balance analysis. The point-scale estimates were upscaled, coupled with Australian Water Resources Assessment (AWRA) outputs and normalised to yield a spatially explicit time series of recharge, which was implemented using the MODFLOW Recharge package and varied via multipliers during the sensitivity and uncertainty analyses.

Perennial reaches of the Richmond River network were explicitly simulated using the MODFLOW River package by imposing stage-height time series derived from river-gauging sites. Estimates for the riverbed hydraulic conductivity and thickness were informed by the riverbed topography. Initial riverbed conductance was calculated using the two parameters along with river reach width and length. The initial values were adjusted with the aid of pilot points during the sensitivity and uncertainty analyses.

Other existing groundwater bores that were not drilled for coal seam gas (CSG) extraction were simulated using the MODFLOW Multiple Node Well package where the bores remained operational at a constant pumping rate equal to the current allocation during the entire simulation.

2.6.2.4.1 Lateral

A general-head boundary was implemented in areas where the simulated aquifers continue beyond the groundwater model domain (Figure 12). As indicated by the three-dimensional hydrogeological model described in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b), some aquifers simulated in the groundwater model do not terminate at the model's northern and southern borders. Hence, general-head boundaries were used along the southern and northern sides of the groundwater model domain. Although the eastern side of the groundwater model domain follows the extents of the Walloon Coal Measures, the Richmond River alluvium does extend beyond this boundary as far as the coastline, so a general-head boundary was applied to the cells that intersect the Richmond River alluvium along this part of the groundwater model domain. The hydraulic conductance for the general-head boundary was allowed to vary by using three multipliers (Table 4) during the sensitivity and uncertainty analysis. Note that they were not transient parameters, that is, they were varied across simulations but kept constant during individual simulations.

The western side of the groundwater model domain that follows the extents of the Walloon Coal Measures, the eastern side of the groundwater model domain that does not intersect the Richmond River alluvium, and the bottom boundary of the groundwater model domain were all assumed to be impermeable, and were hence assigned no-flow boundaries.

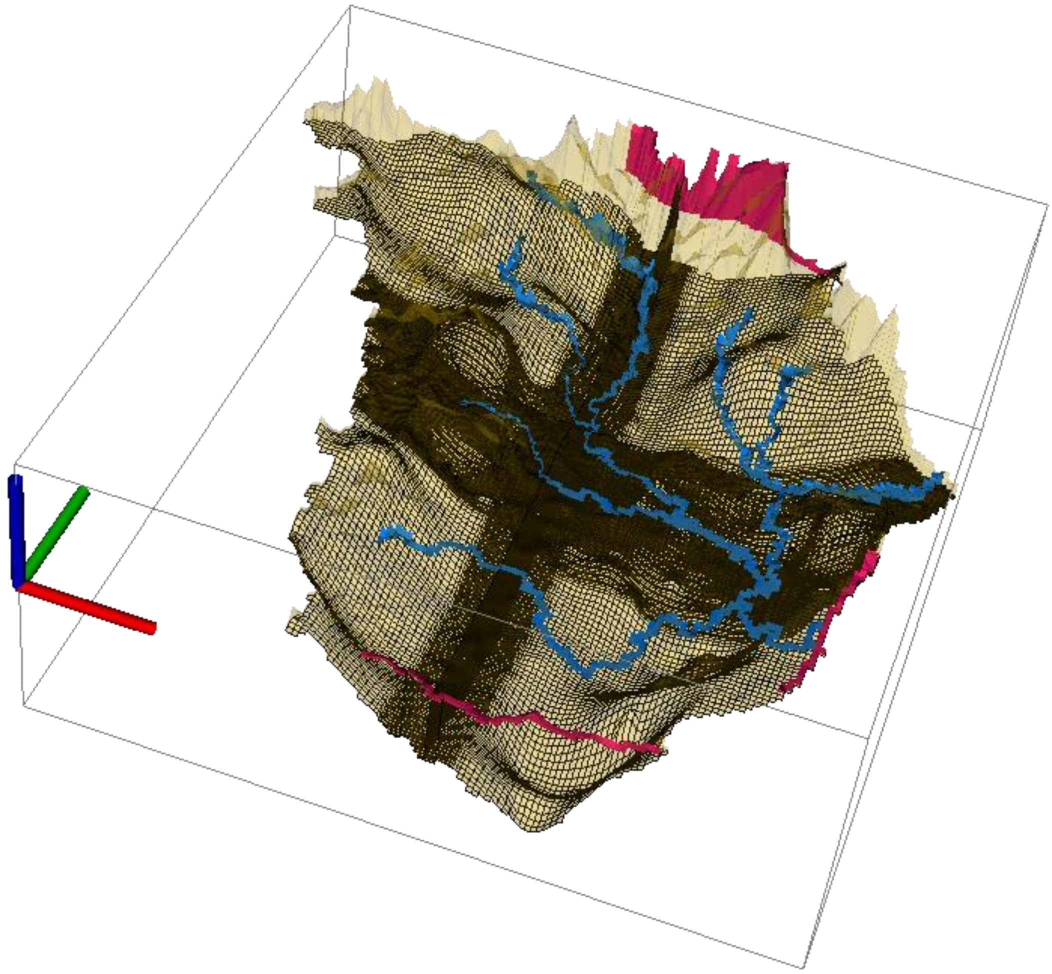

Figure 12 Grid shell and grid lines of the Clarence-Moreton groundwater model

Red and blue cells show locations where General-Head Boundary and River packages were applied, respectively.

Table 4 Adjustable parameters associated with initial and boundary conditions during sensitivity and uncertainty analysis, and their corresponding bounds

Group	Parameter name	Initial value	Minimum	Maximum	Unit	Description
General-head boundary	*GHB_N*	5.04	0.01	1,000	na	Multiplier* for conductance of the north general-head boundary
	GHB_S	0.80	0.001	10,000	na	Multiplier* for conductance of the south general-head boundary
	GHB_E	1,000	0.1	1,000,000	na	Multiplier* for conductance of the east general-head boundary
Recharge package	*RCH_1*	1	0.2	2	na	Multiplier* for recharge of the recharge zone 1 (alluvium)
	RCH_2	1	0.3	2	na	Multiplier* for recharge of the recharge zone 2 (Lamington Volcanics)
	RCH_3	1.00	0.2	5	na	Multiplier* for recharge of the recharge zone 3 (Grafton Formation)
	RCH_4	1.50	0.2	5	na	Multiplier* for recharge of the recharge zone 4 (Bungawalbin Member)
	RCH_5	1.50	0.2	5	na	Multiplier* for recharge of the recharge zone 5 (Kangaroo Creek Sandstone)
	RCH_6	2.00	0.3	5	na	Multiplier* for recharge of the recharge zone 6 (Walloon Coal Measures: Maclean Sandstone)
	RCH_7	0.41	0.2	5	na	Multiplier* for recharge of the recharge zone 7 (Walloon Coal Measures: coal seams)
	RCH_8	0.30	0.2	5	na	Multiplier* for recharge of the recharge zone 8 (Walloon Coal Measures: coal seams)
	RCH_9	0.59	0.5	5	na	Multiplier* for recharge of the recharge zone 9 (Walloon Coal Measures: coal seams)
Drain package	*DRN_C_2*	1.00	0.2	5	na	Multiplier* for conductance of drain cells in layer 1
River package	*Rinc*	0.00	–0.5	0.5	M	Parameter to stochastically change river stages
	rp1	5.07	0.1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 1
	rp2	86.89	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 2
	rp3	47.35	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 3

Group	Parameter name	Initial value	Minimum	Maximum	Unit	Description
	rp4	45.82	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 4
	rp5	5.48	0.1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 5
	rp6	1.03	0.01	1,000	m^2d^{-1}	Riverbed conductance at pilot point 6
	rp7	0.01	0.0001	100	m^2d^{-1}	Riverbed conductance at pilot point 7
	rp8	37.12	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 8
	rp9	91.48	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 9
	rp10	0.01	0.0001	100	m^2d^{-1}	Riverbed conductance at pilot point 10
	rp11	49.20	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 11
	rp12	59.37	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 12
	rp13	77.76	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 13
	rp14	4.95	0.1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 14
	rp15	27.42	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 15
	rp16	5.08	0.1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 16
	rp17	32.89	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 17
	rp18	20.14	1	1,000	m^2d^{-1}	Riverbed conductance at pilot point 18
	rp19	596.68	1	10,000	m^2d^{-1}	Riverbed conductance at pilot point 19
	rp20	526.61	1	10,000	m^2d^{-1}	Riverbed conductance at pilot point 20
	rp21	599.62	1	10,000	m^2d^{-1}	Riverbed conductance at pilot point 21
	rp22	506.91	1	10,000	m^2d^{-1}	Riverbed conductance at pilot point 22

*A multiplier is a dimensionless scalar to scale up/down parameters. For example, *RCH_1* is a multiplier for the recharge of recharge zone 1 with a range from 0.2 to 2. This means that the recharge of recharge zone 1 was varied in a range between 0.2 and 2 times of the initial recharge of recharge zone 1.
na = not applicable
Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.4.2 Recharge

The long-term average recharge was estimated using chloride mass balance (Anderson, 1945) and empirical relationships based on annual rainfall, soil clay content and vegetation type as described in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016a). The estimated point-scale recharge was upscaled using annual average rainfall as a covariate to yield a continuous surface that represents recharge (Crosbie et al., 2015). The upscaled recharge surface was then assigned to the first stress period (steady state) of the groundwater model using the MODFLOW Recharge package (Harbaugh, 2005).

The upscaled estimates of recharge derived from the chloride mass balance method only provide a long-term average rate. In order to obtain a transient recharge boundary, a temporal sequence of recharge was generated by the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) (Hafeez et al., 2015), which is able to reproduce the temporal trends of groundwater recharge when compared to time series field data in a limited number of locations. However, it cannot reproduce the spatial heterogeneity in long-term average recharge at the local scale (Shi et al., 2015). Hence, the AWRA-L outputs were normalised to generate a time series of recharge change (Figure 13), which was then used to scale the upscaled long-term average recharge derived from the chloride mass balance analysis into a spatially explicit time series of recharge. The adjustment of recharge during the sensitivity and uncertainty analysis was implemented using nine multipliers (Table 4) that correspond to various surface hydrogeological units as shown in Figure 8 in the Section 2.6.2.3. The Walloon Coal Measures outcrop areas are represented in the model by three recharge zones because they are located in different parts of the Richmond river basin where the hydrological characteristics (e.g. topography or rainfall) are very diverse. This three-zone representation also increases the flexibility of constraining the numerical model during the uncertainty analysis.

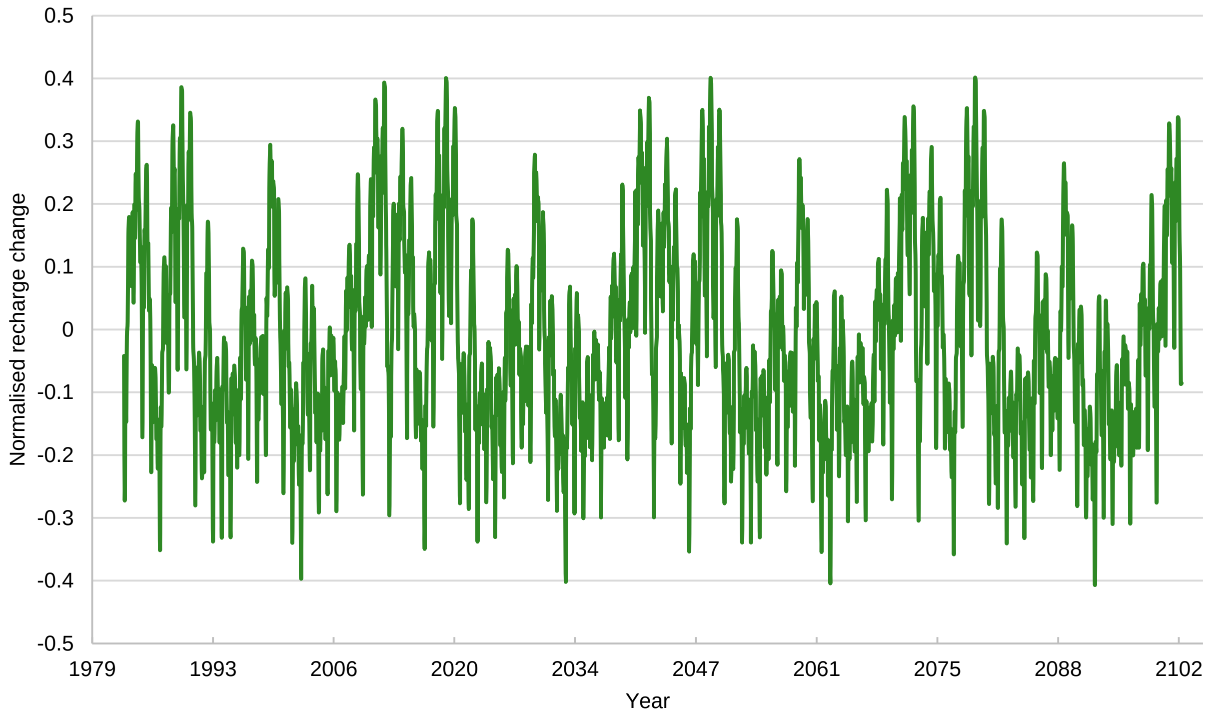

Figure 13 Normalised recharge change in the groundwater model domain

Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.4.3 Surface water – groundwater interactions

The perennial reaches of the Richmond River network were explicitly simulated using the MODFLOW River package (Harbaugh, 2005). Long-term average river stages for the steady-state model were interpolated from measurements obtained at 12 gauge sites located within the model domain (Figure 14). Transient river stages at the 12 gauges were derived from rating curves based on historical records and the runoff component of the AWRA-L outputs. Figure 15 demonstrates an example of the derived river stage time series at gauge 203004 for the period between 1983 and 2102.

Another key controlling parameter is the riverbed conductance, which is defined as follows:

$$\mathrm{CRIV}_n = \frac{K_n L_n W_n}{M_n} \quad (1)$$

where K_n and M_n represent the hydraulic conductivity and thickness of the riverbed, respectively, and L_n and W_n represent the length and width of the river reach, respectively (Harbaugh, 2005). Due to a lack of data in the Clarence-Moreton bioregion, the initial hydraulic conductivity of the riverbed was assigned values that range from $1e^{-6}$ to $1e^{-3}$ m/day, which were sourced from a previous study conducted in the Murray-Darling Basin (Taylor et al., 2013). It is widely accepted that the riverbed hydraulic conductivity is primarily a function of reach geometry, streamflow velocity, composition and erodibility of catchment, and bed disturbance frequency (Stewardson et al., 2016). The riverbed hydraulic conductivity generally increases with riverbed slope when other factors are similar (Pérez-Paricio et al., 2010). In the current study, we assume that the hydraulic conductivity varies directly with the riverbed slope due to the lack of other data. Riverbed thicknesses that had initial values ranging from 0.5 to 4 m, were assumed to vary inversely with the riverbed slope.

The initial values of the riverbed conductance were adjusted through 22 pilot points during the sensitivity and uncertainty analysis (Figure 16). Twelve pilot points were placed at locations where gauges exist (Figure 14). Cross-sections of the stream at these locations were used to obtain reach-width information. Another 10 pilot points were placed where gauges are not available to provide an even coverage of the stream network in the groundwater model. Reach-width data for these locations were sourced from the hydrographic survey data by NSW Office of Environment and Heritage (2012).

Apart from the perennial streams that were explicitly simulated in the groundwater model, there were other surface water features such as local intermittent streams and swamps, which were considered to function as local discharge features (Raiber et al., 2016b); such features were lumped together and implicitly simulated using the MODFLOW Drain package. A drain boundary condition is assigned to each model grid cell in layer 1 with a drainage elevation equal to topography. The drainage conductance is set to 1 m^2/day and allowed to vary through a multiplier (*DRN_C2*) in the uncertainty analysis.

Figure 14 Locations of gauges for river stage interpolation

PAE = preliminary assessment extent
Coal resource development pathway = baseline + additional coal resource development (ACRD)
Data: Bioregional Assessment Programme (Dataset 2)

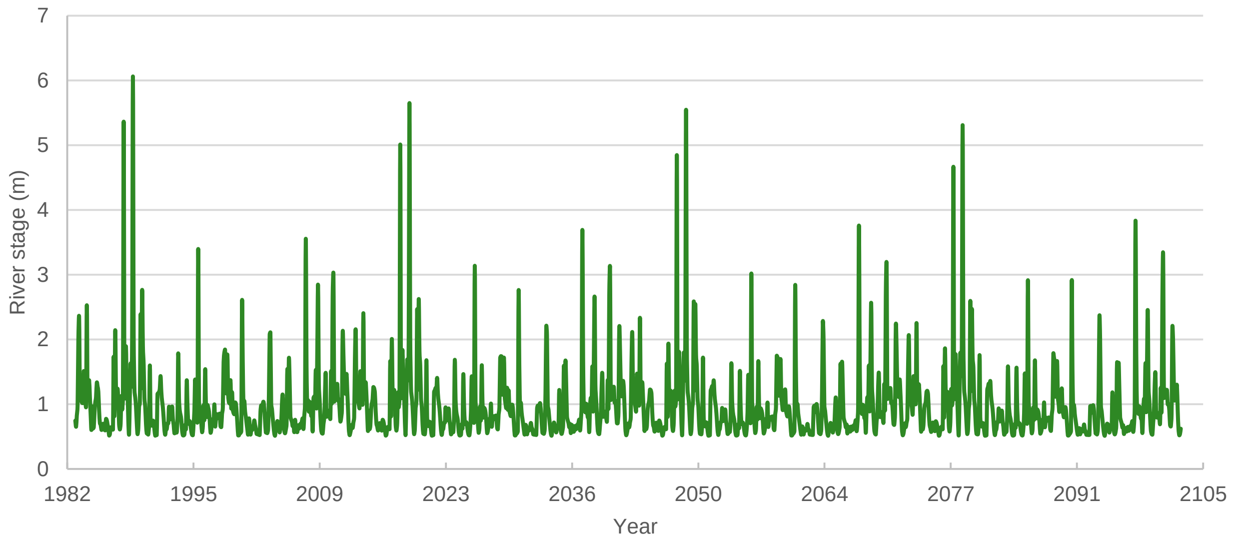

Figure 15 River stage time series at gauge 203004

The river stage is referred to the local gauge reference elevation.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.2.4.4 Non-coal seam gas pumping bores

There are 2454 non-coal seam gas (CSG) bores within the model domain. Note that the number of simulated bores is fewer than the total number of 2505 reported in companion product 1.5 for the Clarence-Moreton bioregion (McJannet et al., 2015). This is because some bores are screened in hydrogeological units that are below the Walloon Coal Measures, while other bores were located in the same model grid cell and were hence modelled as a single well. These bores were simulated using the MODFLOW Multiple Node Well (MNW) package. The activation date was assumed to be the same date the bore was constructed. Once a bore is activated, it remains operational at a constant pumping rate during the entire simulation. Due to the lack of metered data, the pumping rate was calculated using the latest allocation data in the state groundwater database when the data was compiled (Bioregional Assessment Programme, Dataset 2). It is expected that the derived pumping rate will result in an overestimate of the total water level change; however, it should have a minor impact on the drawdown due to the additional coal resource development.

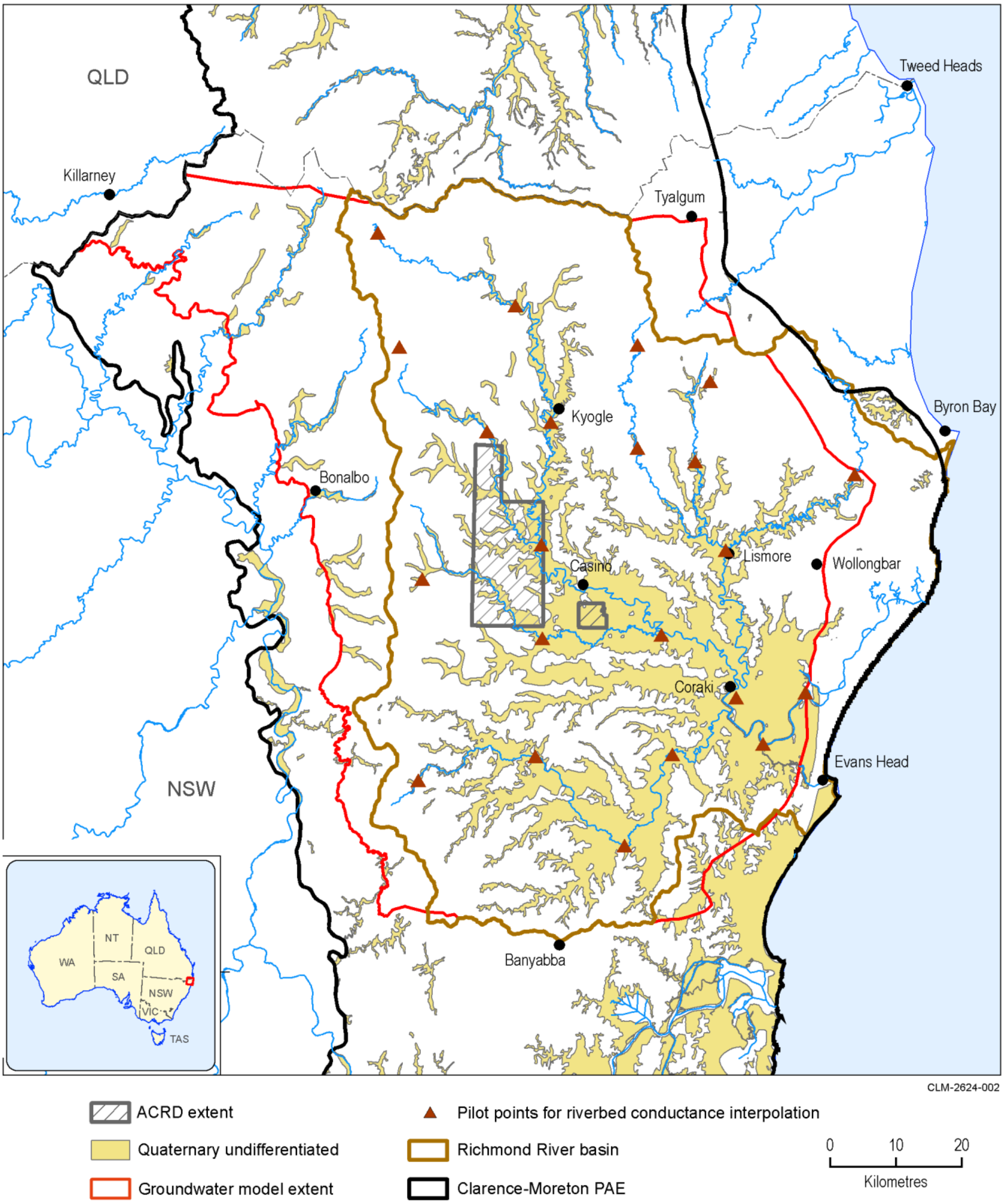

Figure 16 Distribution of pilot points for riverbed conductance

PAE = preliminary assessment extent
Coal resource development pathway = baseline + additional coal resource development (ACRD)
Data: Bioregional Assessment Programme (Dataset 1)

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2.6.2.5 Implementation of the coal resource development pathway

Summary

The baseline coal resource development (baseline) for the Clarence-Moreton bioregion includes only one operational coal mine (Jeebropilly Mine, west of Ipswich, Queensland). In addition to this coal mine, the coal resource development pathway (CRDP) includes one additional coal resource development, Metgasco Limited's West Casino Gas Project. The Jeebropilly Mine will be closed in 2017 before the start of the West Casino Gas Project, and is believed to be beyond the potential impact zone of the additional coal resource development. While the Jeebropilly coal mine is included in the CRDP, it is not modelled because it is distant and hydrologically disconnected from Metgasco's West Casino Gas Project. The coal seam gas extraction wells in the coal seams of the Walloon Coal Measures (layer 6) were simulated in the numerical groundwater model using the MODFLOW Drain package, with a variable conductance that aims at matching the independently predicted volumes of extracted water and achieves the target pressure head.

2.6.2.5.1 Coal seam gas wells

Only one coal mine, the Jeebropilly Mine west of Ipswich, Queensland, is included in the baseline coal resource development (baseline) for the Clarence-Moreton bioregion. The coal resource development pathway (CRDP) was developed in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016) based on information reported in companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014) and consultation with stakeholders at two workshops conducted in Sydney and Brisbane in December 2014. In addition to this coal mine, the CRDP includes one additional coal resource development, which is Metgasco Limited's West Casino Gas Project, in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016). It should be noted that in December 2015 Metgasco decided to discontinue its proposed development of the West Casino Gas Project. However, as per the CRDP methodology (see companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014)), once the CRDP is determined, it is not changed for bioregional assessment (BA) purposes. This means that the timeline described will continue to form the basis for the groundwater modelling.

The West Casino Gas Project consists of two potential gas fields (one to the south and one to the west of Casino). There are 90 wells in the current development plan (Parsons Brinckerhoff, 2013) for the gas field west of Casino, which will be drilled into the Walloon Coal Measures to extract coal seam gas (CSG) over a period of 20 years starting in 2018. The gas field south of Casino corresponds to an area for which, as of July 2015, a pending petroleum production license application (PPLA 9) by Metgasco existed (NSW Trade and Investment, Dataset 1). As the number of wells was unconfirmed and PPLA 9 is partly located within the 2 km residential exclusion zone, it was assumed for the purpose of the model development that PPLA 9 would only be a small project with five wells (Raiber et al., 2016). Figure 17 shows the locations and activation years of the extraction wells.

To facilitate CSG extraction, the target coal seams are usually depressurised to a target water level; the MODFLOW Drain package was implemented in the Walloon Coal Measures (model layer 6) to achieve this target level. The target water level can vary depending on a number of parameters, such as gas saturation and hydraulic properties of the target coal seam and the surrounding hydrogeological units. Previous studies (APLNG, n.d.; Sydney Catchment Authority, 2012; Parsons Brinckerhoff, 2013) suggest that the target water level is approximately equivalent to 30 to 35 m above the top of the target coal seam. A water level of 35 m above the top of the Walloon Coal Measures was used as the target water level in the current model. Conductance in the MODFLOW Drain package was adjusted to match the predicted volumes of water produced in the development and to explore the uncertainty associated with water production rates. According to Metagasco's preliminary report (Parsons Brinckerhoff, 2013), the CSG-producing wells penetrate to depths exceeding 500 m, targeting the Richmond Seam and the deeper coal seams. However, the coal seams were not explicitly represented in the groundwater model but were lumped into one hydrostratigraphic unit (layer 6) to reduce model execution time and also due to the lack of information about the internal structure of Walloon Coal Measures.

The dual-phase flow process near CSG wells was not modelled in the current project. Previous studies (Moore et al., 2013; Moore et al., 2015; Herckenrath et al., 2015) have shown the omitting of dual-phase flow overestimates drawdown impact, especially for prediction near CSG wells, depending on hydraulic properties, development plans and simulation time. For example, Moore et al. (2015) reported a drawdown overestimate of 15 m at a distance of 7 km from the well extraction centre at a simulation time of 20 years within the targeted coal seam formation in their model. Nevertheless, the single-phase model is deemed fit for purpose in accordance with the principle of conservatism at the current stage of the BA. If a negligible impact is generated by the single-phase model, then a dual-phase model will certainly provide negligible-impact prediction. If the single-phase model finds a large impact, then this may trigger a next step with a dual-phase model to get a more realistic impact prediction.

The Jeebropilly Mine in the baseline is near Amberley, west of Ipswich in south-east Queensland, and about 200 km away from the additional coal resource development (Figure 17). The coal mine will be closed and rehabilitated after 2017 before the start of the additional coal resource development. It is also believed that the coal mine is beyond the probable impact zone of the additional coal resource development because it is distant and hydrologically disconnected from Metgasco's West Casino Gas Project (according to companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)). Thus, the coal mine is not included in the groundwater model.

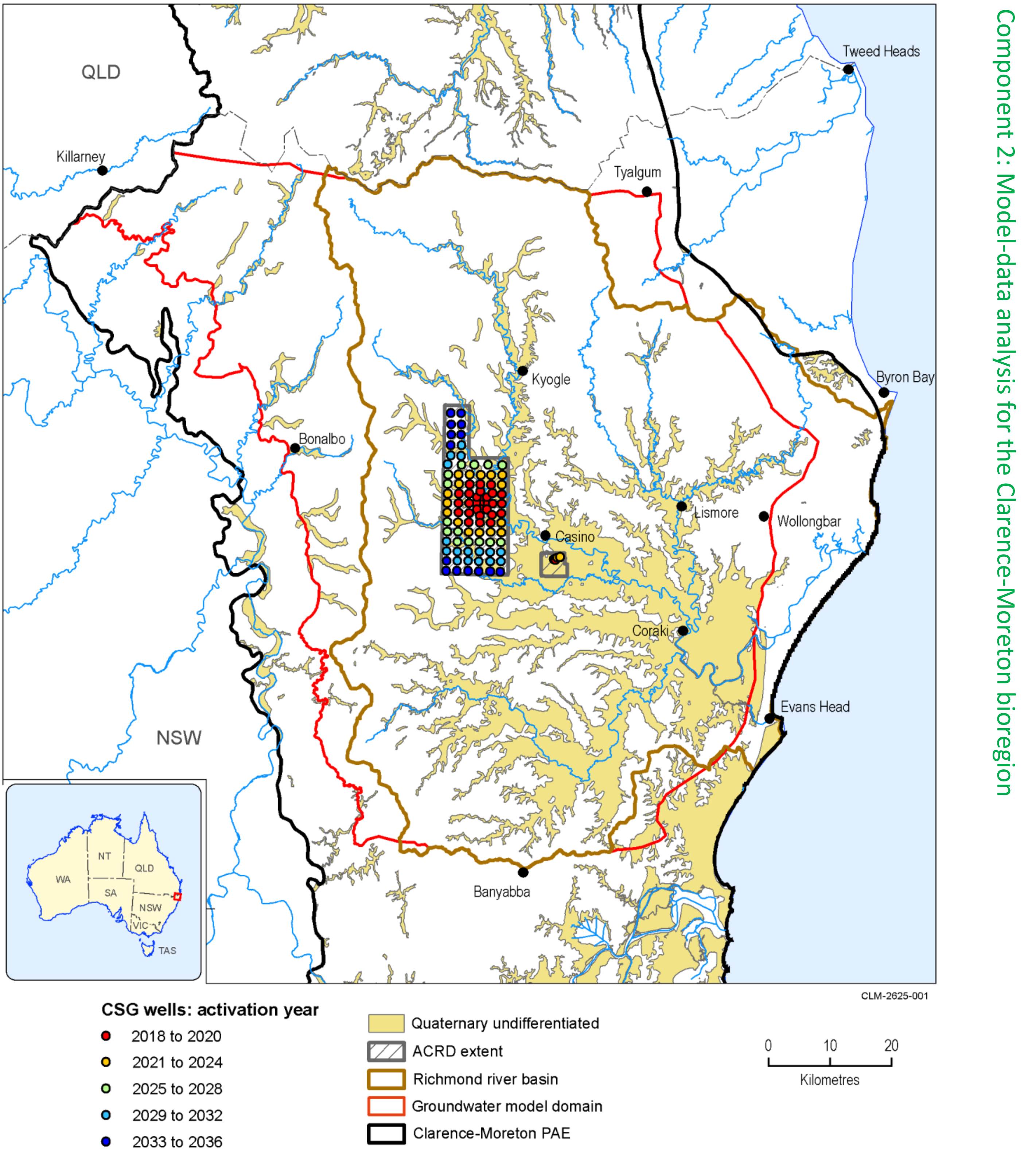

Figure 17 Distribution of the coal seam gas (CSG) wells in the groundwater model

The symbol colours indicate activation time of a specific bore. Coal resource development pathway = baseline + additional coal resource development (ACRD); PAE = preliminary assessment extent
Data: NSW Trade and Investment (Dataset 1); Bioregional Assessment Programme (Dataset 2)

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2.6.2.6 Parameterisation

Summary

This section reports on the process that was adopted to identify the initial hydraulic parameters of the numerical groundwater model: the hydraulic conductivity and storage parameters.

Two different approaches were adopted to identify the hydraulic conductivities of the shallow and deeper layers of the groundwater model. The horizontal hydraulic conductivities of the top layer were derived from 130 existing pumping test records, while those belonging to deeper layers were derived from drill stem tests (DST) and pumping test data. Two mathematical relationships were derived to describe the variation of hydraulic conductivity with depth, which were mostly based on data from geologically similar formations in the Surat Basin.

The upper and lower bounds of the storage parameters, the specific yield and specific storage, were derived from a previous modelling study conducted in the Surat Basin. The initial storage parameters were assumed to vary linearly with depth within those bounds.

Note that the parameterisation process described in this section merely provides initial estimates for the model parameters, which are significantly varied during the uncertainty analyses. Hence, the goal was to start the models with realistic parameter estimates that ensure numerically stable simulations.

2.6.2.6.1 Hydraulic conductivity

Depending on data availability, two different approaches were adopted to assign initial horizontal hydraulic conductivities (*Kx*) for all layers in the groundwater model. The horizontal hydraulic conductivities for the top layer were derived from existing pumping test records, whereas the horizontal hydraulic conductivities for the deeper layers were derived from *Kx*-depth relationships based on drill stem tests (DST) and pumping test data.

The horizontal hydraulic conductivities were derived from existing pumping test records using the TGUESS approach (Bradbury and Rothschild, 1985); more details can be found in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016). Most of the original pumping records in the NSW state groundwater database (NSW Office of Water, Dataset 1) do not include a hydraulic conductivity value. The initial horizontal hydraulic conductivities for the top layer were interpolated from the 130 *Kx* estimates derived from the pumping test records found within the area covered by the model domain (Figure 18) (Bioregional Assessment Programme, Dataset 2). For bores with multiple records, an average value was used during the interpolation process. Table 5 provides a summary of *Kx* values for the various hydrogeological units. Note that most of the pumping tests were performed in the unconfined part of the aquifers, mostly in the alluvium and volcanics.

Table 5 Summary of the horizontal hydraulic conductivity data derived from pumping test data within the groundwater model boundary

Hydrogeological unit	Number of bores	Minimum (m/d)	Median (m/d)	Maximum (m/d)
Alluvium	73	0.04	1.20	233.59
Volcanics	45	0.05	0.82	9.40
Grafton Formation	5	0.21	0.66	3.97
Walloon Coal Measures	7	0.49	3.82	17.22

Data: Bioregional Assessment Programme (Dataset 2)

The initial horizontal hydraulic conductivities for the deeper layers were computed from *Kx*-depth relationships based on DST and pumping test data. Due to a lack of bedrock aquifer data in the Clarence-Moreton bioregion, relevant data were sourced from hydrogeological strata in the Surat Basin (Figure 19), where much more data are available. However, as the correlation between the sedimentary bedrock stratigraphic units above the Walloon Coal Measures in the Surat and Clarence-Moreton basins is poorly understood, it is not possible to directly use the hydraulic parameters from a particular unit in the Surat Basin to inform the hydraulic characteristics of a unit in the Clarence-Moreton Basin. Instead, all data from the BMO Group (consisting of the Bungil Formation, Mooga Sandstone and the Orallo Formation), the Gubberamunda Sandstone, the Westbourne Formation, and the Springbok Sandstone of the Surat Basin were combined (Figure 19). The resulting patterns of the hydraulic conductivity versus depth relationship were then used to inform parameter ranges that constrain the *Kx* of the Grafton Formation (model layer 2), the Bungawalbin Member (model layer 3) and the Kangaroo Creek Sandstone Member (model layer 4) in the Richmond river basin. Data from the Walloon Coal Measures in the Surat Basin (Figure 20) were used to constrain parameter variation in the Maclean Sandstone Member of the Walloon Coal Measures (model layer 5) and the lumped coal seams of the Walloon Coal Measures (model layer 6).

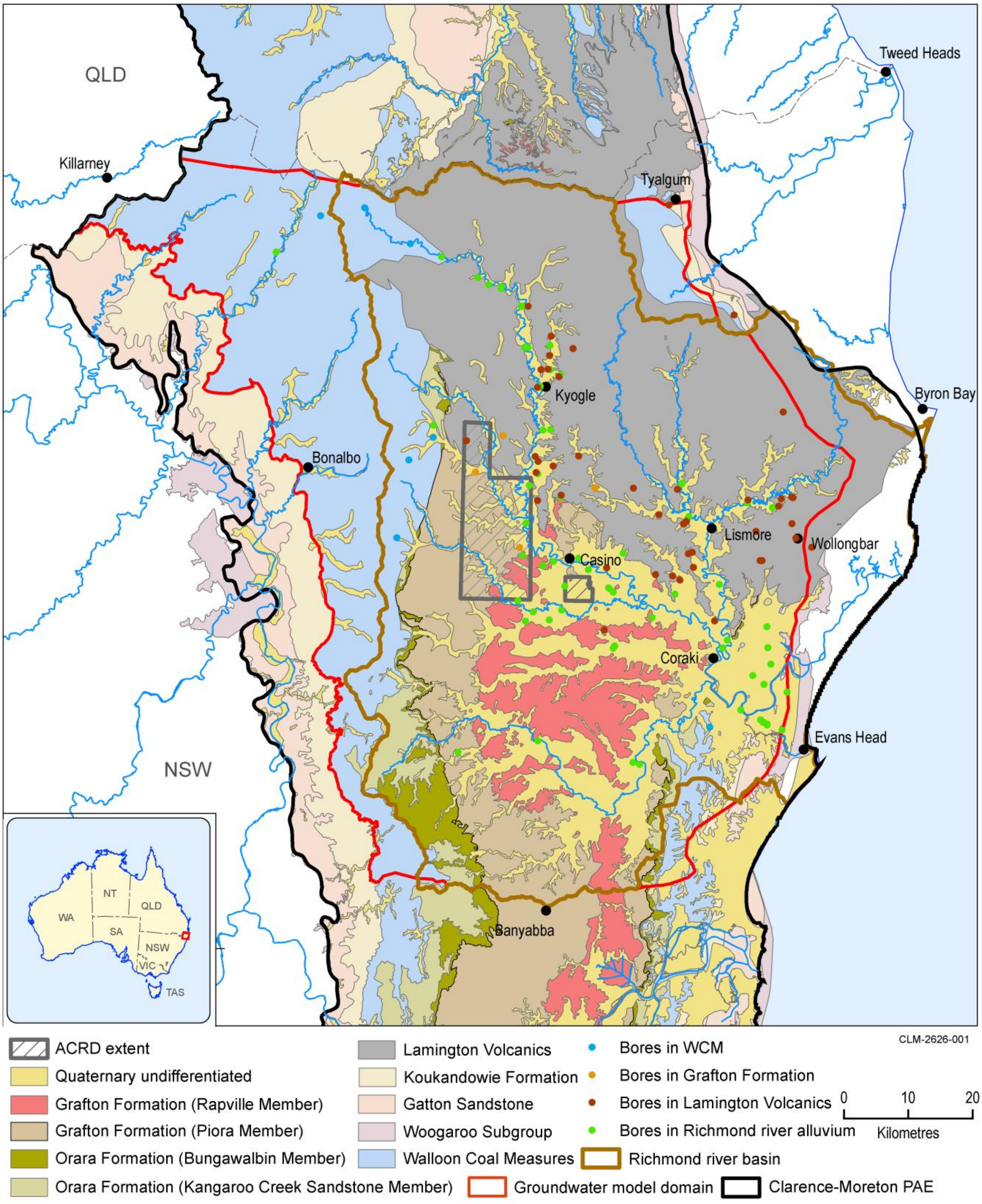

Figure 18 Distribution of bores where hydraulic conductivities can be derived from pumping test data

WCM = Walloon Coal Measures; coal resource development pathway = baseline + additional coal resource development (ACRD); PAE = preliminary assessment extent
Data: Bioregional Assessment Programme (Dataset 2)

Porosity/permeability-depth relationships have been extensively studied within the petroleum industry (e.g. Magara, 1980; Nelson, 1994). Many studies have shown a linear or exponential decline in porosity down to depths of about 3 to 4 km, depending on rock compositions and geological settings. As hydraulic conductivity is generally correlated with porosity, it is deemed that a similar trend would exist between hydraulic conductivity and depth. Two different relationships were used depending on the available data. The following log(*Kx*)-depth linear relationship was implemented for layers 2, 3 and 4:

$$\log(Kx) = -0.0009h + m \qquad (2)$$

where *h* is depth, and *m* is the value of log(*Kx*) close to ground surface. For layers 5 and 6, the following exponential decay relationship was implemented:

$$\log(Kx) = \mathrm{c}\left(1 - b^{\frac{-3h}{a}}\right) + d \qquad (3)$$

where *a*, *b*, *c* and *d* are four coefficients that can be adjusted during sensitivity and uncertainty analysis with their initial values listed in Table 6. The adjustment of the parameters in the two log(*Kx*)-depth relationships are restricted by the boundary lines in Figure 19 and Figure 20, that is, the log(*Kx*)-depth lines are not allowed to move outside the boundary lines.

The horizontal anisotropy was assumed to be 1 across the entire model domain. The initial vertical anisotropy (*Kz*/*Kx*) (*Kz*: vertical hydraulic conductivity) was mostly assumed to be 0.1 with some exceptions. The value of 0.1 was used widely in previous studies in the coal seam gas (CSG) context and considered as to be conservative (Todd and Mays, 2005; USQ, 2011; Parsons Brinckerhoff, 2013). In areas where the geological units 'pinch out' (i.e. are interpreted to have negligible or zero thickness), a dummy thickness of 5 m was assumed due to limitations in the numerical MODFLOW model. Horizontal hydraulic properties were assigned from the adjacent underlying geological unit present in that area. The *Kz*/*Kx* ratio was set to 1000 to eliminate modelling artefacts in these dummy zones. The initial vertical anisotropy was scaled using a multiplier during sensitivity and uncertainty analysis (Table 6).

The previously mentioned hydraulic conductivity initial values were allowed to vary during the sensitivity and uncertainty analysis. The variation of *Kx* in layer 1 was achieved by changing two multipliers that correspond to the alluvial or non-alluvial units. For the other layers, the slopes and intercepts of the log(*Kx*)-depth (base 10) relationships were changed instead. Some extra constraints were also imposed on the parameter adjustment. For example, the Bungawalbin Member is expected to have a lower *Kx* than the overlying Grafton Formation and the underlying Kangaroo Creek Sandstone based on a few core samples and gamma log response (Doig and Stanmore, 2012), which means that the m-coefficient for the Bungawalbin Member must be lower than these other two units. Similarly, the Maclean Sandstone Member is also expected to have a permeability lower than the Walloon Coal Measures (Doig and Stanmore, 2012). Hence, the chosen parameter range is based on expert knowledge, local hydrogeological setting and results from a series of model stability tests (Table 6) (Bioregional Assessment Programme, Dataset 3). A minimum *Kx* of 1 x 10^{-6} m/day was applied to the entire model domain based on previous studies in the Surat Basin (USQ, 2011) and compilations of hydraulic properties in the literature (e.g. Freeze and Cherry, 1979; Batlle-Aguilar et al., 2016).

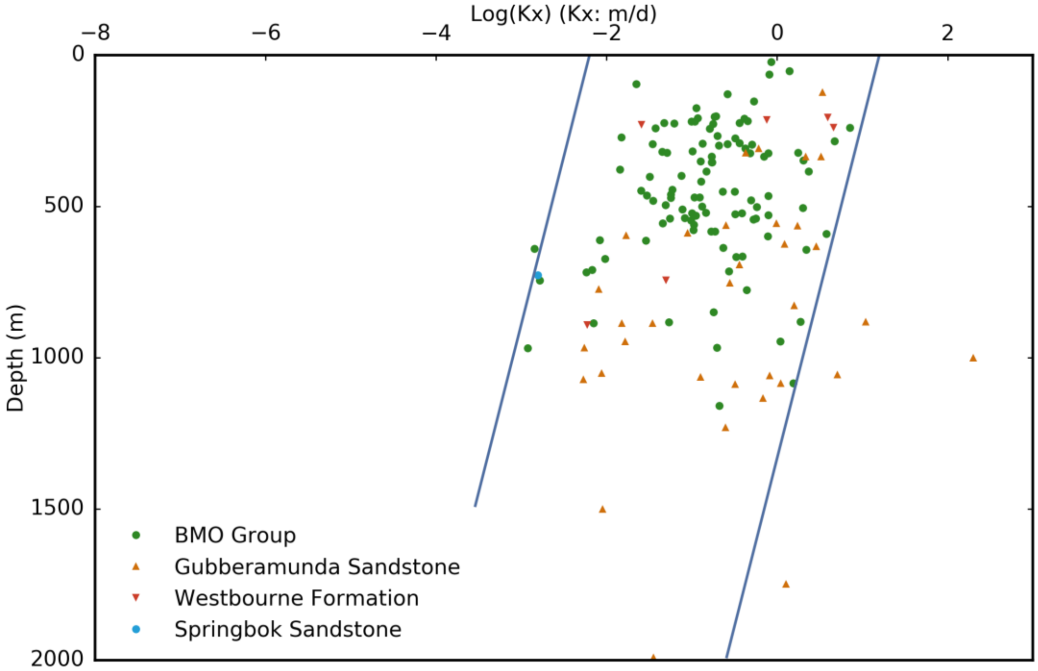

Figure 19 Hydraulic conductivity versus depth for BMO Group, Gubberamunda Sandstone, Westbourne Formation, and Springbok Sandstone within the Surat Basin, and boundary lines (the dark blue lines) of the log(*Kx*)-depth relationship for model layers 2, 3 and 4

BMO Group = Bungil Formation, Mooga Sandstone and the Orallo Formation
Data: Bioregional Assessment Programme (Dataset 2)

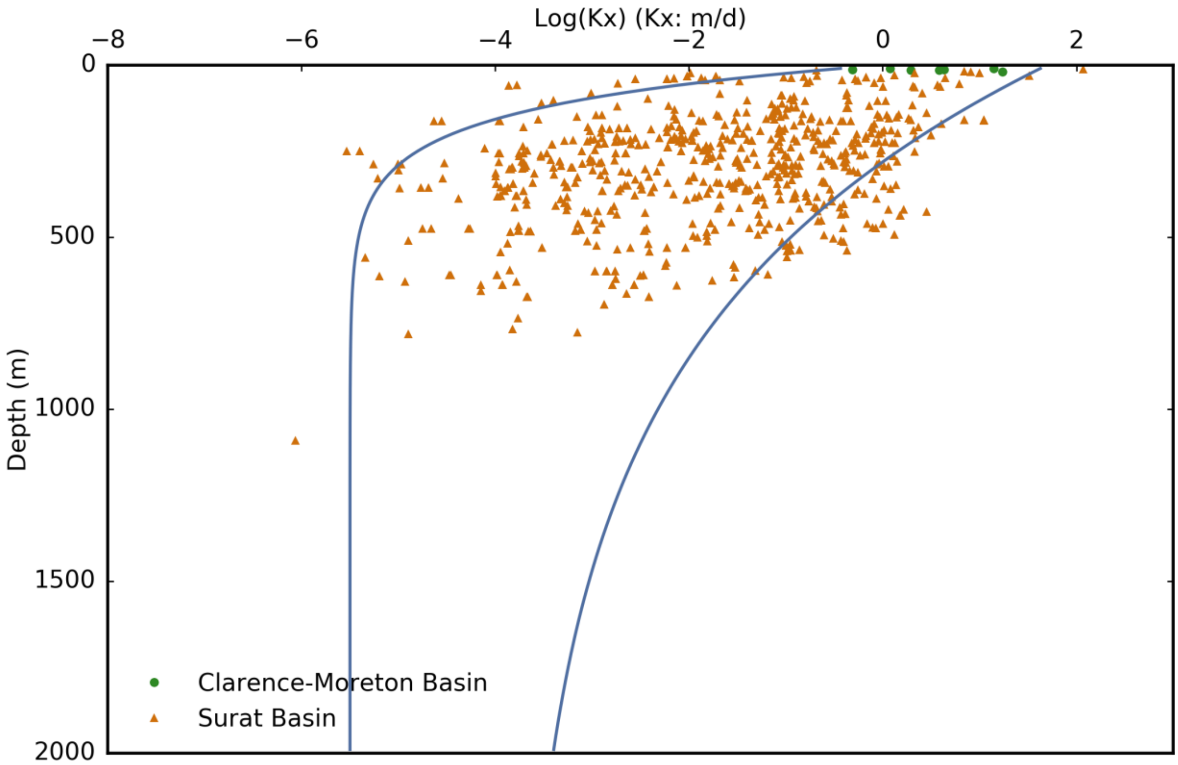

Figure 20 Hydraulic conductivity versus depth for the Walloon Coal Measures within the Clarence-Moreton Basin and the Surat Basin, and boundary lines (the dark blue) for the log(*Kx*)-depth relationship for model layers 5 and 6

Data: Bioregional Assessment Programme (Dataset 2)

Table 6 Adjustable parameters during sensitivity and uncertainty analysis and their corresponding bounds

Parameter group	Parameter name	Initial value	Lower bound	Upper bound	Description
Hydraulic conductivity	*Kx_1_a*	1	0.1	2	Multiplier* for initial *Kx* of the alluvial units in layer 1
	Kx_1_o	1	0.02	5	Multiplier* for initial *Kx* of the non-alluvial units in layer 1
	Kx_2	−0.88	−2.2	1.5	X-intercept of log(*Kx*)-depth relationship for layer 2 (m in equation 1 when h is 0)
	Kx_3_d	−1.28	−3	0.5	X-intercept of log(*Kx*)-depth relationship for layer 3 (m in equation 1 when h is 0). This one is likely lower than *Kx_2* and *Kx_4* based on previous studies
	Kx_4	−0.48	−2.2	1.5	Intercept of log(*Kx*)-depth relationship for layer 4 (m in equation 1 when h is 0)
	Kx_5_a	900	400	900	Parameter *a* in equation 2
	Kx_5_b	2	1.3	3	Parameter *b* in equation 2
	Kx_5_c	−4	−4.5	−3.5	Parameter *c* in equation 2
	Kx_5_d	0.0	−1	0.5	Parameter *d* in equation 2
	Kx_6_a	900	400	900	Parameter *a* in equation 2
	Kx_6_b	2	1.3	3	Parameter *b* in equation 2
	Kx_6_c	−4	−4.5	−3.5	Parameter *c* in equation 2
	Kx_6_d	0	−1	0.5	Parameter *d* in equation 2
	Kx_Kz_1	1	0.01	100	Multiplier* for *Kx*/*Kz* ratio of model layer 1
	Kx_Kz_2	0.99	0.01	100	Multiplier* for *Kx*/*Kz* ratio of model layer 2
	Kx_Kz_3	0.99	0.01	100	Multiplier* for *Kx*/*Kz* ratio of model layer 3
	Kx_Kz_4	1	0.01	100	Multiplier* for *Kx*/*Kz* ratio of model layer 4
	Kx_Kz_5	1	0.01	100	Multiplier* for *Kx*/*Kz* ratio of model layer 5
	Kx_Kz_6	1	0.01	100	Multiplier* for *Kx*/*Kz* ratio of model layer 6
Storativity	*Sy_1*	1	0.5	1.5	Multiplier* for specific yield of model layer 1
	Ss_1	1	0.01	100	Multiplier* for specific storage of model layer 1
	Ss_2	1	0.01	100	Multiplier* for specific storage of model layer 2
	Ss_3	1	0.01	100	Multiplier* for specific storage of model layer 3
	Ss_4	1	0.01	100	Multiplier* for specific storage of model layer 4
	Ss_5	1	0.01	100	Multiplier* for specific storage of model layer 5
	Ss_6	1	0.01	100	Multiplier* for specific storage of model layer 6

*A multiplier is a dimensionless scalar to scale up/down parameters. For example, *Kx_1_a* is a multiplier for the alluvium *Kx* in layer 1 with a range from 0.1 to 2. This means that the alluvium *Kx* was varied in a range between 0.1 and 2 times of the initial alluvium *Kx* during sensitivity and uncertainty analysis.
Kx = hydraulic conductivity; *Kz* = vertical hydraulic conductivity; *Sy* = specific yield; *Ss* = specific storage
Data: Bioregional Assessment Programme (Dataset 3)

2.6.2.6.2 Storage parameters

Upper and lower limits of the storage parameters for various hydrogeological formations modelled in this bioregional assessment (BA) were sourced from a review report by the University of Southern Queensland (USQ, 2011). The USQ (2011) study summarised such parameters and features of existing groundwater models for assessing cumulative drawdown impacts of CSG development in the Surat Basin. The initial specific yield (*Sy*) and specific storage (*Ss*) for the various hydrogeological formations and associated layers modelled in this BA were varied linearly with depth implementing the bounds listed in Table 7 (Bioregional Assessment Programme, Dataset 3). For example, in layer 2 the initial *Ss* in each model cell was changed linearly with depth from 1×10^{-6} to 1×10^{-4} m^{-1}. These parameters were adjusted during model sensitivity and uncertainty analysis by implementing the multipliers listed in Table 6. The storage parameters, in particular the ones with the targeted coal seams, control the propagation of pressure. The ranges of the multipliers in Table 6 were selected conservatively to the best knowledge of the authors to avoid underestimation.

Table 7 Specific yield (*Sy*) and specific storage (*Ss*) ranges

Layer	Hydrostratigraphic unit	Generalised hydraulic characteristics	*Sy* and *Ss* range
1	Alluvium / volcanics / unconfined part of other units	Aquifer	*Sy*: 0.1 to 0.3 *Ss*: 1×10^{-5} to 1×10^{-3} m^{-1}
2	Grafton Formation	Aquifer/aquitard	1×10^{-6} to 1×10^{-4} m^{-1}
3	Bungawalbin Member	Aquitard	1×10^{-7} to 1×10^{-5} m^{-1}
4	Kangaroo Creek Sandstone Member	Aquifer	1×10^{-6} to 1×10^{-4} m^{-1}
5	Walloon Coal Measures (Maclean Sandstone)	Aquitard	1×10^{-8} to 1×10^{-5} m^{-1}
6	Walloon Coal Measures (coal seams)	Aquifer/aquitard (variable)	1×10^{-7} to 1×10^{-4} m^{-1}

Sy is not required for confined hydrogeological units.
Data: Bioregional Assessment Programme (Dataset 3)

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2.6.2.7 Observations and predictions

Summary

Three types of data were included in the observation database to constrain the groundwater model parameters in the uncertainty analysis. These include historical groundwater levels, coal seam gas (CSG) water production forecasts and average streamflow in September and October as proxy for the surface water – groundwater flux. This section describes these observation datasets. Section 2.6.2.8 provides a detailed discussion on how these observations are used to constrain the groundwater model parameters.

A total of 188 bores are available in the observation database. Only 30 bores have transient observations. Of the 188 bores, only 43 have surveyed spatial coordinates and ground level and are deemed reliable. While the entire dataset is used to guide initial model development, only the data associated with the 43 reliable bores is used in the uncertainty analysis.

The total CSG water production rates forecasted by Metgaso Limited (Parsons Brinckerhoff, 2013) provide a point of reference for the simulated CSG water production rates.

Likewise, the observed streamflow at the Casino surface water model node (CLM_008) in September and October will provide a point of reference to the simulated average surface water – groundwater flux, as streamflow in these months is most likely dominated by the groundwater contribution.

A total of 38 parameters were varied during the sensitivity and uncertainty analysis. Ten-thousand parameter combinations were generated for the entire parameter space for the model sequence using a maximin Latin Hypercube design. Within the operational constraints of the project it was possible to successfully evaluate a total of 3877 parameter combinations. Recharge, drainage conductance and riverbed conductance were found to be the three most sensitive parameters for head observations in layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock). The impact on layer 3 (Bungawalbin Member) is dominated by the vertical hydraulic conductivity anisotropy of layer 3, followed by the horizontal hydraulic conductivity in layers 3 and 4 (Kangaroo Creek Sandstone). The drain conductance of the CSG wells and the storage coefficient and hydraulic conductivity of layer 6 (coal seams of the Walloon Coal Measures) controlled the amount of water produced from the depressurisation process. As a result, these parameters have a large impact on the drawdown prediction as this defines the stress on the system.

The model generated heads corresponding to head observations are mostly not sensitive to those parameters dominating the change in drawdown due to additional coal resource development (additional drawdown) given the current model implementation. The head observations, therefore, have limited scope to constrain the parameters that generate the most uncertainty in the additional drawdown predictions. The average surface water – groundwater flux is most sensitive to the riverbed conductance followed by the drainage conductance of the drainage boundary at the top of the model and the recharge multipliers of recharge in the alluvium and volcanics.

2.6.2.7.1 Observation data

For the Clarence-Moreton bioregion, three types of observations are available to constrain the parameters for the predictions:

1. groundwater level observations (limited to layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock))
2. an estimate of the expected coal seam gas (CSG) water production rates
3. an estimate of the surface water – groundwater flux.

These observations are introduced and discussed in this section, while Section 2.6.2.8.1.2 describes how these observations are combined in objective functions for the Markov chain Monte Carlo uncertainty analysis.

Historical groundwater level records were organised into two groups to constrain the Clarence-Moreton groundwater model. The first group comprised 188 records sourced from the National Groundwater Information System (NGIS) database (Bureau of Meteorology, Dataset 1), where standing water levels had been recorded as a component of the bore construction information (Figure 21). The second group comprised a total of 712 records in 30 bores between 1983 and 2013, sourced from the NSW Office of Water groundwater database (NSW Office of Water, Dataset 2). These bores are mainly situated in the Richmond River alluvium (Figure 21).

Standing water levels after bore construction are often not the most reliable observations. The observation dataset is filtered and only those observations are retained in the uncertainty analysis for which surveyed spatial coordinates are available and the ground level is obtained from a survey or digital elevation model. Only 43 bores had surveyed coordinates and ground level (Figure 21). These included the 30 bores with transient observations.

While the observations that were deemed not to be reliable are excluded from the formal uncertainty analysis, the entire dataset of head observations was used in the initial stages of model development to guide the initial head surface and parameterisation.

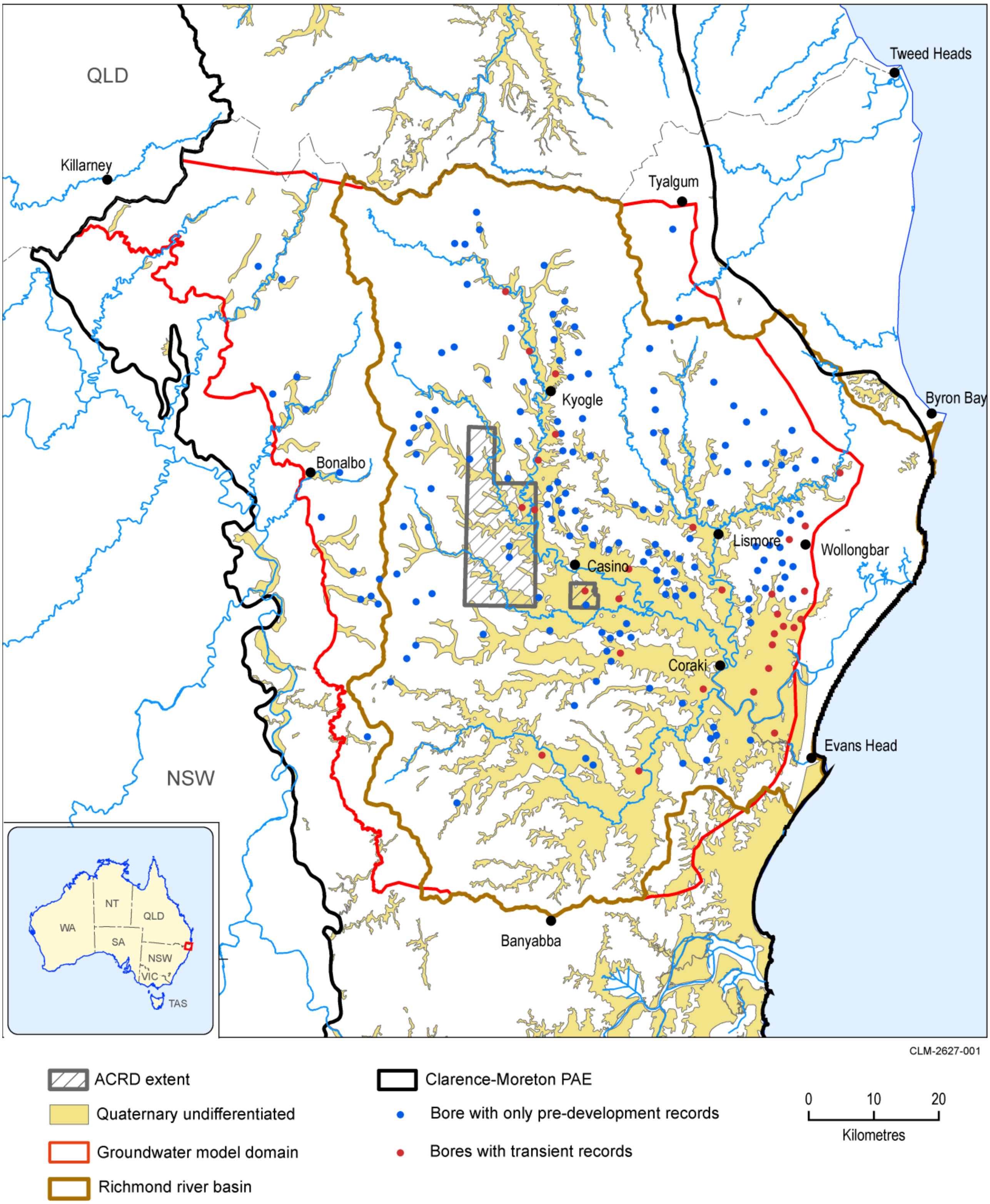

Figure 21 Distribution of selected groundwater bores with historical groundwater level records

Coal resource development pathway = baseline + additional coal resource development (ACRD); PAE = preliminary assessment extent
Data: NSW Office of Water (Dataset 2)

The second type of observation to constrain the groundwater model is the expected annual total water production during CSG production, as reported in Parsons Brinckerhoff (2013) shown in Figure 22. In the MODFLOW model, coal seam gas production is implemented as a drainage boundary condition. The volume of water that needs to be extracted to achieve the specified drawdown at the cells with a drainage boundary will therefore depend on the hydraulic parameters of the model. While it is by no means a goal of the bioregional assessment (BA) modelling to reproduce these values exactly, the simulated water extraction rates should be consistent with the estimates in Figure 22, especially since these are based on detailed local information and pilot production testing.

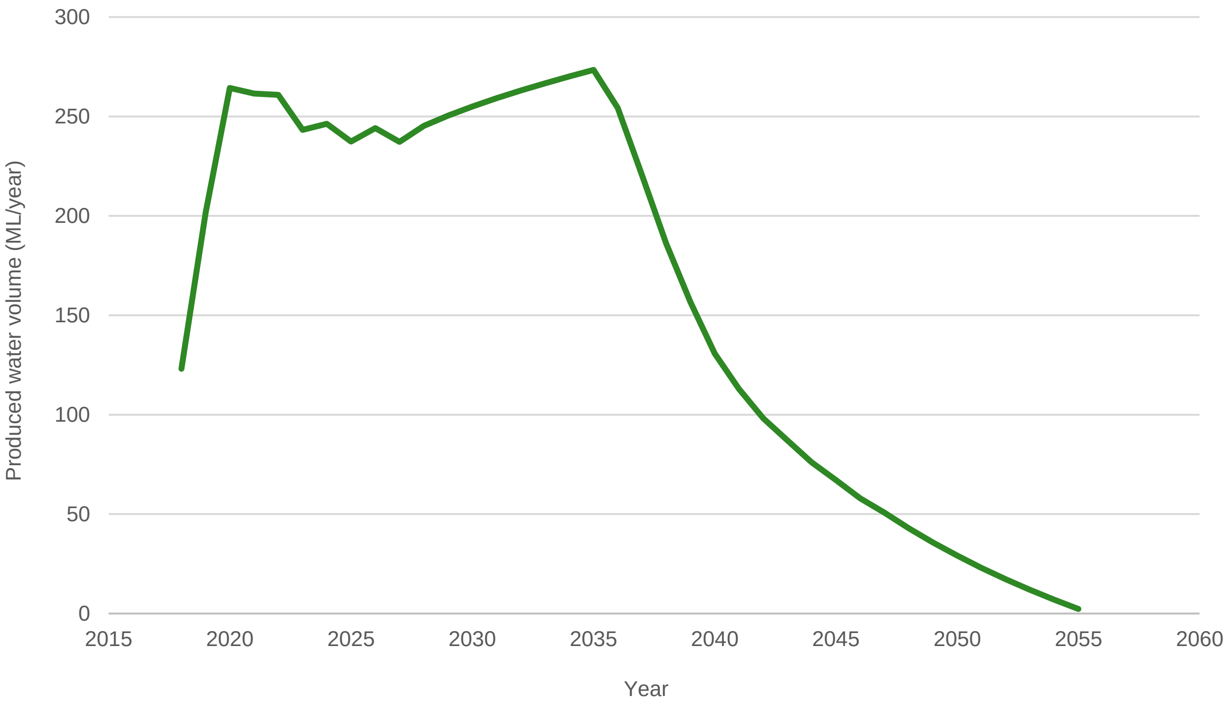

Figure 22 Metgasco's forecasted annual total water production of the additional coal resource development during the planned development period (2018 to 2055) based on modelling and pilot production testing

Data: Bioregional Assessment Programme (Dataset 3)
Source: As reported in Parsons Brinckerhoff (2013)

A third type of observation is the streamflow in the Richmond River between 1983 and 2012 at the Casino surface water model node (CLM_008). Figure 23 shows boxplots of monthly flow at this location between 1983 and 2012. It is apparent that September and October are the months with lowest streamflow. In these months it is therefore likely that a large component of streamflow is groundwater derived. The average surface water – groundwater flux in that reach is therefore unlikely to be higher than the average observed streamflow in September and October.

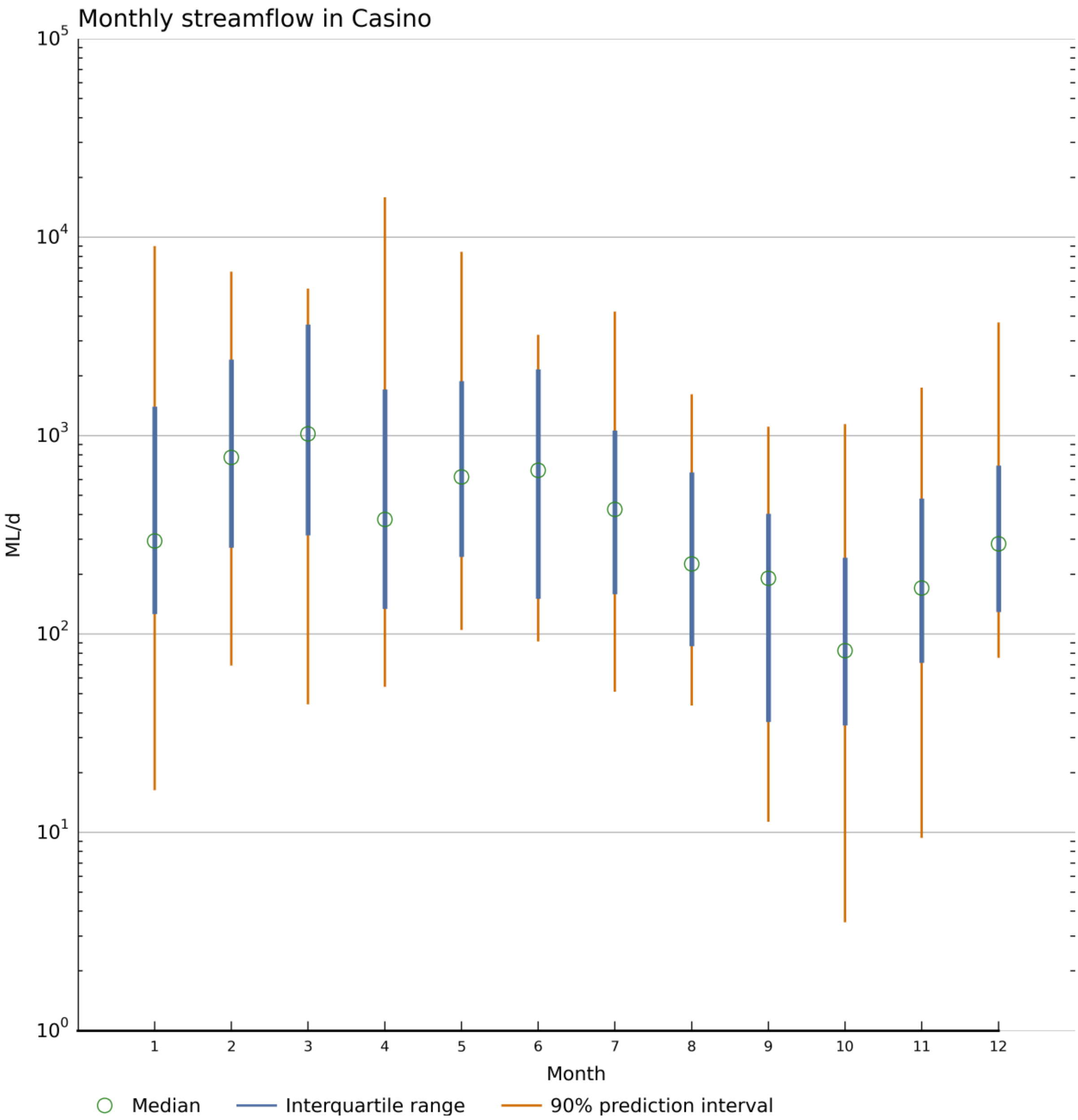

Figure 23 Boxplots of monthly flow between 1983 and 2012 at the Casino surface water model node (CLM_008)

Data: Bioregional Assessment Programme (Dataset 6)

2.6.2.7.2 Predictions

2.6.2.7.2.1 Drawdown due to the additional coal resource development

Two types of groundwater-dependent assets were considered for the groundwater modelling in the Clarence-Moreton bioregion: groundwater-dependent ecosystems (Figure 6 in companion product 1.3 for the Clarence-Moreton bioregion (Murray et al., 2015)), and bores that were classified as economic assets (Figure 12 and Figure 13 in companion product 1.3 for the Clarence-Moreton bioregion (Murray et al., 2015)). For both types, direct impact of CSG extraction is reported as the maximum difference in groundwater level between the baseline and the coal resource development pathway (CRDP) – referred to as additional drawdown, together with the time at which this maximum groundwater level change is realised.

The additional drawdown is simulated at 982 model nodes (Figure 24) for the uppermost layer of the groundwater model. The hydrological change in the watertable aquifer at all model nodes, or any model node, can be computed through interpolation from these nodes. The location of the model nodes was generated with a bivariate normal distribution with the mean centred on the CSG development. A subsequent manual adjustment ensured that redundant nodes (multiple nodes within a single MODFLOW grid cell) were removed and nodes were added in regions with low node density.

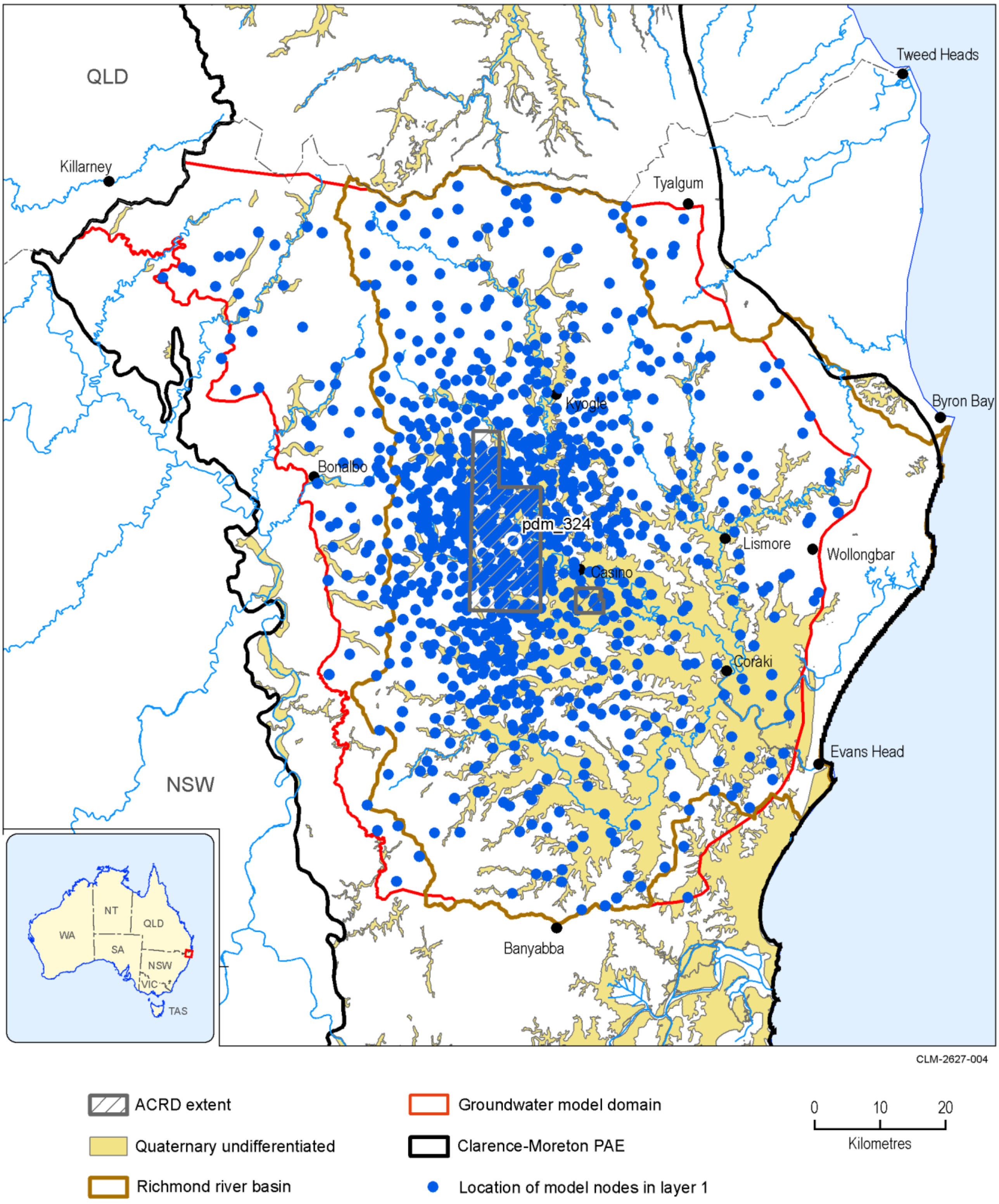

Figure 24 Distribution of the 982 model nodes in layer 1 for prediction interpolation

Coal resource development pathway = baseline + additional coal resource development (ACRD); PAE = preliminary assessment extent

Data: Bioregional Assessment Programme (Dataset 4)

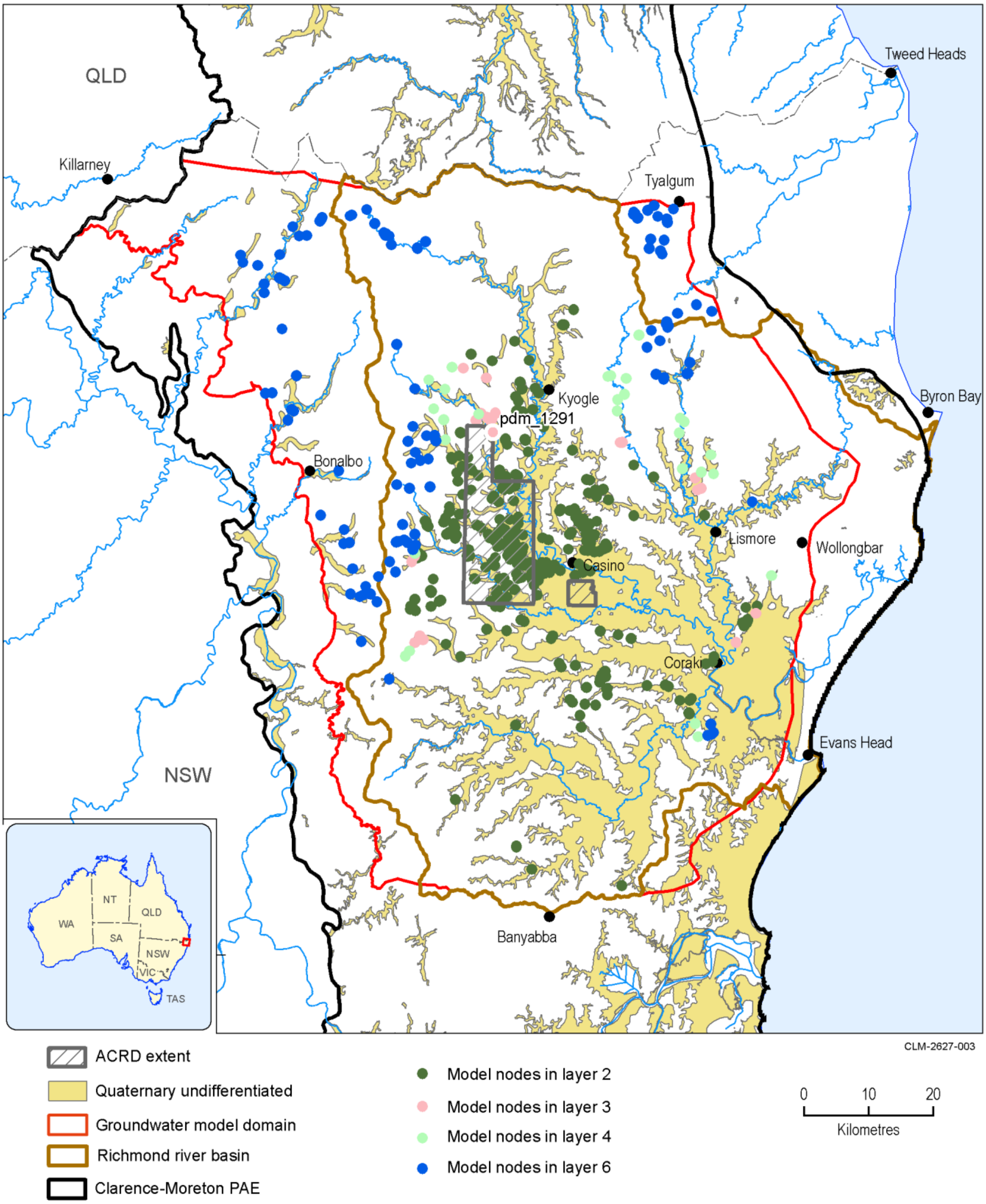

Figure 25 Distribution of model nodes associated with economic assets in layer 2 (Grafton Formation), 3 (Bungawalbin Member), 4 (Kangaroo Creek Sandstone Member) and 6 (Walloon Coal Measures)

Model nodes associated with economic assets (bores) in layer 2 occur across the additional coal resource development (ACRD) extent while model nodes in other layers are mostly outside the extent. No model nodes were identified in layer 5.
Coal resource development pathway = baseline + additional coal resource development; PAE = preliminary assessment extent
Data: Bioregional Assessment Programme (Dataset 5)

The predictions at two representative model nodes are illustrated in Figure 26 using the modelling results from a single realisation, realisation 842. The locations of these model nodes are indicated in Figure 24 and Figure 25. Among all models assessed during the sensitivity analysis, this realisation is the best-fit by comparing model outputs with historical groundwater level observations, water production forecast and estimated baseflow based on historical hydrograph. The model selection procedure was described in companion product 2.5 for the Clarence-Moreton bioregion (Cui et al., 2016). The model-generated baseflow in September and October, averaged from 1983 to 2012, at the Casino surface water model node (CLM_008) for this realisation is 89.2 ML/day, which is consistent with the observed streamflow in these months (Figure 23).

Model node pdm_324 is in layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock) situated in the central part of West Casino Gas Project (Figure 24). The CRDP groundwater model shows an additional drawdown in 2040, after which groundwater level gradually recovers towards the end of the simulation period. The additional drawdown is calculated to occur in 2042. It is noteworthy that the additional drawdown does not coincide exactly with the lowest groundwater level simulated under the CRDP.

Model node pdm_1291 is associated with economic assets (bores) in layer 3 (Bungawalbin Member) near the northern margin of the CSG development field about 10 km west of Kyogle (Figure 25). The additional drawdown is calculated to occur in 2055, which is 13 years later than model node pdm_324.

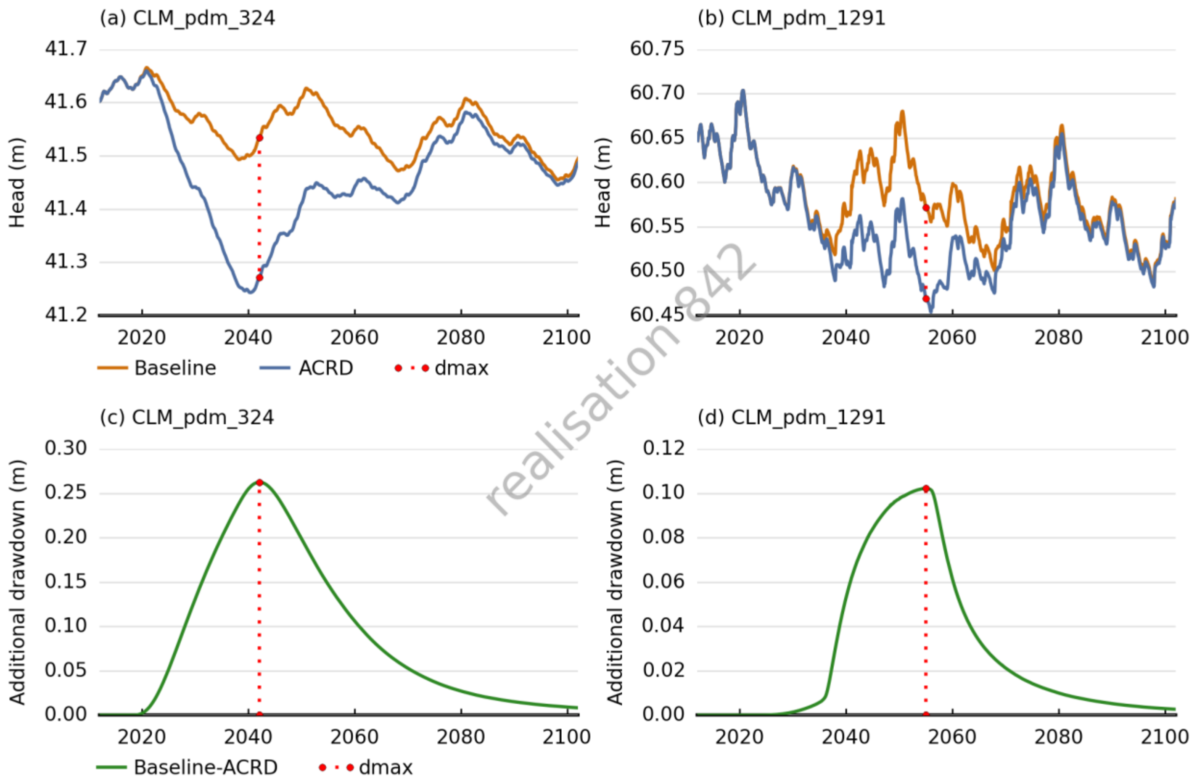

Figure 26 Example of the groundwater model output time series of model nodes pdm_324 in layer 1 ((a) and (c)) and pdm_1291 in layer 3 ((b) and (d))

dmax = maximum difference in drawdown between the coal resource development pathway and baseline, due to additional coal resource development (ACRD)
Coal resource development pathway = baseline + additional coal resource development
Data: Bioregional Assessment Programme (Dataset 3)

2.6.2.7.2.2 Baseflow change due to the additional coal resource development

The difference in exchange flux between aquifers and surface water features due to the additional coal resource development was reported at 16 surface water model nodes located within the groundwater model domain (Figure 27). The results, which reflect a change in river baseflow, were fed back into the Australia Water Resources Assessment (AWRA) landscape model (AWRA-L) to predict changes in total streamflow and other flow indices due to the additional coal resource development. The change due to the additional coal resource development on hydrological response variables associated with surface water is reported in companion product 2.6.1 for the Clarence-Moreton bioregion (Gilfedder et al., 2016). The baseflow change was reported as aggregated flow rate variation over all the cells above a surface water model node. For example, the baseflow change at CLM_014 is a sum of the change at all cells that interact with rivers above CLM_014 (Figure 27).

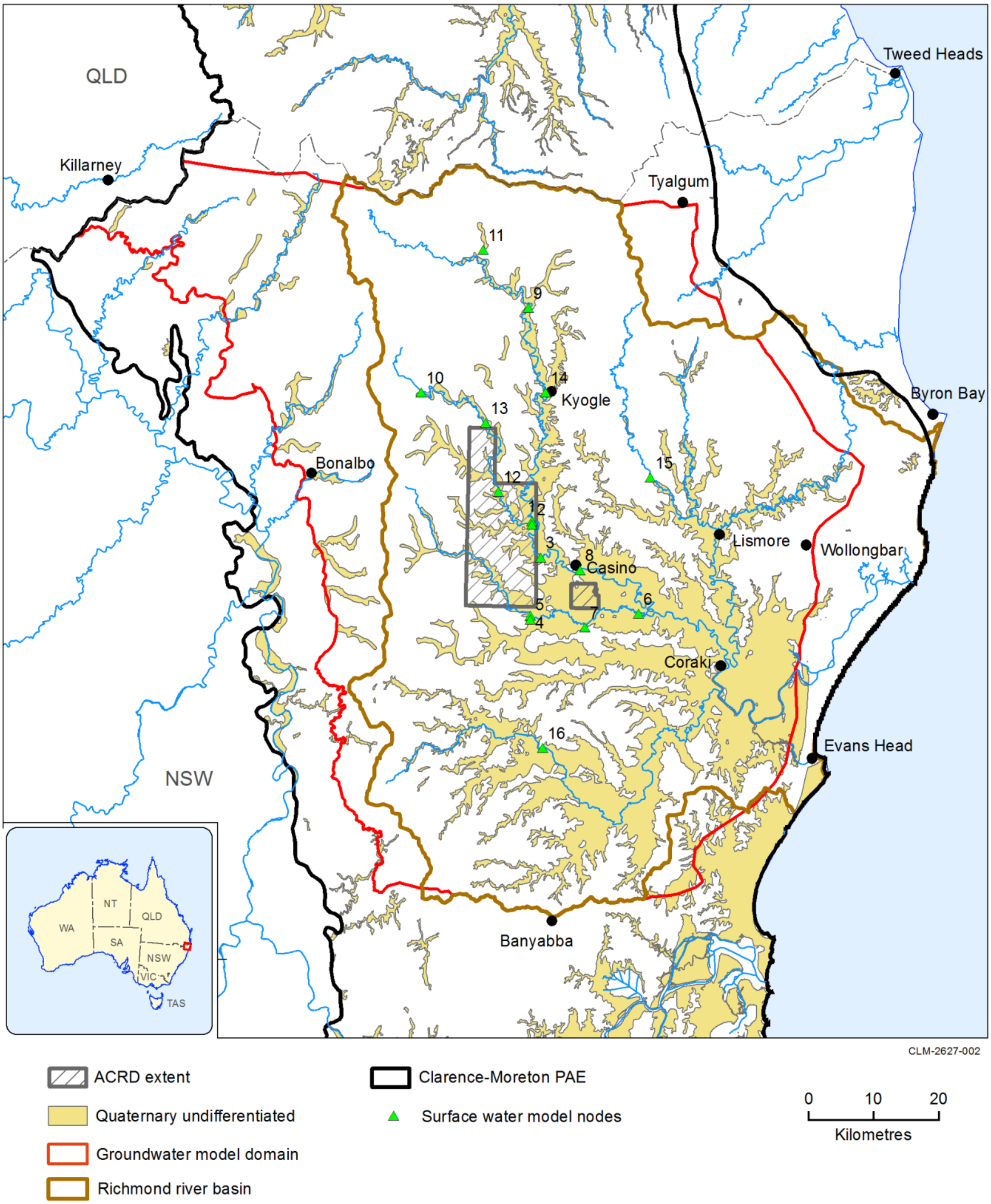

Figure 27 Distribution of surface water model nodes where baseflow change due to additional coal resource development were simulated

Surface water model node CLM_001 is represented as “1”, CLM_002 is represented as “2”, etc.
Coal resource development pathway = baseline + additional coal resource development (ACRD); PAE = preliminary assessment extent
Data: Bioregional Assessment Programme (Dataset 6)

2.6.2.7.3 Design of experiment and sensitivity analysis

As outlined in the Section 2.6.2.1, the groundwater model is evaluated for a wide range of parameter combinations, called the design of experiment. The results of these model runs, the simulated equivalents to the observations described in Section 2.6.2.7.1 and the predictions described in Section 2.6.2.7.2, are used to train statistical emulators, which will replace the original model in the uncertainty analysis. The range of each parameter sample is therefore chosen to be very wide to ensure sufficient coverage of the parameter space. The design of experiment model runs also allow to carry out a comprehensive sensitivity analysis. Such an analysis provides insight in the functioning of the model, aids in identifying which parameters the predictions are most sensitive to and if the observations are able to constrain these parameters.

Table 8 lists all 62 parameters that have been defined in the groundwater model (see Table 4 in Section 2.6.2.4, Section 2.6.2.5, and Table 6 in Section 2.6.2.6). For each parameter, Table 8 lists the section number where that parameter is defined and described.

To limit and rationalise the dimensionality of the parameter space, not all parameters are included in the sensitivity analysis. The coefficients *c* and *d* in the depth – hydraulic conductivity relationship for layers 5 and 6 control the offset and slope of the relationship. While coefficients *a* and *b* modify the shape of the relationship, their effect on the resulting hydraulic conductivity is small compared to the slope and offset parameters. Parameters *Kx_5_a*, *Kx_5_b*, *Kx_6_a* and *Kx_6_b* are therefore excluded from the sensitivity and uncertainty analysis.

The pilot points used to spatially vary the riverbed conductance are included in the analysis. Their values are, however, all tied to parameter *rp1*. This has the effect that while the value at each of the pilot points changes during the sensitivity analysis, the spatial variability of the riverbed conductance will remain the same. Overall, 38 parameters are changed during the sensitivity and uncertainty analysis.

Table 8 Parameters included in the sensitivity analysis

Parameter name	Section	Include	Tied	Transform	Initial	Minimum	Maximum
GHB_N	2.6.2.4.1	Y	na	log_{10}	5.04	0.01	1,000
GHB_S	2.6.2.4.1	Y	na	log_{10}	0.8	0.001	10,000
GHB_E	2.6.2.4.1	Y	na	log_{10}	100	0.1	1,000,000
RCH_1	2.6.2.4.2	Y	na	log_{10}	1	0.2	2
RCH_2	2.6.2.4.2	Y	na	log_{10}	1	0.3	2
RCH_3	2.6.2.4.2	Y	na	log_{10}	1	0.2	5
RCH_4	2.6.2.4.2	Y	na	log_{10}	1.5	0.2	5
RCH_5	2.6.2.4.2	Y	na	log_{10}	1.5	0.2	5
RCH_6	2.6.2.4.2	Y	na	log_{10}	2	0.3	5
RCH_7	2.6.2.4.2	Y	na	log_{10}	0.41	0.2	5
RCH_8	2.6.2.4.2	Y	na	log_{10}	0.3	0.2	5
RCH_9	2.6.2.4.2	Y	na	log_{10}	0.59	0.5	5
DRN_C_1	2.6.2.5	Y	na	log_{10}	0.25	0.01	5
DRN_C_2	2.6.2.4.3	Y	na	log_{10}	1	0.2	5
Kx_1_a	2.6.2.6.1	Y	na	none	1	0.1	2
Kx_1_o	2.6.2.6.1	Y	na	log_{10}	1	0.02	5
Kx_2	2.6.2.6.1	Y	na	none	–0.88	–2.2	1.5
Kx_3_d	2.6.2.6.1	Y	na	none	–1.28	–3	0.5
Kx_4	2.6.2.6.1	Y	na	none	–0.48	–2.2	1.5
Kx_5_a	2.6.2.6.1	N	na	none	900	900	900
Kx_5_b	2.6.2.6.1	N	na	none	2.718	2.718	2.718
Kx_5_c	2.6.2.6.1	Y	na	none	–4	–4.5	–3.5
Kx_5_d	2.6.2.6.1	Y	na	none	0	–1	0.5
Kx_6_a	2.6.2.6.1	N	na	none	900	900	900
Kx_6_b	2.6.2.6.1	N	na	none	2.718	2.718	2.718
Kx_6_c	2.6.2.6.1	Y	na	none	–4	–4.5	–3.5
Kx_6_d	2.6.2.6.1	Y	na	none	0	–1	0.5
Kx_Kz_1	2.6.2.6.1	Y	na	log_{10}	1	0.01	100
Kx_Kz_2	2.6.2.6.1	Y	na	log_{10}	0.99	0.01	100
Kx_Kz_3	2.6.2.6.1	Y	na	log_{10}	0.99	0.01	100
Kx_Kz_4	2.6.2.6.1	Y	na	log_{10}	1	0.01	100
Kx_Kz_5	2.6.2.6.1	Y	na	log_{10}	1	0.01	100
Kx_Kz_6	2.6.2.6.1	Y	na	log_{10}	1	0.01	100

Parameter name	Section	Include	Tied	Transform	Initial	Minimum	Maximum
Sy_1	2.6.2.6.2	Y	na	log_{10}	1	0.5	1.5
Ss_1	2.6.2.6.2	Y	na	log_{10}	1	0.01	100
Ss_2	2.6.2.6.2	Y	na	log_{10}	1	0.01	100
Ss_3	2.6.2.6.2	Y	na	log_{10}	1	0.01	100
Ss_4	2.6.2.6.2	Y	na	log_{10}	1	0.01	100
Ss_5	2.6.2.6.2	Y	na	log_{10}	1	0.01	100
Ss_6	2.6.2.6.2	Y	na	log_{10}	1	0.01	100
Rinc	2.6.2.4.3	Y	na	none	0	–0.5	0.5
rp1	2.6.2.4.3	Y	na	log_{10}	5.07	0.1	1,000
rp2	2.6.2.4.3	Y	*rp1*	log_{10}	86.89	1	1,000
rp3	2.6.2.4.3	Y	*rp1*	log_{10}	47.35	1	1,000
rp4	2.6.2.4.3	Y	*rp1*	log_{10}	45.82	1	1,000
rp5	2.6.2.4.3	Y	*rp1*	log_{10}	5.48	0.1	1,000
rp6	2.6.2.4.3	Y	*rp1*	log_{10}	1.03	0.01	1,000
rp7	2.6.2.4.3	Y	*rp1*	log_{10}	0.01	0.0001	100
rp8	2.6.2.4.3	Y	*rp1*	log_{10}	37.12	1	1,000
rp9	2.6.2.4.3	Y	*rp1*	log_{10}	91.48	1	1,000
rp10	2.6.2.4.3	Y	*rp1*	log_{10}	0.01	0.0001	100
rp11	2.6.2.4.3	Y	*rp1*	log_{10}	49.2	1	1,000
rp12	2.6.2.4.3	Y	*rp1*	log_{10}	59.37	1	1,000
rp13	2.6.2.4.3	Y	*rp1*	log_{10}	77.76	1	1,000
rp14	2.6.2.4.3	Y	*rp1*	log_{10}	4.95	0.1	1,000
rp15	2.6.2.4.3	Y	*rp1*	log_{10}	27.42	1	1,000
rp16	2.6.2.4.3	Y	*rp1*	log_{10}	5.08	0.1	1,000
rp17	2.6.2.4.3	Y	*rp1*	log_{10}	32.89	1	1,000
rp18	2.6.2.4.3	Y	*rp1*	log_{10}	20.14	1	1,000
rp19	2.6.2.4.3	Y	*rp1*	log_{10}	596.68	1	10,000
rp20	2.6.2.4.3	Y	*rp1*	log_{10}	526.61	1	10,000
rp21	2.6.2.4.3	Y	*rp1*	log_{10}	599.62	1	10,000
rp22	2.6.2.4.3	Y	*rp1*	log_{10}	506.91	1	10,000

na = not applicable; Y = yes, included; N = no, not included; parameters are uniformly sampled over their transformed range

Table 8 also lists the transformation of each parameter and their range. Ten-thousand parameter combinations are generated for the entire parameter space for the model sequence (i.e. each parameter combination has parameter values for the groundwater model and the surface water model) using a maximin Latin Hypercube design (see Santner et al., 2003, p. 138). The maximin Latin Hypercube design is generated like a standard Latin Hypercube design, one design point at a time, but with each new point selected to maximise the minimum Euclidean distance between design points in the parameter space. Points in the design span the full range of parameter values in each dimension of the parameter space, but also avoid redundancy among points by maximising the Euclidean distance between two points (since nearby points are likely to have similar model output). The parameter ranges are sampled uniformly from their transformed range (Figure 28).

Within the available time frame and computational resources available, the modelling team was able to evaluate 3,877 out of the 10,000 parameter combinations generated. While the coverage of parameter space is limited with less than 4000 simulations, visual inspection of the successfully evaluated parameters showed that there was adequate coverage of all parameters and no bias or gaps in the sampling of the parameter hyperspace. Section 2.6.2.7.4 describes the development of the emulators with these model results. Part of developing the emulators is verifying that the sampling density is sufficient to train the emulators with an acceptable mismatch between simulated and emulated prediction values.

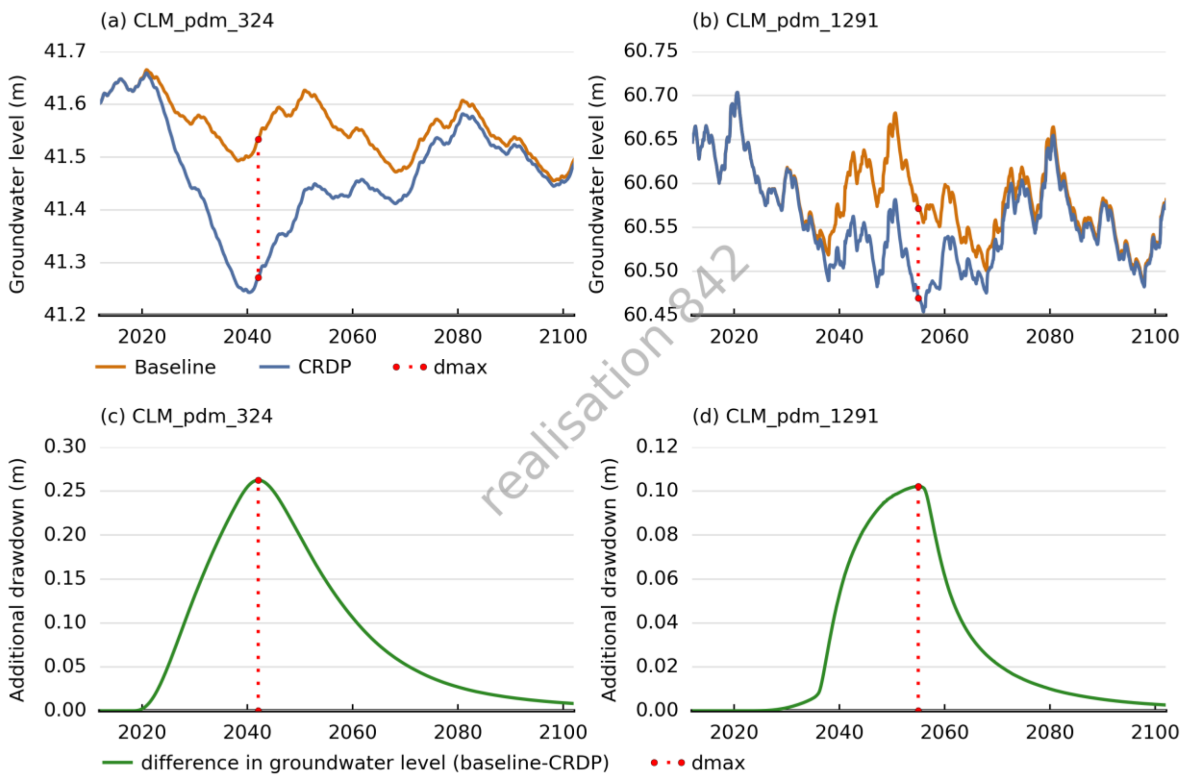

Figure 28 Histograms of the parameter values used in the design of experiment for emulator training and sensitivity analysis

The following sections describe the sensitivity of the observations and predictions to the 38 parameters. The best appreciation of the relationship between a parameter and an observation or prediction is through the inspection of scatterplots. Although the large dimensionality of parameters, observations and predictions precludes this type of visualisation for all parameter–prediction combinations, a selected few scatterplots are provided as illustration. A comprehensive assessment of sensitivity will be provided through sensitivity indices. These indices, computed using the methodology outlined in Plischke et al. (2013), are a density rather than variance-based quantification of the change in a prediction or observation due to a change in a parameter value. It is a relative metric in which large values indicate high sensitivity, whereas low values indicate low sensitivity.

2.6.2.7.3.1 Simulated equivalents to observations from the design of experiment

Figure 29 shows how the predicted groundwater levels at observation bore CLM_oh6 vary with parameter values. For each parameter the sensitivity index is shown as well. The green line indicates the observed groundwater level. It is very clear that there is a wide range of parameter values that result in predicted groundwater levels matching the observed groundwater level at this location. There are only a few parameters, however, that appear to noticeably affect the predicted groundwater levels:

- *DRN_C_2*: the drain conductance multiplier for the drain boundary condition at the top of layer 1
- *Kx_1_o*: the horizontal hydraulic conductivity of layer 1 outside the alluvium
- *Kx_4*: the horizontal hydraulic conductivity of layer 4
- *RCH_2*: the recharge multiplier for recharge zone 2.

The other parameters do have an effect on the predicted groundwater levels, but their effect is much smaller than the effect of the four parameters listed above. The sensitivity of the parameters listed is consistent with the understanding of the groundwater system and the design of the numerical model. Increases in recharge (*RCH_2*) result in higher predicted groundwater levels, while decreases in drainage conductance (*DRN_C_2*) reduce groundwater outflow out of the model and thus lead to higher groundwater levels. An increase in hydraulic conductivity of layer 1 leads to smaller variations in groundwater level. An increase in hydraulic conductivity of layer 4 allows for a larger fraction of recharge to be transmitted to the deeper basin and therefore lower groundwater levels.

Figure 29 Scatterplots of the parameter values versus the simulated groundwater level at observation location CLM_oh6 in layer 1 for all evaluated design of experiment model runs

For each parameter, the corresponding sensitivity index (SI) is provided in the title. The sensitivity index is a relative metric in which high values indicate sensitive parameters and low values indicate less sensitive parameters. The red line indicates the local median of simulated values over the parameter ranges spanned by the line segment. The green line is the observed groundwater level.

Figure 30a shows boxplots of the sensitivity indices for all simulated equivalents to the available groundwater level observations. The plot shows that a large number of groundwater level predictions are sensitive to the same set of parameters as identified to be sensitive for groundwater level prediction at observation bore CLM_oh6.

Out of the 38 parameters included in the design of experiment, 9 appear to have a noticeable effect on the simulated groundwater levels. These are:

- *GHB_E*: the multiplier to the eastern general-head boundary
- *RCH_1* and *RCH_2*: recharge multipliers in zone 1 and 2
- *DRN_C_2*: the drain conductance multiplier for the drain boundary condition at the top of layer 1
- *Kx_1_a, Kx_1_o, Kx_2, Kx_4*: the horizontal hydraulic conductivity respectively in the alluvium of layer 1, outside the alluvium in layer 1, layer 2 and in layer 4
- *rp1*: the conductance of the river boundary condition.

The general-head boundary in the east controls the amount of water entering or leaving the system through the eastern boundary, while parameter *rp1* controls the surface water – groundwater flux and thus the amount of water that can leave the system through the river system. As both of these boundary conditions are linear features in the landscape, only simulated groundwater levels close to these boundary conditions are likely to be sensitive to these parameters.

Figure 30b shows the sensitivity to the simulated average surface water – groundwater flux in September and October at the Casino surface water model node location (CLM_008). This prediction is mostly sensitive to the riverbed conductance (*rp1*), and to a lesser extent to the hydraulic conductivity in layer 1 (*Kx_1_a* and *Kx_1_o*) and recharge (*RCH_1* and *RCH_2*).

The final subplot in Figure 30, plot c, shows the sensitivity indices for the total water production rate simulated by the groundwater model. There are 39 sensitivity indices computed, one for each year of CSG water production and one for the total water produced over the entire production period. The simulated CSG water production rates are most sensitive to the drain conductance assigned to the drain boundary condition used to simulate the CSG wells (*DRN_C_1*) and to the parameters controlling the hydraulic conductivity of the Walloon Coal measures (*Kx_6_c* and *Kx_6_d*) and the storage of the Walloon Coal measures (*Ss_6*).

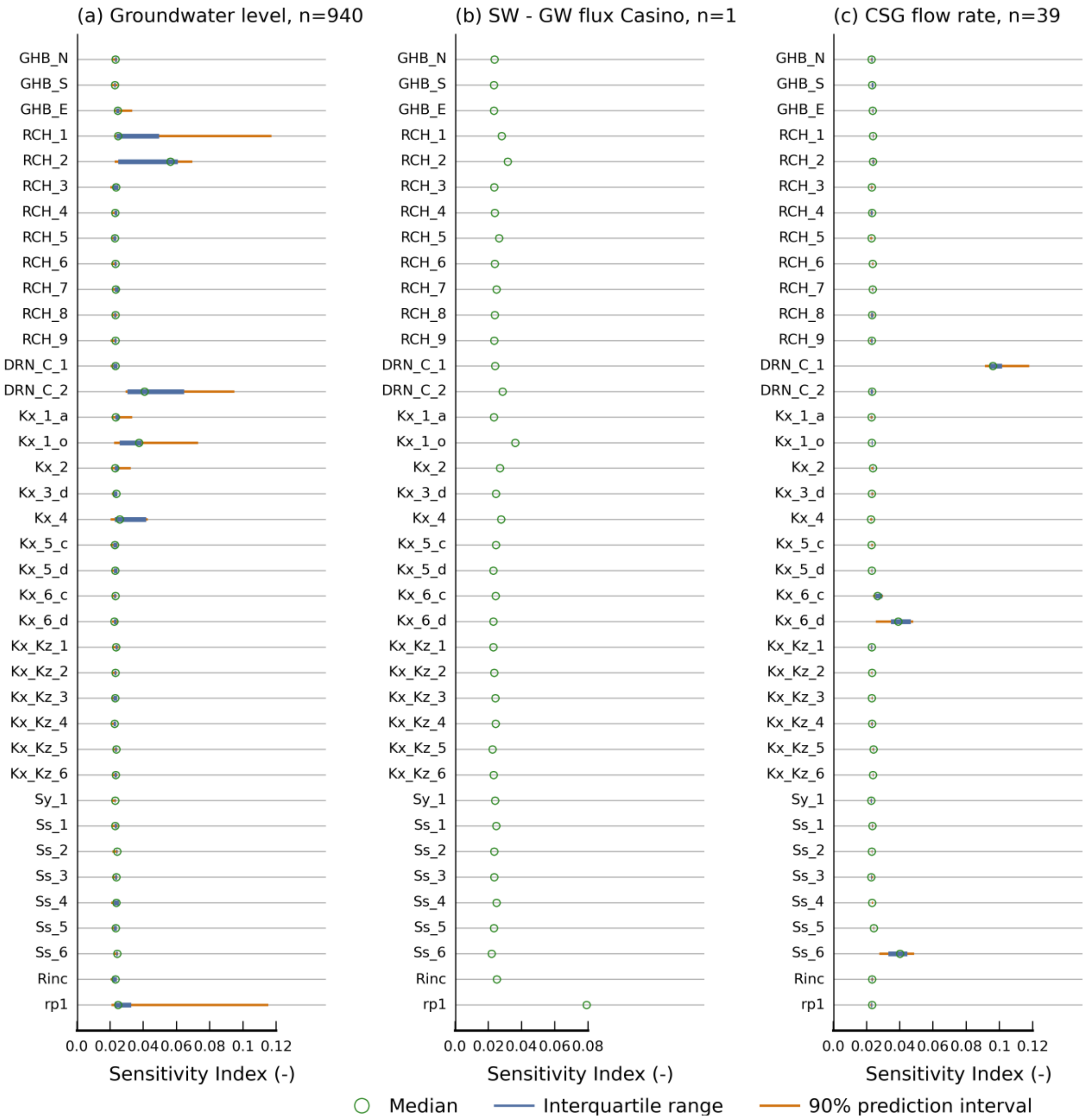

Figure 30 Boxplots of sensitivity indices for (a) simulated equivalents to groundwater level observations, (b) simulated surface water – groundwater flux (SW-GW flux) and (c) simulated coal seam gas water production rate

The sensitivity index is a relative metric in which high values indicate sensitive parameters and low values indicate less sensitive parameters

2.6.2.7.3.2 Simulated predictions from the design of experiment

Figure 31 shows, for the results of the evaluated design of experiment runs, how the predicted additional drawdown at model node pdm_1291 varies as a function of the parameter values. Note that additional drawdowns less than the head convergence criterion in the MODFLOW model, which was set to 0.001 m, are truncated to 0.001 m.

The parameters that have a sensitivity index in excess of 0.03 can be considered to have a major effect on the predicted drawdown, in the context of this particular prediction. These parameters are:

- *DRN_C_1*: the drain conductance assigned to the drain boundary condition used to simulate the CSG wells
- *Kx_3_d, Kx_6_d*: the horizontal hydraulic conductivity of layers 3 and 6
- *Kx_Kz_3, Kx_Kz_5, Kx_Kz_6*: the ratio of horizontal to vertical hydraulic conductivity in layers 3, 5 and 6
- *Ss_6*: the specific storage multiplier for layer 6.

The specific storage multiplier in the Walloon Coal Measures and the drainage conductance multiplier for the CSG drain boundary are the most dominant parameters as they control the water production rate from CSG. The ratios of horizontal to vertical hydraulic conductivity are the next set of important parameters as they control the propagation of the cone of depression through the sedimentary basin. It is noteworthy that increasing the ratio for layers 5 and 6 leads to a decrease in drawdowns, while increasing the ratio for layer 3 leads to increased drawdowns. Increased ratios for layers 5 and 6 implies that the vertical hydraulic conductivity decreases for these layers. Lower vertical hydraulic conductivities impede the propagation of the cone of depression and thus lead to lower additional drawdowns in layer 3. An increase in the ratio of horizontal to vertical hydraulic conductivity in layer 3 also results in lower vertical hydraulic conductivities in layer 3. Lower vertical hydraulic conductivities in layer 3 impede flow from the overlying aquifers into this hydrostratigraphic unit. There will be less compensation of additional drawdown by water from the overlying units and hence higher drawdowns. The horizontal hydraulic conductivities in layers 3 and 6 are important as well as they control the hydraulic conductivity in the source and target hydrostratigraphic units, respectively.

Figure 31 Scatterplots of predicted additional drawdown at model nodes pdm_1291 in layer 3 versus parameter values for the evaluated design of experiment model runs

For each parameter, the corresponding sensitivity index (SI) is provided in the title. The sensitivity index is a relative metric in which high values indicate sensitive parameters and low values indicate less sensitive parameters. The red line indicates the local median of simulated values over the parameter ranges spanned by the red line segment.

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway and baseline, due to additional coal resource development.

Figure 32 shows boxplots of the sensitivity indices for all parameter-prediction combinations. For the additional drawdowns in layers 1, 2, 3, 4 and 6 (Figure 32a to 30e) the same sets of parameters appear to be dominating the predicted drawdown as identified for model node pdm_1291. The most dominant parameter for all layers is the storage multiplier in the Walloon Coal Measures (*Ss_6*), while the horizontal hydraulic conductivity of the Walloon Coal Measures (*Kx_6_d*) is less important. The ratio of horizontal to vertical hydraulic conductivity controls the propagation of the cone of depression through the sedimentary sequence and most predictions are sensitive to these parameters. The drain conductance multiplier for the CSG drainage boundary (*DRN_C_1*) appears most important for predictions in layers 1 to 3 and less so for predictions in layers 4 and 6. This is most likely due to the fact that there are more model nodes close to the CSG well area in layers 1 to 3 than in layers 4 to 6.

The maximum change in historical surface water – groundwater flux (Figure 32f) is most sensitive to the riverbed conductance (*rp1*). The second-most important parameter is the drainage conductance of the CSG wells, followed by the vertical hydraulic conductivity of layers 5 and 6 and the specific storage multiplier and horizontal hydraulic conductivity for the Walloon Coal Measures (*Ss_6* and *Kx_6_d*). The hydraulic conductivity in layer 4 (*Kx_4*) appears to be important for the maximum change in surface water – groundwater flux in some reaches.

By comparing Figure 32 and Figure 30 it becomes apparent that the simulated equivalents to the groundwater level observations are not sensitive to the same set of parameters that are important to the prediction of additional drawdown in layers 1 to 6. This implies that the current set of observations has very little potential to constrain the parameters relevant to the predictions. Traditionally, the fit between observed and simulated groundwater level observations is used to judge if the groundwater model is able to reproduce historical conditions. If the mismatch between observed and simulated groundwater level observation is sufficiently small, the model is then assumed suited to make accurate predictions (Barnett et al., 2012). The sensitivity analysis presented in this section illustrates that this assumption is not valid for the Clarence-Moreton groundwater model. The correspondence between observed and simulated groundwater level data is potentially very misleading as a good fit does not guarantee accurate predictions.

The other information considered to constrain the model parameter, the average streamflow in September and October at the Casino surface water model node (CLM_008) and the expected total CSG water production rate are able to constrain parameters *rp1*, *DRN_C_1* and *Kx_6_d*. These parameters are important for many predictions, and constraining the model parameters with this information will reduce predictive uncertainty.

There are no observations sensitive to the ratio of horizontal to vertical hydraulic conductivity. These parameters, while important to many predictions, will not be constrained during the uncertainty analysis and the predictive uncertainty arising from these parameters will not be reduced.

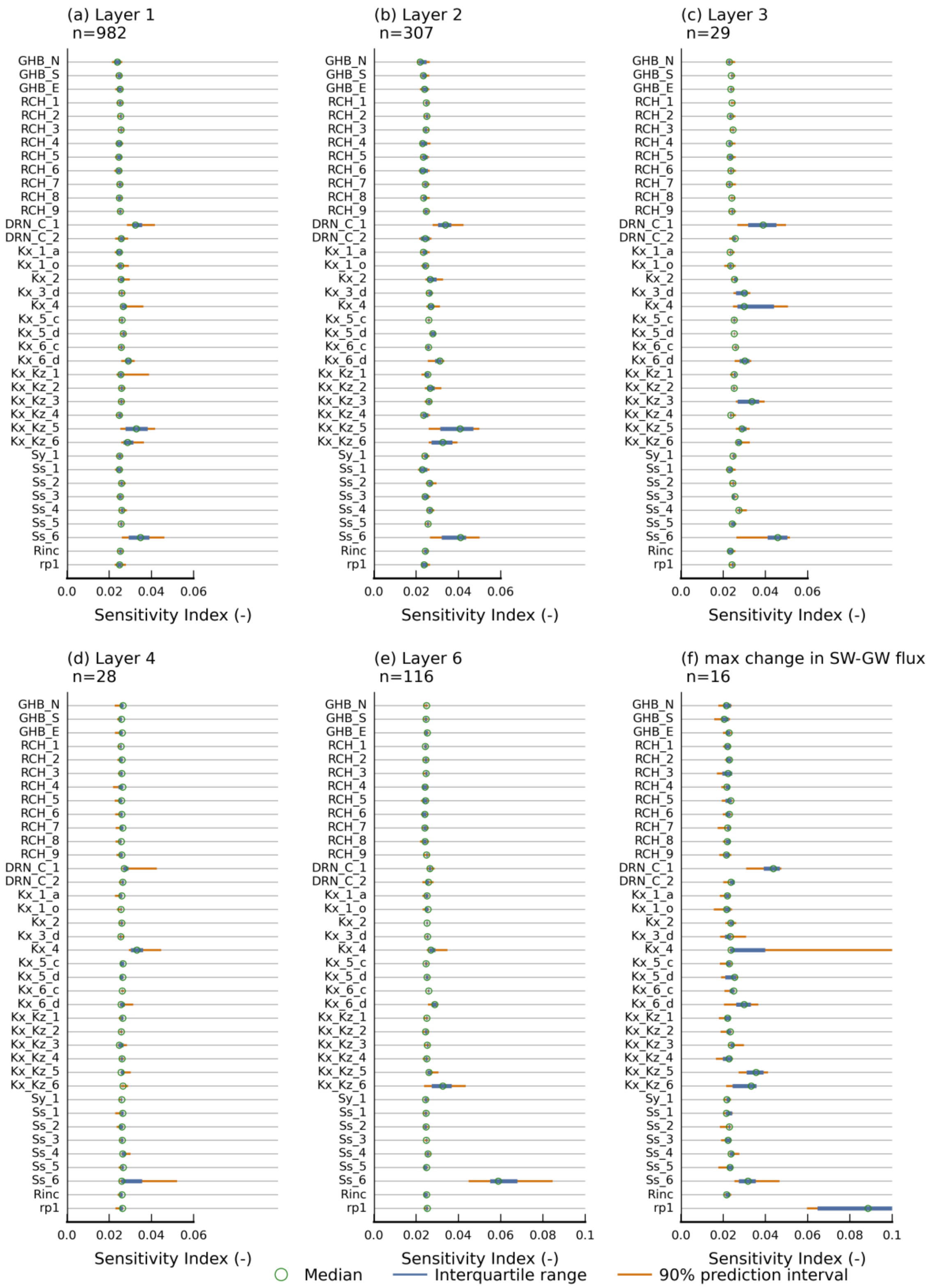

Figure 32 Boxplots of the sensitivity indices for each parameter to the predictions of additional drawdown at the model nodes in layers 1, 2, 3, 4 and 6 (plots (a) to (e)) and to the predicted maximum change in surface water – groundwater flux (SW-GW flux) (plot (f)) at the 16 river reaches that interact with the surface water model

The sensitivity index is a relative metric, high values indicate sensitive parameters, low values indicate less sensitive parameters. Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway and baseline, due to additional coal resource development.
Source: Gilfedder et al. (2016)

2.6.2.7.4 Emulators

The purpose of a statistical emulator is to provide a computationally efficient surrogate for a computationally expensive model. These emulators provide a way to quantify the predictive distribution for a prediction of interest, given a new set of parameters at which the model was not run. As outlined in the uncertainty analysis workflow (Figure 6 in Section 2.6.2.1), an emulator is created for each objective function (see Section 2.6.2.8.1) and for each prediction of additional drawdown and year of maximum change. The objective function emulators are used in the Markov chain Monte Carlo sampling of the prior parameter distribution to create a posterior parameter distribution for each prediction. These posterior parameter distributions are subsequently sampled with the emulator for that prediction to produce the predictive distribution of additional drawdown and year of maximum change at each model node.

The statistical emulation approach employed herein is called Local Approximate Gaussian Processes (LAGPs) as implemented through the ‘aGP’ function of the ‘laGP’ package (Gramacy, 2014) for R (R Core Team, 2013). LAGPs were chosen because: (i) they can be built and run very rapidly in the ‘laGP’ R package; (ii) unlike some other popular emulation approaches (e.g. standard Gaussian process emulators), they allow for nonstationarity in the model output across the parameter space, which provides the emulator with more flexibility to match model output; and (iii) they were found to have excellent performance when compared to a range of other emulation techniques (Nguyen-Tuong et al., 2009; Gramacy, 2014).

The training and evaluating of an individual emulator is implemented through a set of custom-made R-scripts with following input requirements:

- design of experiment parameter combinations
- design of experiment model output
- transform of parameters
- transform of output.

Among the 3877 successfully finished model runs, 121 models were filtered out because their modeling results were considered unrealistic. The set of 3756 parameter combinations that were evaluated and their corresponding model results are used to train the individual emulators for each prediction. As noted before, predictions of additional drawdown less than the convergence head criterion of 0.001 m are considered numerical noise. These values are replaced with zero and the associated year of maximum change values are replaced with 2102, the end of the simulation period. In other words, any predicted drawdown of less than 0.001 m is considered to be equal to no drawdown within the simulation period.

The model parameters were transformed according to the transformations listed in Table 8. Before training the emulator, the quantity to be emulated is transformed using a normal quantile transform (Bogner et al., 2012). The following steps are required to carry out such a normal quantile transformation of a sample *X*:

1. Sort the sample *X* from smallest to largest: $x_1, \ldots, x_n$
2. Estimate the cumulative probabilities $p_i, \ldots, p_n$ using a plotting position like $\frac{i}{n+1}$ such that $p_i = P(X \leq x_i)$
3. Transform each value x_i of *X* in $y_i = Q^{-1}(p_i)$ of the normal variate *Y*, where Q^{-1} is the inverse of the standard normal distribution, using a discrete mapping.

The main advantage of this transformation is that it transforms any arbitrary distribution of values into a normal distribution. Gaussian process emulators tend to perform better if the quantity to emulate is close to the normal distribution. The drawback of the transformation is that it cannot be reliably used to extrapolate beyond the extremes of the distribution. This risk is minimised in this application by purposely choosing the parameter ranges in the design of experiment to be very wide as to encompass the plausible parameter range. In a final step, the resulting value of the emulator is back-transformed to the original distribution.

The predictive capability of LAGP emulators is assessed via 30-fold cross validation (i.e. leaving out 1/30th of the model runs, over 30 tests) and recording diagnostic plots of the emulator's predictive capacity. For each of the 30 runs of the cross-validation procedure, the proportion of 95% predictive distributions that contained the actual values output by the model (also called the hit rate) was recorded. The emulators are considered sufficiently accurate if the 95% hit rate is between 90 and 100%.

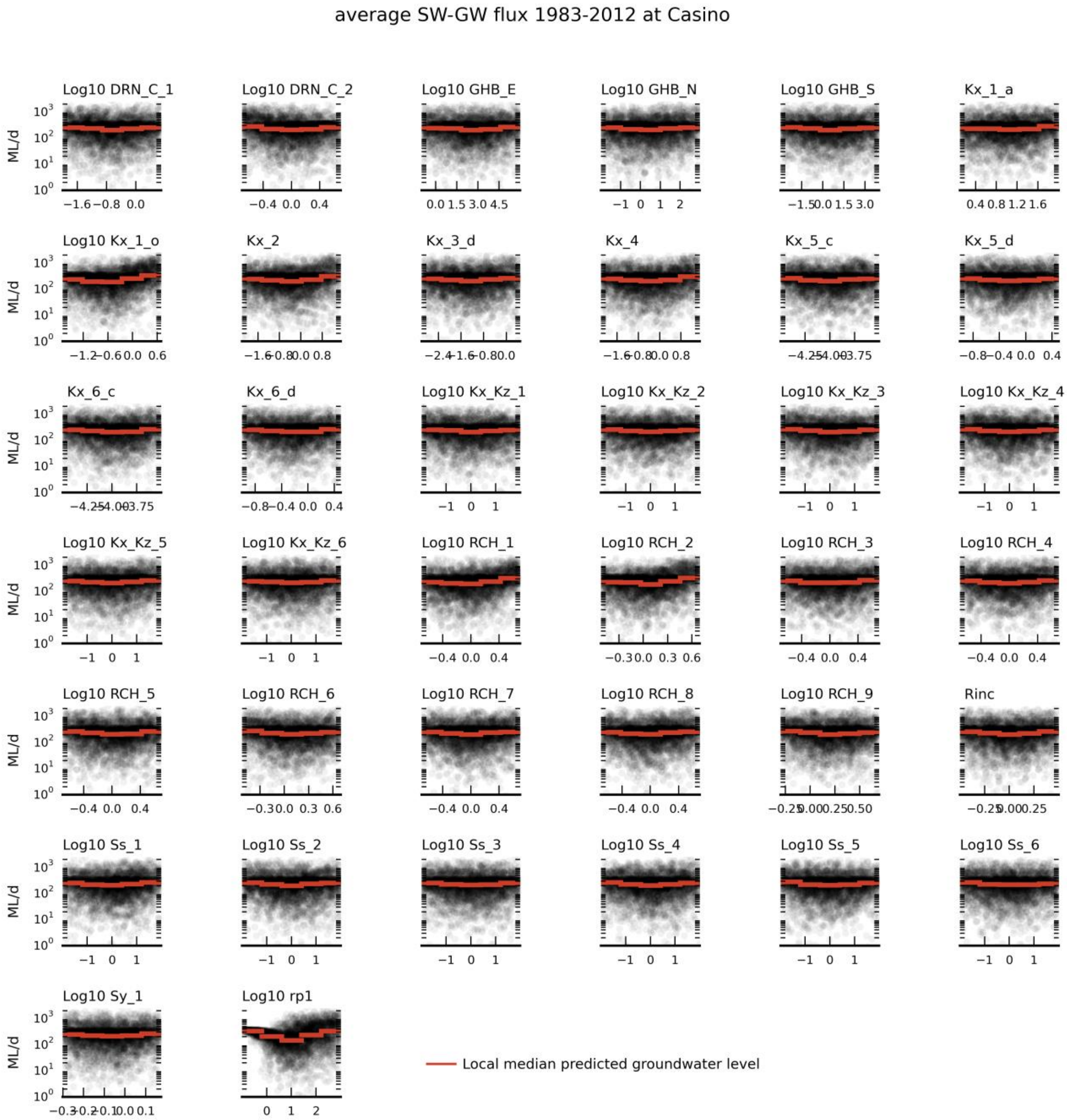

Figure 33 Scatterplots of the simulated average surface water – groundwater flux (SW-GW flux) between 1983 to 2012 at the Casino surface water model node (CLM_008) versus the parameter values of the evaluated design of experiment model runs

The accuracy of the emulator, the degree to which the emulator can reproduce the relationship between the parameters and the prediction, depends greatly on the density of sampling of parameter space. This section examines whether the set of 3756 evaluated parameter combinations provides sufficient information to train emulators. As it would be beyond the scope of this report to examine this for all of the emulators created, the suitability of the number of parameter combinations is illustrated using the average predicted surface water – groundwater flux in September and October at the Casino surface water model node(CLM_008). Emulating this quantity is especially challenging as the flux varies over at least two orders of magnitude and the flux is a non-linear function of several interacting parameters (Figure 33).

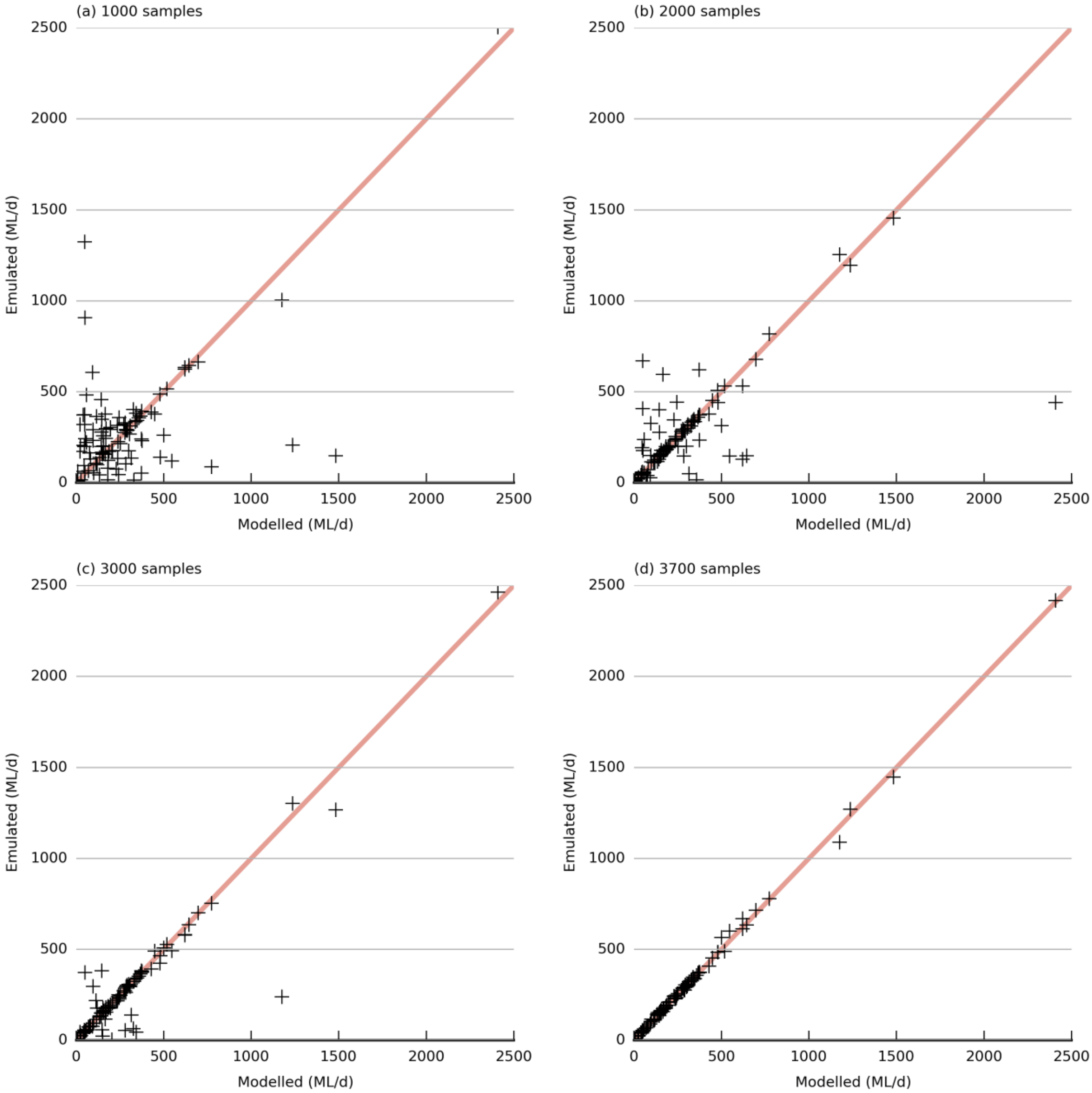

Figure 34 Scatterplots of modelled versus emulated values of average surface water – groundwater flux at Casino between 1983 and 2012 for emulators trained with different training set sizes

Figure 34 (plots a to d) shows the correspondence between modelled and emulated flux predictions using an emulator trained with 1000, 2000, 3000, and 3700 samples, respectively. Emulators trained with less than 2000 samples do not perform well in emulating the flux. The correspondence between modelled and emulated values for the training set of 3700 samples is very high however, with the largest residuals at the high extreme of the flux distribution.

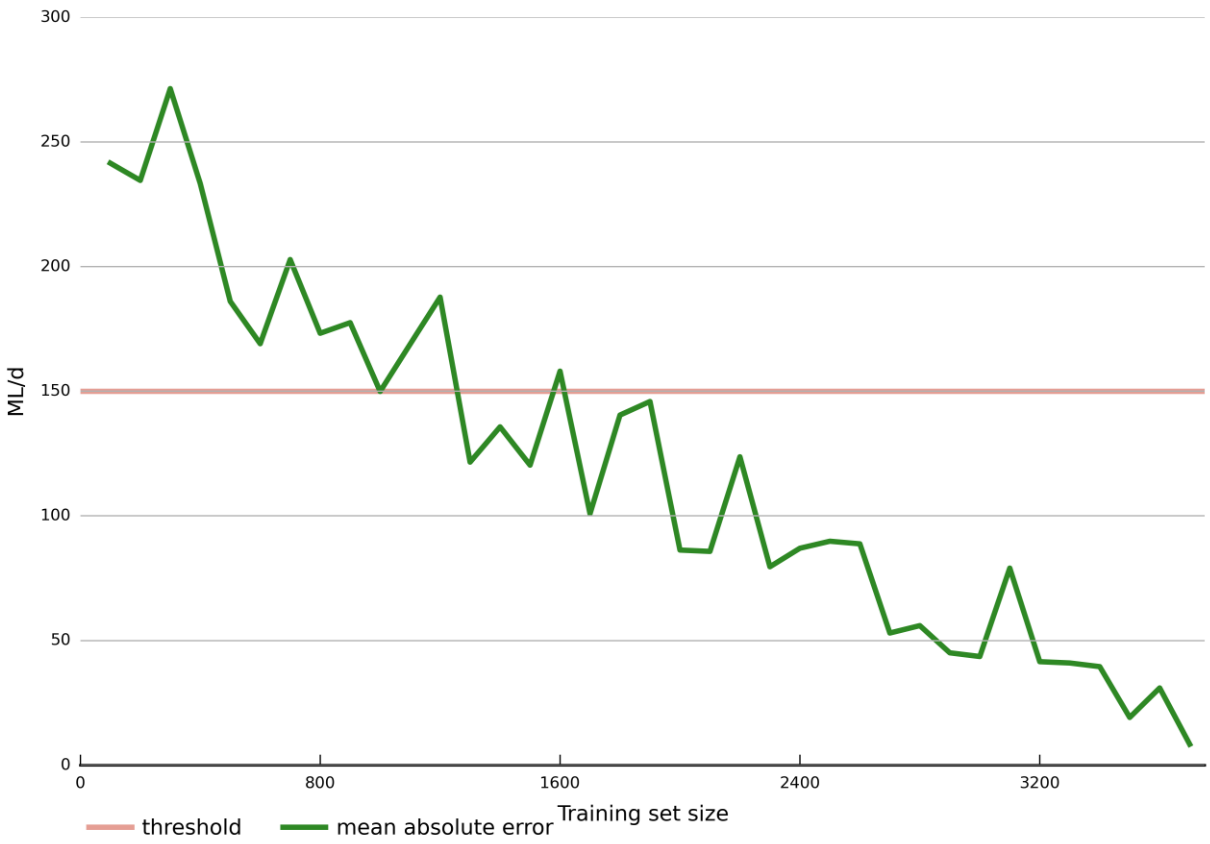

Figure 35 Convergence of mean absolute error between modelled and emulated average surface water – groundwater flux at Casino between 1983 and 2012

Figure 35 shows this evolution in a more quantitative way by visualising the mean absolute error between modelled and emulated flux values produced by emulators trained with training sets that vary from 100 to 3756 in increments of 100. In the uncertainty analysis (Section 2.6.2.8.1), a parameter combination that results in a flux of less than 150 ML/day is accepted. The mean absolute error drops below that threshold value for emulators trained with more than 1600 samples. The emulator trained with the full training set has a mean absolute error of 8.2 ML/day. By using an emulator with this accuracy in the Markov chain Monte Carlo sampling, the risk of wrongly accepting or rejecting a parameter combination is very small. Emulators with this level of accuracy also provide confidence that predictions obtained with the emulators are very close to predictions generated with the original model.

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2.6.2.8 Uncertainty analysis

Summary

In the uncertainty analysis the uncertainty in groundwater model parameters, expressed through their prior parameter distributions, is propagated to the predictions. These prior parameter distributions are constrained by estimates of baseflow and coal seam gas (CSG) water production rates, maximum hydraulic conductivity ratios between layer 3 (Bungawalbin Member) and layer 4 (Kangaroo Creek Sandstone) and, for predictions in layers with groundwater level observations, distance-weighted groundwater level observations. As a result, each prediction in layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock) has an individual parameter posterior distribution.

As discussed in the sensitivity analysis, the observation dataset contains limited information to constrain the parameters relevant to the predictions. The exceptions are the drainage parameter controlling CSG water production rate, the hydraulic properties of layer 6 (coal seams of the Walloon Coal Measures), recharge multipliers in zone 1 and 2 and the riverbed conductance multiplier.

The head observations identify zones in the model that, regardless of the parameter values, will have a mismatch between observed and simulated groundwater level that either is always below or always above the predefined acceptance threshold. These zones are regions in the model where simulated groundwater levels are not controlled by parameter values given the current parameterisation, but by the specified boundary conditions or model structure issues.

The median predicted change in groundwater level due to the additional coal resource development across the modelled domain at the prediction locations is less than 0.01 m, with the 95th percentile not exceeding 1 m. The drawdown due to additional coal resource development (additional drawdown) is realised the earliest at model nodes in layer 6, within the planned production period. For model nodes in layer 1, the median year of maximum change is around 2060, after production ceases.

The qualitative uncertainty analysis discusses the perceived effect of the major model assumptions on the model predictions. The assumptions that have the most potential to profoundly alter the results and conclusions of the groundwater modelling are the implementation of the coal resource development pathway (CRDP) and the characterisation of the hydraulic properties of the groundwater system, especially if additional observations of these properties would warrant the conceptual model to be revisited.

2.6.2.8.1 Factors included in formal uncertainty analysis

Section 2.6.2.7 described the available observations, predictions required of the model and sampling of parameter space as the design of experiment to train the emulators, as well as the sensitivity analysis based on these model runs. The same set of parameters as evaluated in the sensitivity analysis is considered in the formal uncertainty analysis, although the sensitivity analysis highlighted that a number of these parameters only have limited influence on the predictions.

As described in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016) and in Section 2.6.2.1, the parameter space is constrained by the observations relevant to the predictions through a Markov chain Monte Carlo sampling using the Approximate Bayesian Computation (ABC) methodology (Beaumont et al., 2002; Vrugt and Sadegh, 2013). As in any Bayesian methodology, a set of prior parameter distributions needs to be defined that encapsulates the current information and knowledge, including correlation or covariance of parameters. This is described under Section 2.6.2.8.1.1 'Prior parameter distributions'.

These prior parameter distributions are constrained by observations with the ABC methodology to generate posterior parameter distributions. The posterior parameter distributions are then used to generate the final set of predictions. The process of constraining the prior parameter distributions by observations is described and discussed in Section 2.6.2.8.1.2 while the resulting posterior predictive distributions are detailed in Section 2.6.2.8.1.3

2.6.2.8.1.1 Prior parameter distributions

The parameterisation of the groundwater model, using multipliers of spatially variable properties and empirical relationships between depth and hydraulic conductivity, makes it very difficult to describe the distributions of the parameters directly from observations and measurements of the hydraulic properties. The Assessment team created the prior parameter distributions (blue lines in Figure 36) based on the available information in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016a) and the initial model runs. The prior distributions are parameterised as a multivariate normal distribution with the mean of each parameter centred on the initial value listed in Table 8 in Section 2.6.2.7. The standard deviation is chosen such that more than 99% of the probability mass is within the range identified for the parameter. Some of the recharge parameters have an initial value very close to the lower boundary. For those the mean of the prior distribution is shifted to a higher value.

Hydraulic conductivity and storage are hydraulic properties that are both largely controlled by the lithological properties and cementation of the sediments or sedimentary rocks. It is, therefore, physically unlikely that high hydraulic conductivity values occur together with low storage values and vice versa (Delleur, 2007). For all layers, a covariance is specified between the hydraulic conductivity and storage parameters (Figure 37). The Pearson product moment correlation coefficient (ρ) is provided in the title of each subplot and is calculated as

$$\rho_{AB} = \frac{\sigma_{AB}^2}{\sqrt{\sigma_A^2 \sigma_B^2}} \tag{4}$$

with ρ_{AB} the covariance between parameters A and B, and σ_A^2 and σ_B^2 the variance of parameters A and B, respectively. The covariance is purposefully chosen to result in a weak correlation between the variables. This allows a wide range of values to be chosen while reducing the likelihood of low and high values of hydraulic conductivity and storage occurring together.

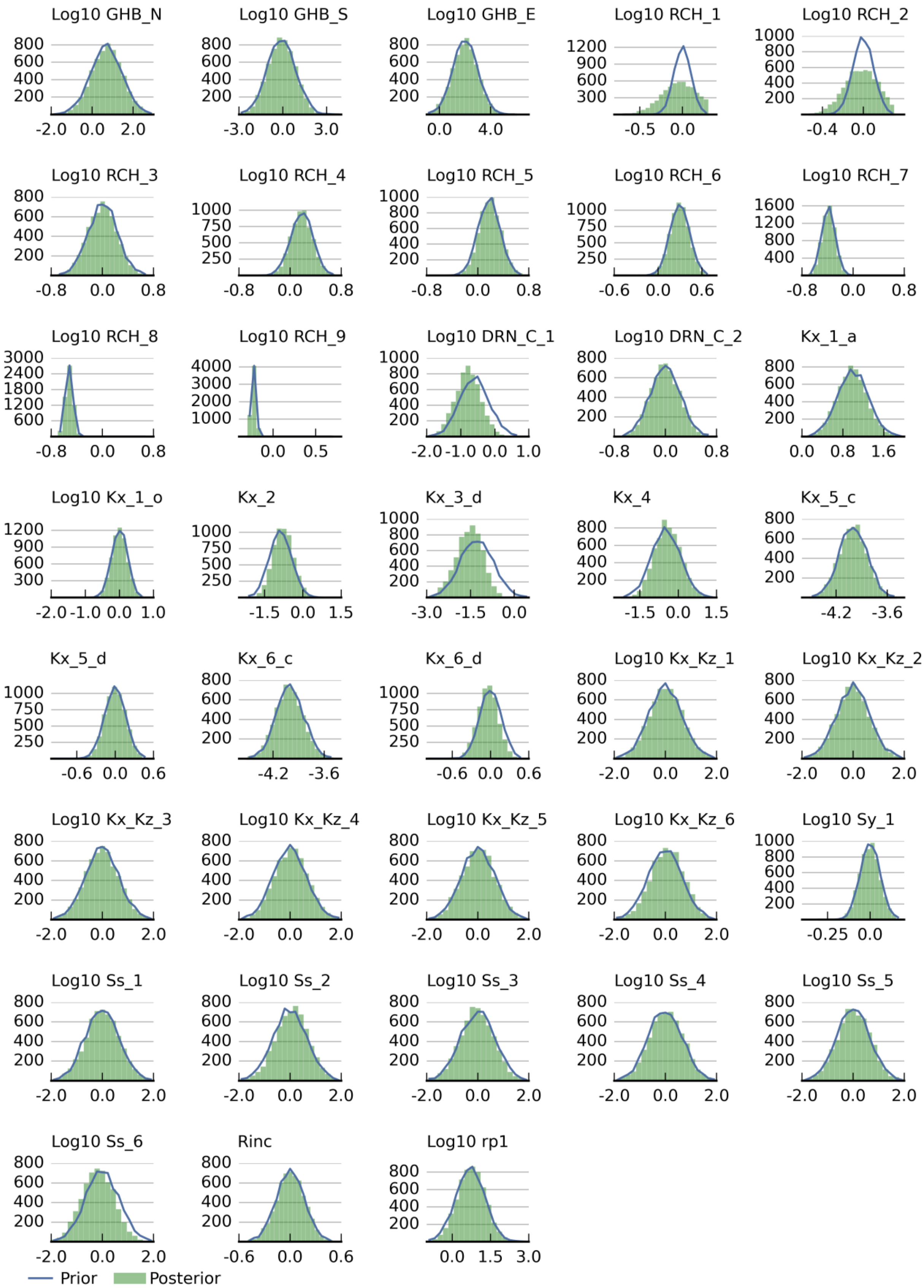

Figure 36 Histograms of prior (blue line) and posterior (green bars) parameter distributions of the groundwater model for the Clarence-Moreton bioregion

Posterior parameter distributions as obtained by the general objective function; Total sample size is 10,000; Refer to Table 4 in Section 2.6.2.4 for a detailed description and units of parameters

Data: Bioregional Assessment Programme (Dataset 1)

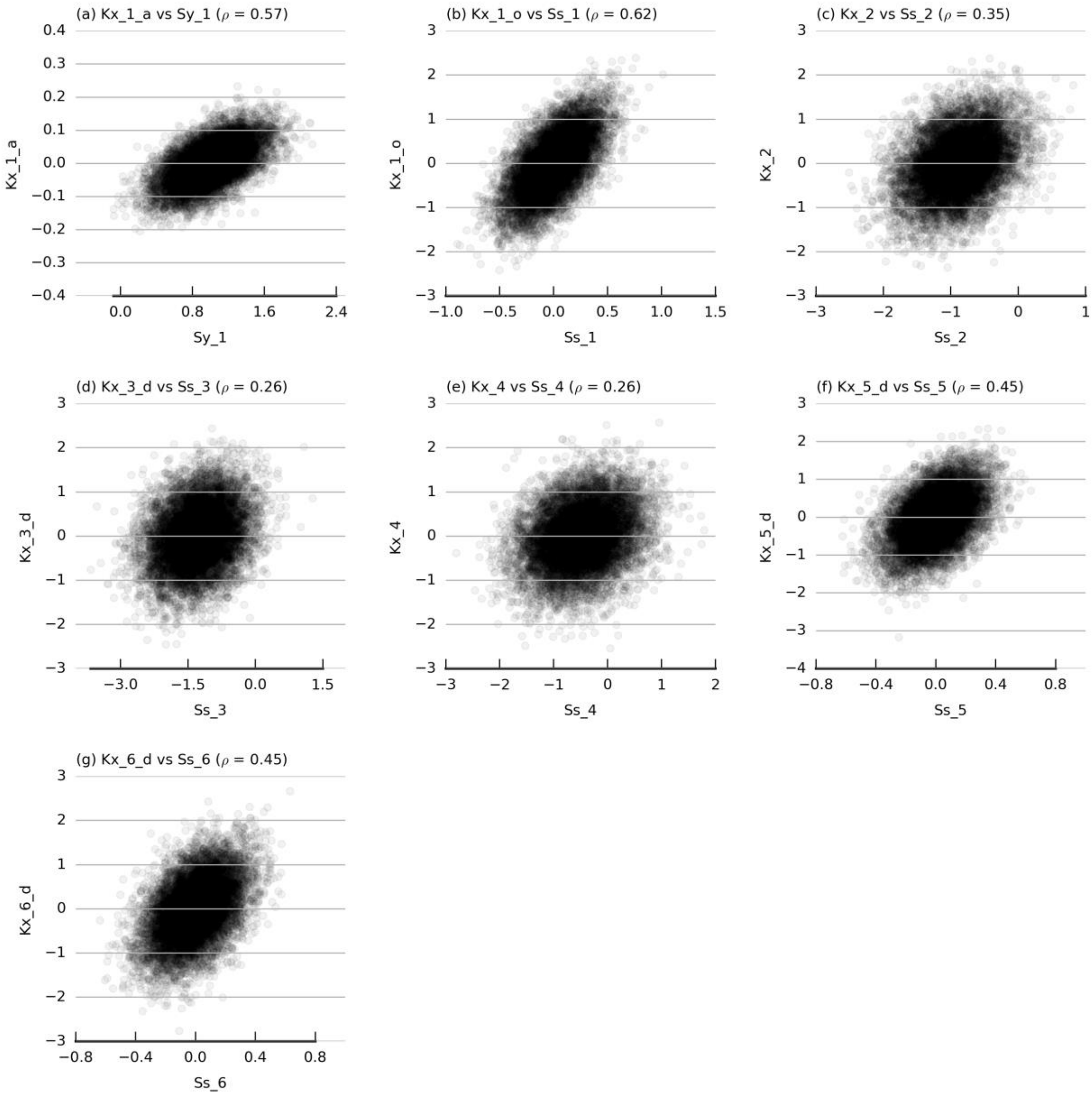

Figure 37 Prior parameter covariance

Refer to Table 4 for a description of parameters; *Ss* = specific storage; *Sy* = specific yield; *ρ* is the Pearson product moment correlation coefficient
Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.8.1.2 Posterior parameter distributions

The posterior parameter distributions are obtained through a Markov chain Monte Carlo sampling of the prior parameter distributions with a rejection sampler based on the ABC methodology. The rejection sampler only accepts a parameter combination, randomly drawn from the prior parameter distribution, if a model run with these parameters satisfies a predefined objective function threshold. This objective function is a summary of the model output that can be linked to groundwater level observations, the forecasted coal seam gas (CSG) water production rates and estimated baseflow rates. An example of an objective function is the mean absolute difference between observed and simulated groundwater levels. A crucial aspect in the ABC methodology is not only to define such an objective function, but to provide a threshold value as well that needs to be satisfied for a parameter set to be acceptable. Ideally this threshold is based on an independent estimate of the observation error.

For the Clarence-Moreton bioregion, three types of observations are available to constrain the parameters for the predictions:

1. groundwater level observations (limited to layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock))
2. an estimate of the surface water – groundwater flux
3. an estimate of the expected CSG water production rates.

Additionally, there are rules that can further constrain the parameter values based on the conceptual understanding and data analysis (see companion product 2.1-2.2 (Raiber et al., 2016a) and companion product 2.3 (Raiber et al., 2016b) for the Clarence-Moreton bioregion), such as the condition that the hydraulic conductivity of layer 4 (Kangaroo Creek Sandstone) needs to be larger than the hydraulic conductivity of layer 3 (Bungawalbin Member).

The sensitivity analysis (Section 2.6.2.7.3) made it apparent that the various observation groups constrain different parameters, which are not necessarily the most important parameters for the predictions of change in groundwater level or surface water – groundwater flux. As a result, the Assessment team created an objective function tailored for each individual prediction. The simulated values at the locations and times in layer 1 where observations of groundwater level are available appeared to be mostly sensitive to recharge multipliers and drainage conductance of the drainage boundary at the top of the model. However, the predictions of change in groundwater level – especially in layers 2 to 6 (Grafton Formation to Walloon Coal Measures; see Section 2.6.2.3 for detailed layer structure) – are not sensitive to these parameters, and including the head observations in the objective function for these predictions will not constrain the relevant parameters. While this is mostly true for the predictions in layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock), the sensitivity analysis indicates that the groundwater level predictions have some information to constrain the hydraulic properties of this layer, which are also important for the change in groundwater level predictions.

The objective function for predicted change in groundwater level due to the additional coal resource development in layers 2 to 6 and changes in surface water – groundwater flux consist of four acceptance criteria:

1. Hydraulic conductivity in layer 2 is larger than hydraulic conductivity in layer 3.
2. Hydraulic conductivity in layer 3 is less than hydraulic conductivity in layer 4.
3. The average difference between simulated and estimated CSG water production rates is less than 1000 m^3/day. This ensures that the simulated CSG water production rate is within an order of magnitude of the estimated values.
4. The average difference between surface water – groundwater flux at the Casino surface water gauge for the months of September and October between 1983 and 2012 is less than 150 ML/day. During September and October rainfall is low and the contribution to streamflow from groundwater is highest (Rassam et al., 2014). Analysis of historical flow rates during periods of no rainfall at Casino indicated flow rates are rarely above

150 ML/day (Figure 21). This number can therefore be considered an upper bound to the surface water – groundwater flux.

Only parameter combinations that satisfy all four acceptance criteria are accepted in the posterior parameter distributions. Criteria 1 and 2 are implemented by directly rejecting any proposed sample from the prior parameter distributions that does not satisfy these criteria.

For criteria 3 and 4 the average difference between simulated and estimated CSG water production rates and the average difference between simulated and estimated surface water – groundwater flux at Casino is computed for all successful runs of the design of experiments. These values were used to create an emulator for criteria 3 and 4.

During the Monte Carlo simulation, a random sample of the prior parameter distribution is generated and evaluated with the two emulators. If all four acceptance criteria are satisfied, then the sample is accepted into the posterior parameter distribution. If not, then the sample is rejected. This process is repeated until a predefined number (in this case 10,000) of samples is accepted.

The green histograms in Figure 36 show the resulting posterior parameter distributions. As expected from the sensitivity analysis, the majority of parameters are unconstrained by the objective function and the posterior distribution for these is almost identical to the prior distributions. The parameters for which the posterior distribution is noticeably different to the prior distribution, are the drainage conductance of the CSG wells (*DRN_C_1*), the hydraulic conductivity and storage of layer 6 (*Kx_6_d, Ss_6*), the recharge multipliers of recharge zones 1 and 2 (*RCH_1, RCH_2*) and the riverbed conductance (*rp1*). For most of these parameters the change entails a shift of the mean of the distribution to a lower or higher value. For the recharge multipliers the mean does not change much, but the shape of the distribution changes with more values on the lower end of the range included in the parameter distributions.

For predictions of the change in groundwater level in layer 1 (alluvium, Lamington Volcanics and unconfined parts of the sedimentary bedrock), in addition to the four earlier defined criteria, the groundwater level observations are also used. The distribution of groundwater level observations in the model domain is not uniform, with a bias towards the alluvial system close to the rivers and a high density in the vicinity of Lismore. The groundwater level fluctuations observed close to a river are likely to be dominated by local processes, especially the dynamics of the river. Likewise, groundwater level fluctuations in the flat-lying areas in the east of the model domain are likely to be dominated by local recharge–discharge processes. These observations are not very likely to be of great value to constrain properties and processes relevant to groundwater levels in areas upstream with a more pronounced topography.

To acknowledge the difference in spatial support of each observation, an objective function is tailored for each prediction of groundwater level in layer 1 by weighting the difference between observed and simulated values of groundwater level based on the distance between the prediction location and the observation and the distance of the observation point to the nearest blue line network. The additional criterion for predictions of change in groundwater level in layer 1 is therefore defined as:

$$O_j = \sum_{i=1}^{k} \frac{r_i}{n_i}\left(1 - \tanh\left(\frac{d_i}{w}\right)\right)\left(h_{o,i} - h_{s,i}\right)^2 \qquad (5)$$

where O_j is the criterion for prediction j, $h_{o,i}$ is the *i*th observed groundwater level, and $h_{s,i}$ is the simulated equivalent to this observation. r_i is the distance (in km) of observation i to the nearest blue line network while d_i is the distance (in km) between observation i and prediction j. Coefficient w controls the distance at which the weight of observation i drops to zero. To account for transient observations, the weights are divided by n_i, the number of observations at the observation location. The tanh function allows the weight of an observation to decrease almost linearly with distance and to gradually become zero at a distance of approximately $3w$. This is illustrated in Figure 38 for different values of w.

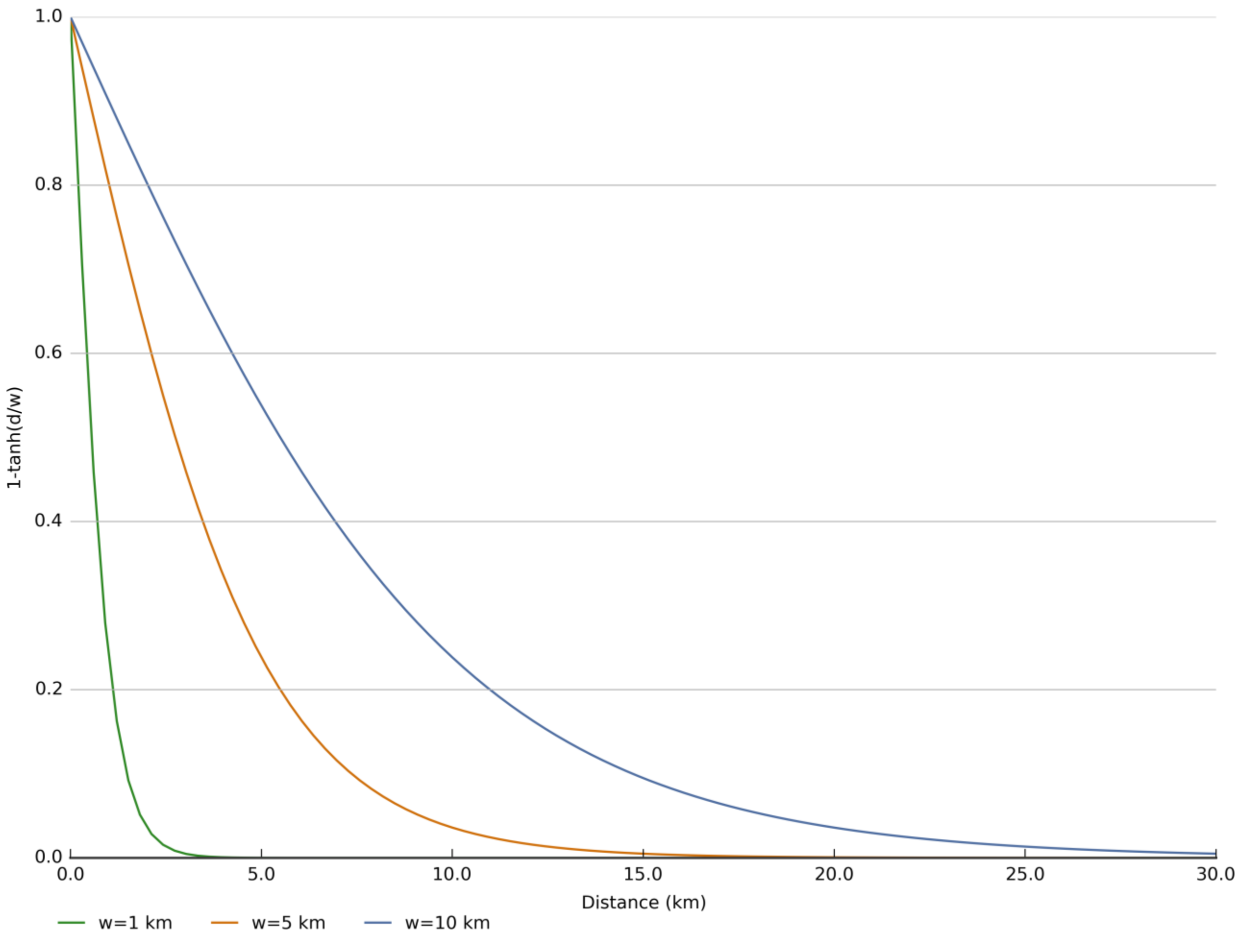

Figure 38 Weights of observations in objective function in function of the distance between observation and prediction for different values of *w*

d = distance between observation and prediction (km); w = shortest distance between observation location and blue line network (km)

In the uncertainty analysis of the groundwater model for the Clarence-Moreton bioregion the value of w is set equal to 5 km, which means that an observation has a weight of zero if the distance between the prediction and the observation is more than 15 km. The choice of this value is a pragmatic decision on behalf of the Assessment team. Ideally, the distance weighting function is chosen based on a spatial analysis of the available groundwater level observations. The sparsity of observations, especially transient observations, did not allow such an analysis. At a distance of 15 km the Assessment team judged that it is very likely that the groundwater system is affected by different stresses (recharge, surface water interaction) and has different hydraulic properties.

The threshold T_j, the upper limit, for each prediction is defined as:

$$T_j = \sum_{i=1}^{k} \frac{r_i}{n_i} \left(1 - \tanh\left(\frac{d_i}{w}\right)\right) (10)^2 \qquad (6)$$

This means that any parameter combination that results in an average difference between observed and simulated groundwater level equal or less than 10 m is deemed acceptable. While this might be considered as a weak constraint, in a traditional calibration this would correspond to a normalised root mean squared error of 5% as the range of groundwater level observations spans about 180 m (Bioregional Assessment Programme, Dataset 1).

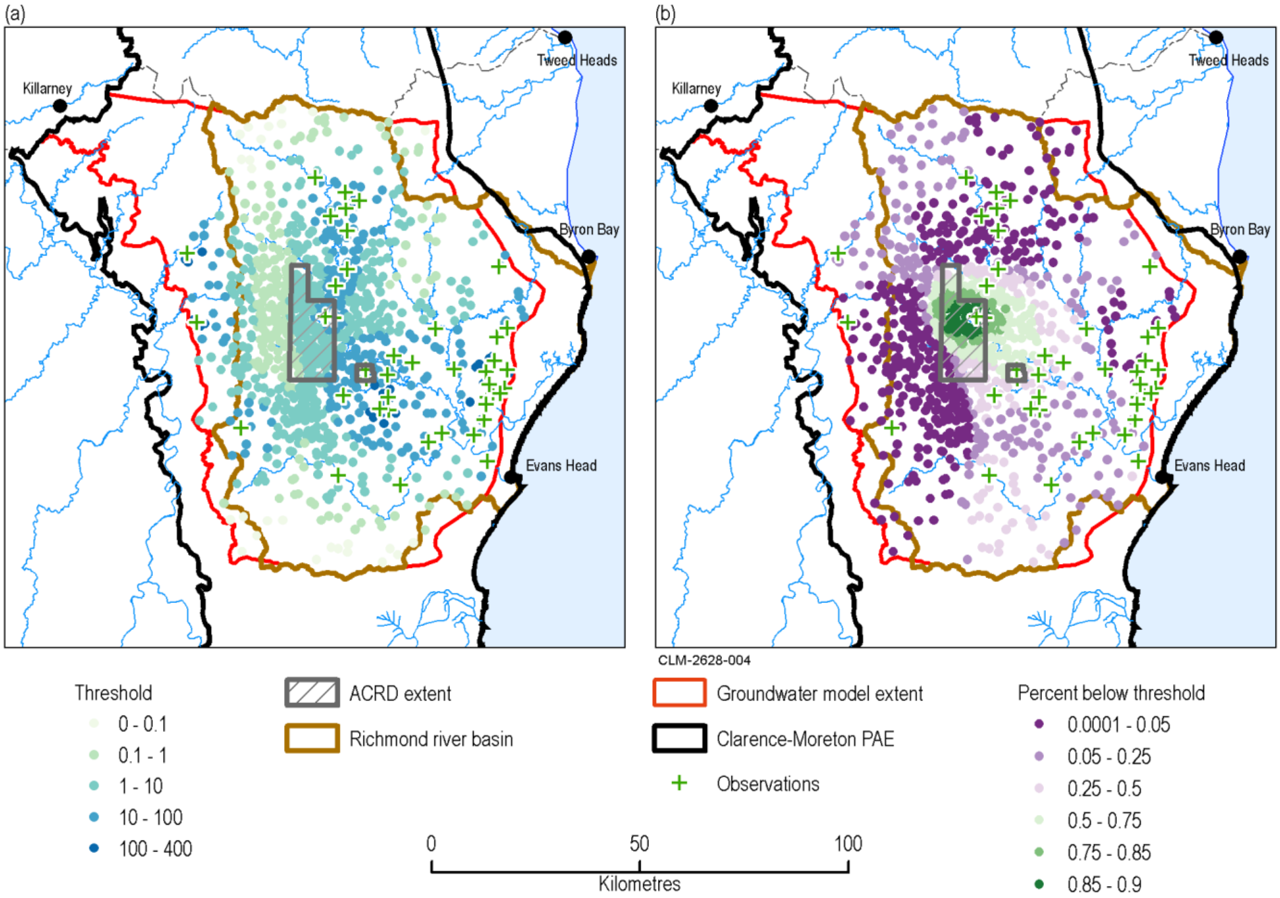

Figure 39 (a) Groundwater level criterion threshold value for each prediction in layer 1 and (b) the fraction of successful design of experiment runs that meet the groundwater level acceptance criterion

Small threshold values in (a) indicate prediction locations that cannot be constrained by groundwater level observations. The acceptance rate in (b) is a proxy for conceptual model uncertainty: regions with very low acceptance rates indicate that it is not possible to locally match observations, despite the wide parameter range used. Regions with very high acceptance rates indicate that the model results agree with the observations, regardless of the parameter values.
Data: Bioregional Assessment Programme (Dataset 1)

Figure 39a shows the value of the threshold value for each individual prediction in layer 1, calculated with Equation 6. The value of the threshold as such is not that important, but high values indicate that a prediction is within the zone of influence of one or more observations. This means that the parameter distribution used for that prediction potentially can be constrained by groundwater level observations. Conversely, low values close to zero indicate that a prediction is far removed from any observation and therefore has a low potential to be constrained.

Figure 39b shows the fraction of successful runs of the design of experiment that meet the groundwater level acceptance criterion. High values, in excess of 0.8, indicate that a majority of the parameter combinations evaluated in the design of experiment result in groundwater level predictions that agree with the observations in that region (within the specified acceptable range). This means that the simulated groundwater levels in a region with high values of this acceptance rate are not very sensitive to the parameter values. This also means that the observations have limited potential to constrain the parameters in these regions and thus have limited potential to constrain the predictions. In other words, a good fit between modelled and simulated values in these areas does not guarantee reliable predictions.

In the groundwater model for the Clarence-Moreton bioregion, the central region with high acceptance rates is probably due to a few observations that are close to a surface water boundary. The simulated groundwater levels in that region are mostly affected by the boundary conditions, rather than the parameter values.

Very low acceptance rates on the other hand, indicate that only a very limited number of parameter combinations result in simulated groundwater levels at the observation location that correspond to the observed values. As the parameter bounds in the design of experiment are deliberately chosen to be wide, low acceptance values indicate localised conceptual shortcomings of the model because it is not possible to get an acceptable correspondence between observed and simulated values. In some extreme cases, the acceptance rate is equal to zero, which occurs in three ellipse-shaped regions in the model. These are predictions within the overlapping zones of influence of two observation locations for which the simulated values cannot simultaneously agree with both observed groundwater levels. While this can be an indication of the shortcomings of the spatially uniform parameter multipliers within a layer, it is also likely that this is due to the boundary conditions, the local conceptualisation or even artefacts or errors in the observation database.

Figure 39b can be used as a proxy of the conceptual model uncertainty of the groundwater model. Very high acceptance rates indicate insensitivity to parameter values although the groundwater level predictions agree with observations. Low values, on the other hand, indicate regions of the model where it is unlikely to make groundwater level predictions that match the observations and where it is likely that the conceptualisation is locally inadequate. Three such areas can be identified in Figure 39b (black dots): north of the CSG development area, the western edge of the groundwater model and the eastern edge of the model closest to Byron Bay. While the extent and shape of these regions is determined by the weighting function, the presence of these zones indicates that for some sets of observations the model is not able to simultaneously match the observations within the prescribed error threshold.

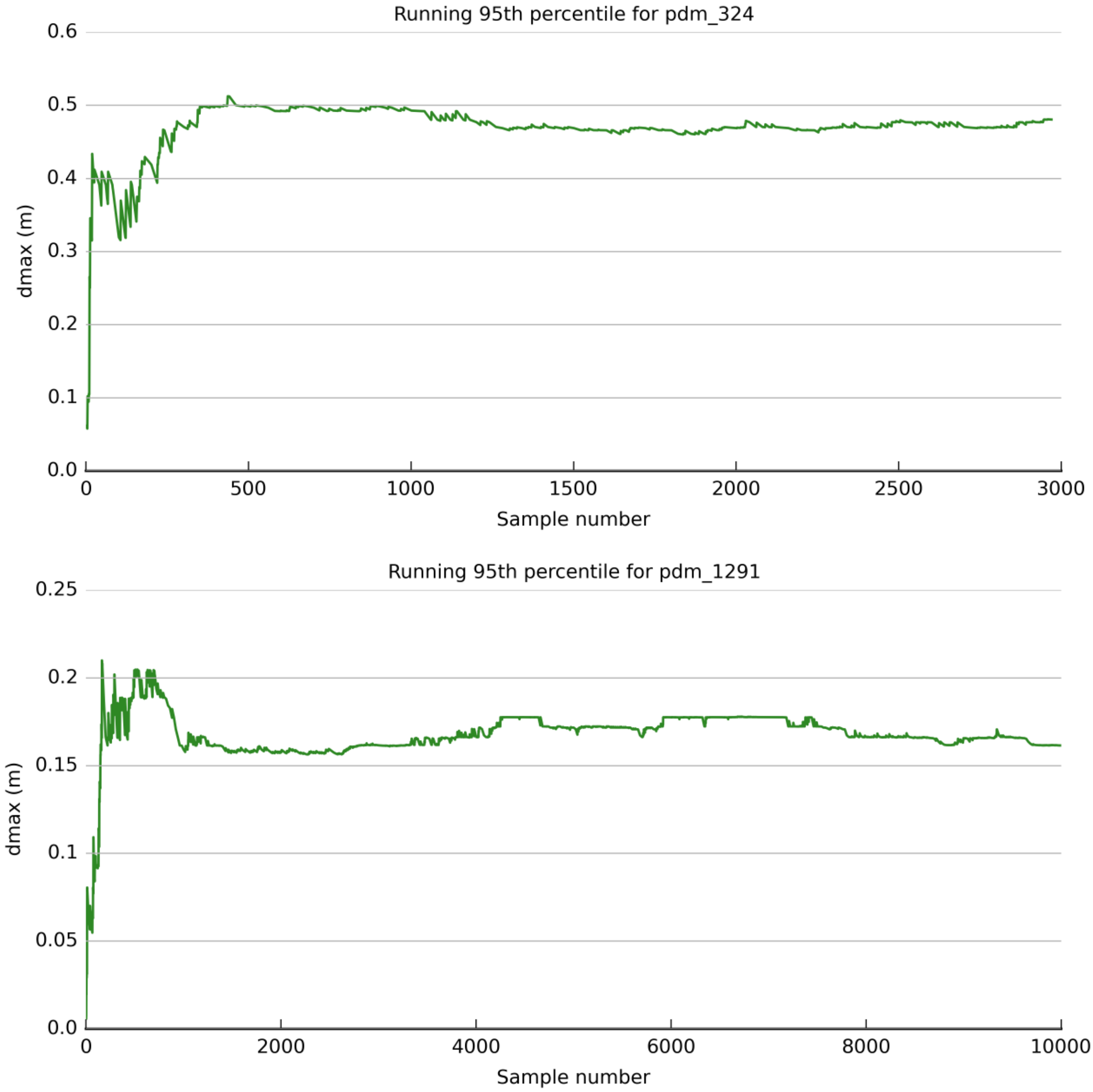

Figure 40 Convergence of the 95th percentile of the posterior distribution of additional drawdown with the number of samples from the posterior parameter distribution for model nodes pdm_324 (a) and pdm_1291 (b)

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway and baseline, due to the additional coal resource development.

The posterior parameter distributions are sampled for each prediction until the 5th, 50th and 95th percentiles of the drawdown due to additional coal resource development (additional drawdown) stabilise. As the predictive distributions are heavily skewed to the right, that is, most of the predictions are close to zero with a small number of large drawdown values, the 5th and 50th percentile already stabilise for a small number of samples. The 95th percentile requires more samples to stabilise. This is illustrated in Figure 40 for the predictions of additional drawdown at model nodes pdm_324 and pdm_1291. The 95th percentile of *dmax* for pdm_324 already stabilises after 1500 samples, while at least 6000 samples are required for the prediction at pdm_1291 to stabilise. Do note that for both model nodes the 95th percentile of *dmax* is within 5 cm of the final stabilised value after 500 samples from the posterior parameter distribution.

2.6.2.8.1.3 Predictions

For 1462 locations within the model domain (see Figure 42), predictions of additional drawdown and year of maximum change are made by sampling the appropriate posterior parameter distribution. Figure 41 shows histograms of the 5th, 50th and 95th percentile of drawdown summarised per model layer. Figure 41e shows that in layer 3 the 5th percentile and the median predicted drawdowns (50th percentile) are less than 5 cm at all 29 model nodes. At 10 model nodes the 95th percentile of drawdown is also less than 5 cm. For 13 model nodes the 95th percentile of *dmax* is between 5 and 10 cm, for 4 model nodes between 10 and 15 cm, and for 2 model nodes the 95th percentile of *dmax* is between 15 and 20 cm.

The 5th percentile of additional drawdown in all layers at the model nodes is less than 5 cm. The median *dmax* is mostly less than 5 cm in all layers, with the exception of layers 1 and 2, where there are about 30 model nodes in each layer for which the median *dmax* is between 5 and 15 cm. The 95th percentile of additional drawdown at the model nodes can reach values up to 1 m in layers 1 and 2. In the Walloon Coal Measures there is one model node for which the 95th percentile of *dmax* is equal to 2.2 m. These plots highlight that the posterior distributions of predicted additional drawdown are very skewed, with most of the simulations resulting in *dmax* close to 0 m, with a smaller proportion of drawdowns up to 1 m in model nodes in layer 1 and 2, up to 20 cm in model nodes in layer 3 and 4 and up to 2.2 m in model nodes in layer 6.

The posterior distributions for year of maximum change (*tmax*) are less skewed (Figure 41). The earliest year of maximum change shown in Figure 41 is 2038, which corresponds to the end time of the planned CSG exploitation. For most of the models nodes, however, the year of maximum change is at or beyond 2102. A considerable number of model nodes in layers 1 to 4 have median predicted year of maximum change values in the decades following cessation of active depressurisation, while the median values in layer 6 are all shown as 2102. Several model nodes in layers 1 to 4 are within or close to the proposed CSG development area. The median *tmax* values less than 2102 illustrate the vertical propagation of the cone of depression through the sedimentary basin.

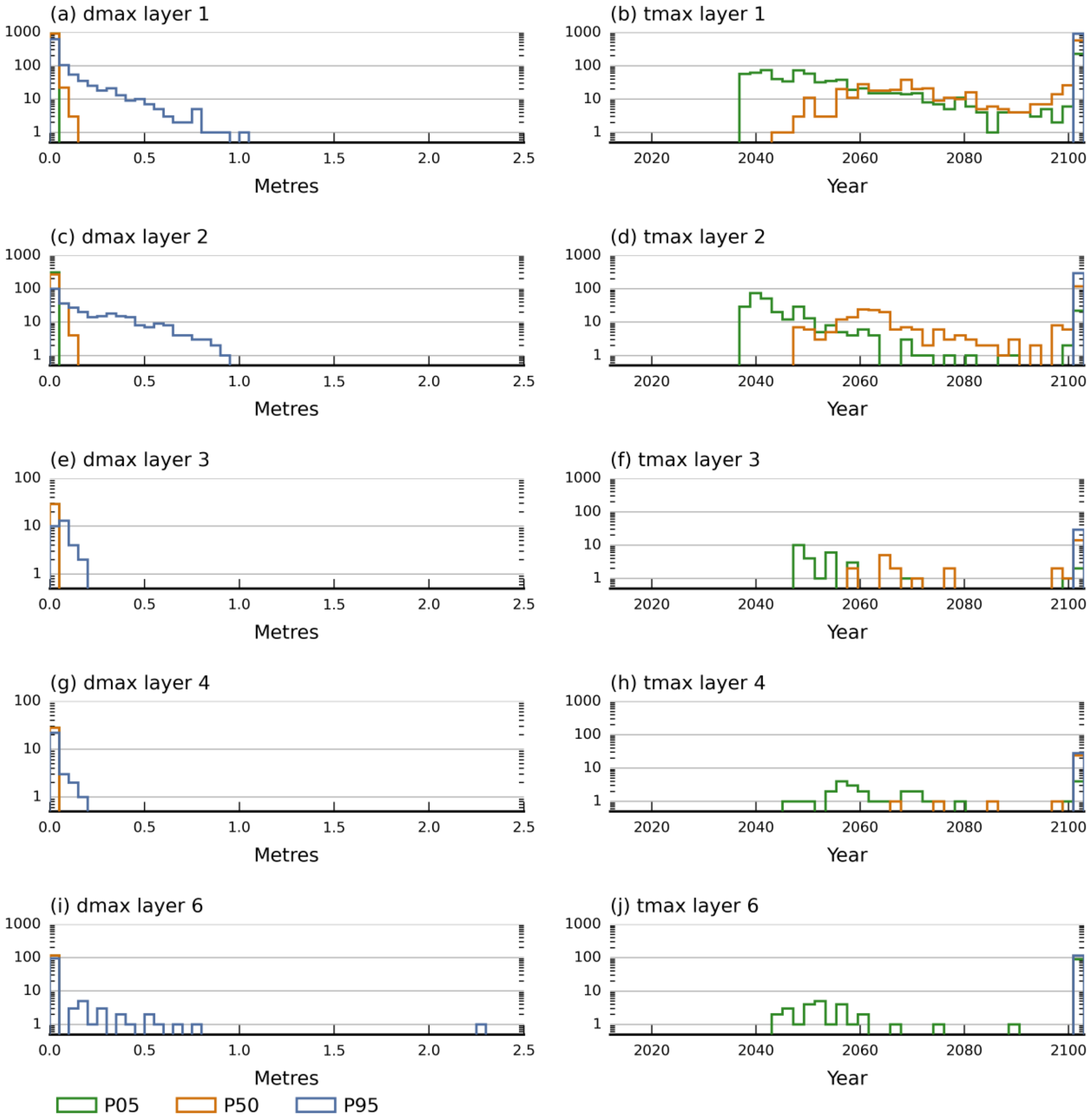

Figure 41 Histograms of 5th, 50th and 95th percentile of additional drawdown (left) and year of maximum change (right)

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway and baseline, due to the additional coal resource development; *tmax* = year of maximum change; 5th percentile of *dmax* is not visible as it is covered by the line for the 50th percentile

Data: Bioregional Assessment Programme (Dataset 1)

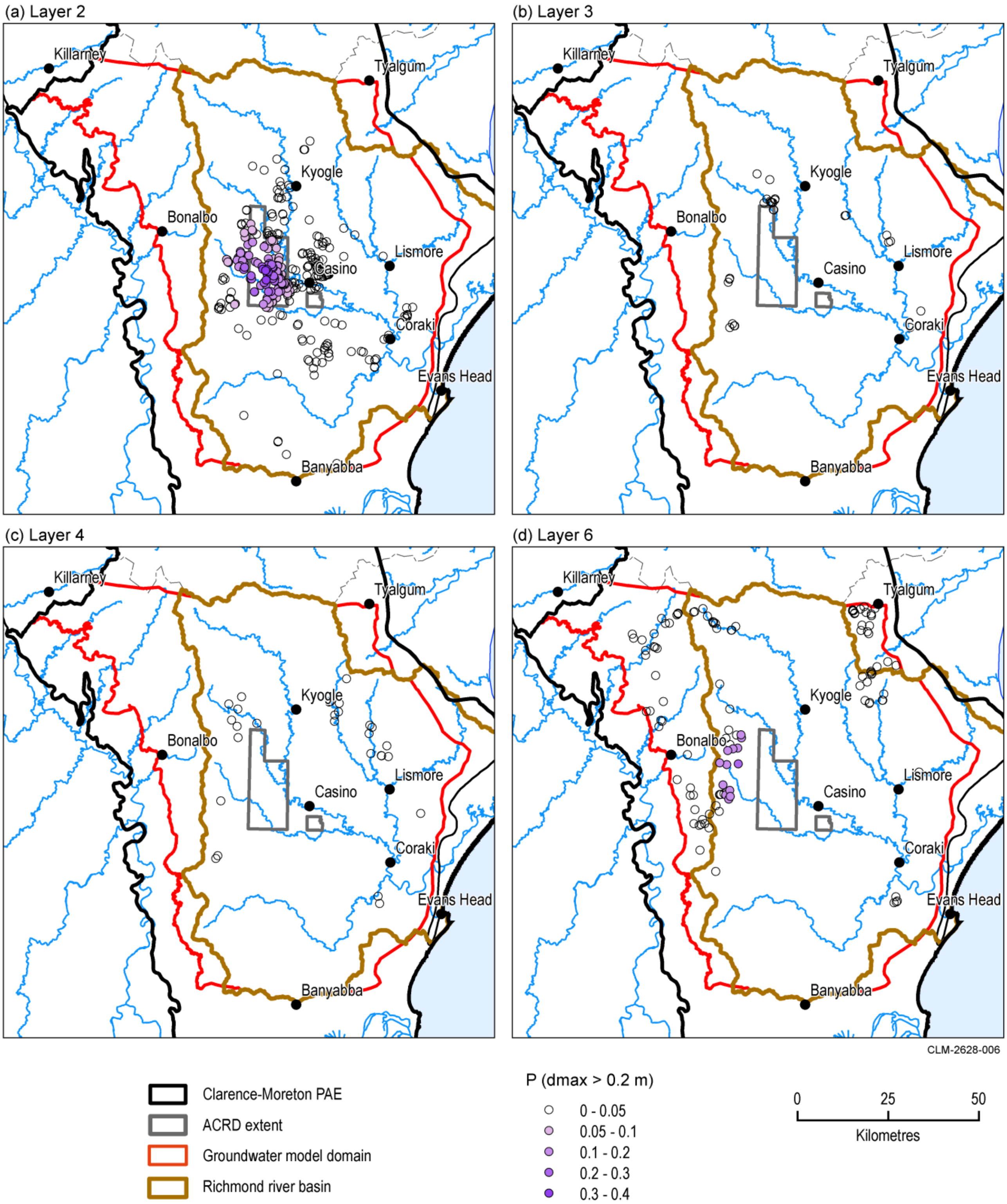

Figure 42 Probability (P) of exceeding 0.2 m drawdown at the model nodes in layer 2 (a), layer 3 (b), layer 4 (c) and layer 6 (d)

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway and baseline, due to the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 1)

Figure 42 shows the probability of drawdown exceeding 0.2 m for each layer. This threshold corresponds to the impact threshold in the NSW aquifer interference policy (NSW DPI, 2012) for impact on groundwater-dependent ecosystems. Figure 43 shows the gridded probability of additional drawdown exceeding 20 cm for layer 1. As such, this threshold is only relevant for layer 1, as the predictions in layers 2 to 6 are all at licensed groundwater bores, where the threshold for impact is 2 m. As shown in Figure 41, the 95th percentile of additional drawdown only exceeds the 2 m threshold at a single model node in layer 6. The exceedance probabilities of 20 cm drawdown show that model nodes close to the proposed CSG area have the highest probabilities of exceeding 20 cm additional drawdown. The highest probability of exceeding 20 cm drawdown is recorded in layer 2 and is 38%. The predicted additional drawdown in the model nodes in layer 6 are mostly small as the majority of model nodes are situated more than 10 km from the centre of the proposed CSG development area.

Figure 43 shows that the area where the probability of exceeding 20 cm additional drawdown exceeds 0.05 extends at most 10 km west of the CSG development area. The map also shows the mitigating effect of the major rivers on additional drawdown.

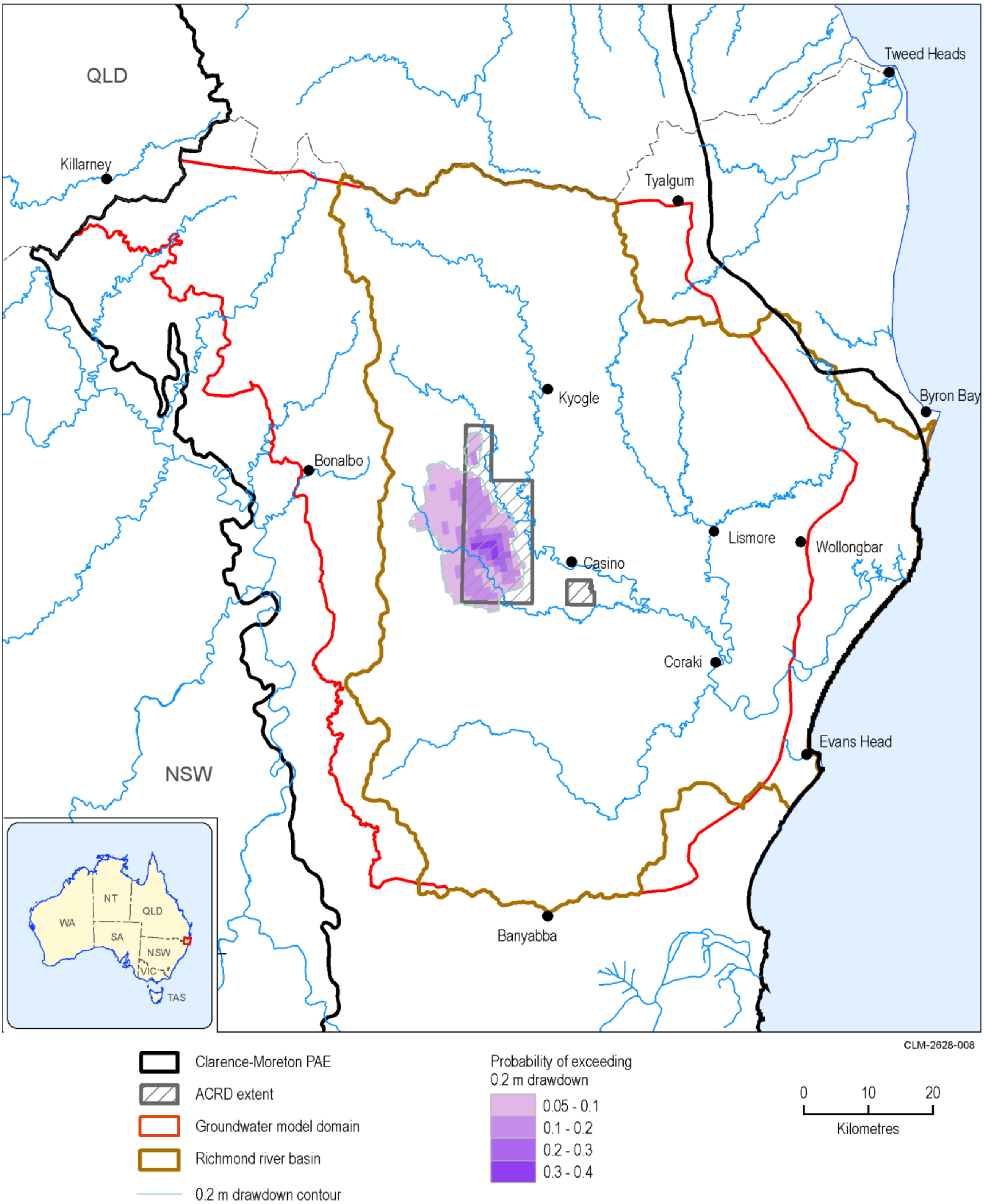

Figure 43 Probability of exceeding 0.2 m additional drawdown in layer 1

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway and baseline, due to the additional coal resource development (ACRD).

These results are generally comparable with the findings of the groundwater modelling carried out for the Metgasco IES (Parsons Brinckerhoff, 2013). The BA modelling indicates a non-negligible probability of exceeding 20 cm drawdown beyond the additional coal resource development area (Figure 42a), especially to the west. The Metgasco model shows very limited impact outside the additional coal resource development area in the watertable aquifer. The Metgasco model predicts that the drawdown due to the CSG abstraction is generally less than 0.2 m in layer 1 and the Piora Member (layer 2). The 95th percentile of additional drawdown predicted by the bioregional assessment (BA) model at any model nodes in layer 1 or layer 2 is not in excess of 0.48 m. While there are no model nodes in the Walloon Coal Measures within the additional coal resource development area, the relatively small changes in the Walloon Coal Measures at the existing model nodes agree with the rapid decline of drawdown due to the low hydraulic conductivity in the Walloon Coal Measures simulated in Parsons Brinckerhoff (2013).

2.6.2.8.2 Factors not included in formal uncertainty analysis

The major assumptions and model choices underpinning the Clarence-Moreton groundwater model are listed in Table 9. 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.

In the table 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’ code 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 dominantly 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 the model predictions, with ‘low’ indicating a minimal effect and ‘high’ a large effect. Especially for the assumptions with a large potential impact on the predictions, it will be discussed that the precautionary principle is applied; that is, the hydrological change is over rather than under estimated.

Table 9 Qualitative uncertainty analysis for the groundwater model of the Clarence-Moreton bioregion

Nr	Assumption or model choice	Data	Resources	Technical	Effect on predictions
1	Single geological and conceptual model	high	medium	medium	medium
2	Faults	high	medium	medium	medium
3	Boundary conditions	medium	medium	medium	medium
4	Groundwater observation data	high	medium	low	medium
5	Distance-based weighting of observations	medium	medium	low	low
6	Zonal recharge from chloride mass balance	high	low	low	low
7	Spatial variability of hydraulic properties	high	medium	medium	medium
8	Prior parameter distributions	high	low	low	low
9	CSG water production rates	high	low	low	high
10	Water usage for irrigation, stock and domestic	high	low	low	low
11	Length of simulation period	low	high	medium	low
12	Only represent major rivers in groundwater model	high	high	medium	low

CSG = coal seam gas

2.6.2.8.2.1 Single geological and conceptual model

The development of the groundwater model was based on a single conceptualisation underpinned by the geological model (companion product 2.1-2.2 (Raiber et al., 2016a) and companion product 2.3 (Raiber et al., 2016b) for the Clarence-Moreton bioregion). The uncertainties associated with the three-dimensional geological and conceptual hydrogeological model are highlighted in companion product 2.3 (Raiber et al., 2016b) and summarised briefly below.

Three-dimensional geological models are created from datasets that are inherently uncertain because they sample the subsurface at a limited resolution (Wellmann et al., 2010; Raiber et al., 2012; Raiber et al., 2016b). Uncertainties in three-dimensional geological models can arise from various factors with data density, data quality, geological complexity and conceptual uncertainties being the most common sources of uncertainties (e.g. Mann, 1993; Davis, 2002; Raiber et al., 2012; Raiber et al., 2016b).

In the three-dimensional geological models developed as part of the Assessment, geological uncertainty is mostly related to the lack of well-intersection data of deeper sedimentary bedrock formations. In addition, the lack of seismic data in some areas is another source of uncertainty. This means that the geological contacts between the volcanic and sedimentary bedrock units as well as those between the different sedimentary bedrock units are uncertain in some areas (Raiber et al., 2016b).

One particular area of high uncertainty in the geological model occurs near the crests of the Lamington Volcanics at the boundary between the Logan-Albert and Richmond river basins. However, this uncertainty is likely to have a very limited effect on the predictions due to the well-established dominant hydrological role of the Lamington Volcanics in this area. Furthermore, there are very few model nodes there. In contrast to this area of high uncertainty, the interfaces between the shallow alluvial and volcanic and sedimentary bedrock aquifers are comparatively well constrained in most parts of the groundwater model domain due to an abundance of groundwater bores with lithological and/or stratigraphic data.

Importantly, although there are many geological uncertainties across the entire Clarence-Moreton bioregion, the confidence level in aquifer geometry and the presence and continuity of aquitards is highest in the additional coal resource development area.

The existing groundwater monitoring network likely explains only a small component of the hydrodynamics of the Clarence-Moreton Basin. Based on the existing data, groundwater dynamics in shallow alluvial aquifers are relatively well understood. However, the lack of nested groundwater-monitoring bores means that it is very difficult to identify vertical groundwater fluxes between different hydrostratigraphic units within the Richmond river basin (Raiber et al., 2016b). Note that auxiliary evidence from hydrochemical data (i.e. the freshness of most alluvial groundwaters at the eastern boundary of the Clarence-Moreton Basin) within the Richmond river basin and other catchments within the Clarence-Moreton bioregion (Section 2.3.2.2.4 in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b)) suggests that discharge from sedimentary bedrock is not the major source of water for alluvial aquifers.

The geological and conceptual models are limited by data availability, in terms of their density, quality and type. This is particularly relevant to the hydraulic properties of aquitards, where currently only very limited data are available. Any additional information would reduce the uncertainty in the geological model and thus has the potential to change the conceptualisation of the groundwater system. The data column in Table 9 is hence scored ‘high’.

It is technically possible to formalise the development of geological models and conceptual models to stochastically account for the sources of uncertainty in the groundwater model that they underpin, for example, see Rojas et al. (2008). The discretisation of a geological model into a numerical MODFLOW model grid is almost always associated with a loss of information and the potential introduction of artefacts due to the idiosyncrasies of the MODFLOW code that requires spatially continuous model layers. In the Clarence-Moreton case, geological layers had to be converted to spatially continuous layers; a process that involved multiple steps of splitting the three-dimensional geological model layers, adding thin continuous dummy layers outside the original extent of the layers followed by re-assembly. While a recent version of MODFLOW, namely MODFLOW-USG, can accommodate spatially discontinuous layers, it was not available at the start of the modelling task. The technical aspect is therefore scored ‘medium’ in Table 9. The operational constraints in BA however prevent going along those alternative pathways, mostly due to the large development time required to formalise and script the development of geological models and the considerable computational load required to jointly run the geological and groundwater model. The resources and technical attributes are assigned a ‘medium’ score accordingly.

This limitation will be addressed as part of a CSIRO strategic project ‘Next generation methods and capability for multi-scale cumulative impact assessment and management’ (sub-theme ‘Tracer-based improvement of groundwater model conceptualisation and predictability’).

Notwithstanding the 'high' score for data and 'medium' score for resources, the overall impact on predictions is scored 'medium'. The most basic conceptualisation of the system, relevant to the impact assessment of CSG production, is a CSG development in a laterally continuous coal seam that is separated from other aquifers by laterally continuous aquitards. The range of predictions provided in this product are valid as long as this general conceptual understanding holds. The largest discrepancy would arise if new information becomes available that indicates that aquitards separating the coal seams from aquifers containing model nodes are discontinuous in the vicinity of the CSG development, or, if new hydraulic property data become available that would warrant re-evaluating the role of different stratigraphic units as aquitards. The high degree of gas saturation of coal seams in the central Richmond river basin (Doig and Stanmore, 2012) suggests that an effective aquitard is in place that prevents leakage of gas or water. Additional information indicating that the coal seams are not laterally continuous would reduce the predicted impacts as the cone of depression will not spread as far laterally with less water needed to be extracted to achieve the same level of depressurisation in the coal seams.

2.6.2.8.2.2 Faults

Fault displacements of hydrostratigraphic units are neither represented in the three-dimensional geological model nor in the groundwater model. However, it is a well-known fact that faults are present in the Clarence-Moreton bioregion where significant vertical displacements of hydrostratigraphic layers occur (e.g. Ingram and Robinson, 1996; Raiber et al., 2016b).

A prevalent conceptualisation of the hydrodynamic behaviour of faults is that the disturbed zone parallel to the fault provides a conduit to flow vertically, while the shale gouge on the fault plane impedes flow horizontally. This can potentially compromise the integrity of aquitards. Without data from nested groundwater monitoring bores, there is no direct evidence to determine the significance of vertical groundwater fluxes between different hydrostratigraphic units within the Richmond river basin (Raiber et al., 2016b). Note that the high groundwater salinities in the alluvium near Coraki and the similarity between the course of Myrtle Creek and the orientation of Coraki Fault are an indication that this fault does act as a conduit for upward discharge of deep groundwater to shallow aquifers, or to the surface (companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016b)). However, this fault is located a considerable distance from the additional coal resource development, and it was also highlighted in companion product 2.3 that the Lamington Volcanics have a very dominant hydrological role in the Richmond river basin, which is likely to overwhelm the influence of faults in most areas. This indicates that at the regional scale, the influence of faults on predictions is likely to be relatively minor in most areas, yet it can be locally significant.

The lack of reliable data relevant to fault density and location is the main driver in the uncertainty related to faults and receives a 'high' score. Including faults in the three-dimensional geological model and the groundwater model was not feasible within this BA due to resourcing limitations and the timing as to when crucial relevant data for fault modelling (i.e. seismic data) was made available for use in the BA, hence the 'medium' score. Finally, explicitly representing faults in MODFLOW models, at least in MODFLOW 2005, as linear features that act as vertical conduits and horizontal barriers is not trivial and is technically challenging, hence the 'medium' score.

To reflect this uncertainty, the role of faults and their effect on predictions was assigned a 'medium' score, mostly because the effect is likely not to be regionally considerable, yet can be significant locally. Similar to effects of bore integrity (Doble et al., In press), the potential for regional drawdown in shallower aquifers induced by faults depends mainly on the density of faults and locally on the contrast between hydraulic conductivities of the fault zone and the aquifers. On a regional scale, Doble et al. (In press) show that the drawdown above an aquitard will only be noticeably affected by faults or failed bores when the density of faults is close to the ratio of the hydraulic conductivity of the aquitard and the fault zone. As an extreme example, assume that the vertical hydraulic conductivity of the fault zone is four orders of magnitude larger than the vertical hydraulic conductivity of the aquitard. In an area of 1 km2 this would require 10 faults with a length of 1 km and a width of 1 m before drawdown is noticeably affected. Although multiple regional fault systems and minor faults are known in the Clarence-Moreton Basin, the geological understanding of the Clarence-Moreton Basin indicates that such a fault density is unlikely. On a local scale, however, the flow through a fault is not only controlled by the hydraulic gradient across the fault and the hydraulic properties of the fault, but also by the hydraulic properties of the aquifers that the fault connects. Especially when the hydraulic conductivity of the lower aquifer is low, the flow rate through the fault will be controlled by the rate at which water can flow towards the fault, not by the rate that water can be transmitted through the fault. In the Clarence-Moreton bioregion, the main CSG target, the Walloon Coal Measures, has a low hydraulic conductivity especially at depth. It is therefore likely that the rate of water transmitted through a hitherto not known fault within the drawdown area of CSG is limited by the low hydraulic conductivity of the Walloon Coal Measures.

To formally assess the effect of faults on groundwater dynamics, faults will be incorporated in a future model realisation that will be developed as part of a CSIRO strategic funding project 'Next generation methods and capability for multi-scale cumulative impact assessment and management' (sub-theme 'Tracer-based improvement of groundwater model conceptualisation and predictability'). This will allow a direct comparison between predictions derived from a faulted and an unfaulted model. Although this will further reduce uncertainty, it is important to note that the lack of deep and nested groundwater observation bores still leads to conceptual uncertainties on the hydraulic role of faults. This highlights the importance of installing nested groundwater monitoring bores in those areas.

2.6.2.8.2.3 Boundary conditions

The conceptual model necessitates the definition of several lateral and internal boundary conditions to groundwater flow, such as lateral general-head boundaries, the drainage of water from the top of the model to represent groundwater evapotranspiration and the major rivers.

The boundary conditions are assigned a 'medium' score for all three attributes, indicating that no single attribute dominates the choice and implementation of the boundary conditions. Additional data and resources will allow more detailed and complex representations of these boundary conditions. The resulting increased dimensionality, however, will increase the technical challenge of carrying out a comprehensive uncertainty analysis.

The overall effect of boundary conditions is scored 'medium'. This score, however, needs to be nuanced as shown by the sensitivity analysis. The general-head boundary condition and recharge boundary condition have little effect on the change in groundwater level predictions. The riverbed conductance and drainage conductance of the top of model drainage boundary, can have an effect on predictions. A reduction in the uncertainty in these boundary conditions has the potential to at least partly reduce the uncertainty in the predictions.

2.6.2.8.2.4 Groundwater observation data

Groundwater level observations are often the only data used to constrain the parameters and conceptualisation of a groundwater model. In the groundwater model for the Clarence-Moreton bioregion groundwater level observations are used to constrain predictions in the top layer of the model.

In Section 2.6.2.7.1 the available groundwater observation data from the NSW Office of Water database in the groundwater model domain are presented and discussed. A large number of these observations date back to the late 1970s or early 1980s and mostly correspond to single water level readings carried out directly after completing a groundwater bore. The metadata associated with these measurements often indicate that the coordinates of the observation location are not surveyed, but estimated from a map. The elevation of ground level or the reference points for depth-to-watertable measurements is in the majority of cases not surveyed either, but estimated from maps or digital elevation models.

All of these observations are invaluable in building a conceptual understanding of groundwater flow in the region and identifying general trends in piezometric surface. Unfortunately, the uncertainties in spatial location and representativeness of measurements in groundwater bores shortly after installation greatly reduce the value of an observation in a formal comparison with the results of a groundwater model. Any observations that have no surveyed coordinates or are not carried out in groundwater observation wells are therefore excluded from the dataset used to constrain the groundwater model.

The amount of data available to constrain the groundwater model obviously scores ‘high’ in the data column (Table 9). A more extensive observation network will undoubtedly provide a stronger knowledge base to create and constrain groundwater models in this region. This issue receives a ‘medium’ score on the resources attribute. The quality control and assurance of the database entries, and their suitability to be included in the observation dataset to constrain the model, is entirely based on a desktop study based on the information provided in the database. A more comprehensive analysis of the original records or a field campaign to identify and verify spatial coordinates of the database entries has the potential to greatly reduce the uncertainty in the observation record. There are no technical issues for collecting, verifying or using groundwater level observations, hence the ‘low’ score for the technical attribute.

The final score on the effect on the predictions, despite the limited data availability and uncertainties in the observation record, is ‘medium’. This means this issue is important but not deemed to dominate the predictions. A larger observation database with less observation uncertainty has the potential to locally change the conceptual understanding of the system and change the final posterior parameter probability distributions. The sensitivity in Section 2.6.2.7.3, however, indicated that the changes in groundwater level predictions and surface water – groundwater flux are dominated by different parameters than the parameters to which the current groundwater level observations are sensitive. Constraining the parameters with additional groundwater level observations in the alluvium will therefore have limited effect on the predictions. The predictions of change in surface water – groundwater interactions are the main prediction. These predictions are sensitive to the riverbed conductance, which is a parameter that groundwater level observations close to river boundaries are sensitive to as well. It is very difficult, however, to constrain riverbed conductance greatly with groundwater level predictions as the groundwater levels will have a large influence from the recharge and river stage boundaries as well.

Predictions in the deeper layers are most sensitive to vertical hydraulic conductivity and storage. Any observations that have the potential to constrain these parameters, such as groundwater level observations in multi-level wells, time series of groundwater level in deeper layers or environmental tracers, will reduce the predictive uncertainty. Single or isolated groundwater level readings in the deeper layers will suffer from the same drawbacks as observations in the alluvial system. The observations have a lot of information on flow directions, but have little information on vertical gradients or storage properties.

2.6.2.8.2.5 Distance-based weighting of observations

Closely related to the previous assumption is the weights assigned to each groundwater level observation. The weight of an observation in constraining parameters for a particular prediction is based on the distance between observation and prediction and the distance of the observation to the nearest blue line network.

With the available data density and operational constraints, the development of a tailored weighting for each observation based on the aquifer it is situated in and the local hydrogeological conditions, is not possible. Therefore, the data and resources columns are scored ‘medium’. Technically it is trivial to implement a different weighting scheme, so the technical column scores ‘low’.

The overall effect on predictions is small, as the information in the groundwater level observations is not able to constrain the parameters relevant to the groundwater change predictions. Locally, however, the effect on predictions can be important such as in regions where none of the simulated groundwater levels are in agreement with the relevant observations and the model is not deemed reliable. The extent and shape of these regions is fully governed by the observation weighting function.

2.6.2.8.2.6 Zonal recharge from chloride mass balance

Groundwater recharge is implemented spatially in function of the outcropping geology as a correction factor to the temporal recharge signal obtained from the surface water model output. The correction factors are based on measurements of chloride in groundwater and rainfall with the chloride mass balance method (companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016a)). The spatial coverage of bedrock groundwater chloride measurements in the Clarence-Moreton bioregion is variable, and there are only relatively limited data points in the Richmond river basin. Other reliable and representative measurements of diffuse recharge are not available in this bioregion.

More evenly distributed chloride measurements in groundwater observations across the outcropping geological units or other estimates of diffuse recharge will undoubtedly improve the zonation and parameterisation of groundwater recharge. For this reason, a 'high' score is attributed to the data column. It is unlikely that additional resources or different techniques will improve the recharge estimates based on the currently available data. Both these columns are therefore given a 'low' score.

Recharge estimates with reduced uncertainty will reduce uncertainty in groundwater level predictions; however, as the change in groundwater level is not sensitive to recharge, it will not, or only minimally, affect changes in groundwater level predictions. The effect on the predictions attribute is therefore scored 'low'.

2.6.2.8.2.7 Spatial variability of hydraulic properties

The hydraulic properties of each hydrostratigraphic unit are implemented as spatially uniform horizontally although the hydraulic conductivity can vary with depth.

In comparison to the linked Surat Basin, the Clarence-Moreton Basin is a data-poor region, with very limited information on the hydraulic properties of key aquifers such as the Walloon Coal Measures and the overlying aquitards such as the Maclean Sandstone, Bungawalbin Member and Rapville Member. As outlined in Section 2.6.2.8.2.3, insufficient data are available to inform spatial variability at a regional scale. The data availability attribute therefore receives a 'high' score.

The level of spatial detail that can be accommodated in a numerical model is governed by the horizontal and vertical discretisation which, especially in the vertical direction, will always require an upscaling. This upscaling remains a challenging technical task with a wide variety of techniques available to upscale point measurements into equivalent hydraulic properties for a numerical model (Renard and de Marsily, 1997). The technical column is scored 'medium'.

These technical challenges can be partly overcome through stochastic simulation of the hydraulic properties. The time and computational resources required to develop and apply stochastic hydraulic property simulators tailored to the subregion are not available within the operational constraints of the Bioregional Assessment Programme. The resources column is therefore scored 'medium' as well.

The effect on the final predictions of the uncertainty in hydraulic properties is deemed to be moderate and is therefore scored 'medium'. Any change in the hydraulic properties will affect the predictions directly, especially the deeper-layer storage and vertical hydraulic conductivity parameters. The wide prior distributions defined for the parameters ensure, however, that this uncertainty is adequately captured in the predictive distributions of drawdown and change of flux.

The validity of not accounting for spatial heterogeneity explicitly in the groundwater model hinges on the assumption that the representative elementary volume approach is valid at this scale and for these predictions. At the regional scale for groundwater quantity predictions, this is widely accepted to be the case as exemplified in guiding principle 7.3 in the *Australian groundwater modelling guidelines* (Barnett et al., 2012).

While introducing spatial heterogeneity might have a local effect in the changing extent of change in groundwater level predictions in the immediate vicinity of the largest stress, at larger scales the effect is minimal (see companion submethodology M07 for groundwater modelling (Crosbie et al., 2016)).

2.6.2.8.2.8 Prior parameter distributions

The prior parameter distributions are established by the Assessment team based on the available information for the Clarence-Moreton bioregion and equivalent analogue basins in Australia and the world.

Additional data will allow adjustment of these prior distributions to agree more closely with the conditions in the Clarence-Moreton bioregion. This warrants the 'high' score for the data component. Specifying prior distributions are not constrained by resources and there are no technical issues as the uncertainty analysis methodology is not prescriptive in the type of prior distribution used in the analysis. Both of these attributes score 'low'.

The effect of the choice of parameter distributions is potentially important as there is little information available to constrain the majority of the parameters. Some of the most influential parameters, especially those controlling the CSG water production rate, are constrained only by the available production rate estimates. The posterior parameter distributions for these parameters are very similar to the prior distributions. The effect on predictions is therefore chosen to be scored 'medium'.

To mitigate this, the distribution is chosen to be conservative, spanning at least two orders of magnitude for most of the hydraulic properties, as to ensure the predictive uncertainty is overestimated rather than underestimated.

2.6.2.8.2.9 Coal seam gas water production rates

In the groundwater model, CSG dewatering is implemented as a drainage boundary condition in the deepest model layer. Water is sourced from the entire layer, not from individual coal seams.

While non-trivial and challenging (Moore et al. 2015), it is technically possible, and within the resources of the BA, to implement a more detailed conceptualisation of the CSG depressurisation. However, insufficient data are available, both on the physical system and on the dimensions of the planned development, to adequately parameterise the added complexity. This motivates the scoring of 'high' on the data column with 'low' for resources and technical attributes.

One of the limitations of the current modelling approach is that it is not able to simulate dual-phase flow. Using a single-phase model is, however, likely to overestimate drawdowns and water extraction volumes (Herckenrath et al., 2015), in line with the precautionary principle. The codes do allow for specifying pumping rates, but these are not known and, because of the dual-phase aspect, will be unlikely to result in a drawdown that is representative of the depressurisation required for CSG extraction (see submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016)).

The effect of changing the water production rates on the prediction is large, as is shown in the sensitivity analysis, where most of the change in groundwater level predictions is very sensitive to the parameters related to the implementation of the CSG water production. A different configuration or number of wells or a change in the target depressurisation level (currently at 35 m above the top of the Walloon Coal Measures) has the potential to greatly change the predicted impacts. This explains the 'high' scoring for effect on predictions.

Constraining all parameter combinations with the estimated water production rates – at the very least – ensures that the predicted impacts are, to a degree, consistent, with the more detailed reservoir simulation carried out by the proponent.

2.6.2.8.2.10 Water usage for irrigation, stock and domestic

Metered-use data of groundwater pumping for irrigation, stock and domestic use were not available for the Clarence-Moreton team when the assessment was conducted. The pumping rates assigned to the model are therefore based on licensed use rather than actual use.

This assumption is driven by data availability, and scores 'high' in that column. Resources and technical attributes are scored 'low' as they do not form a limitation in implementing pumping rates.

The effect of water pumping for uses other than coal seam depressurisation on the prediction is deemed to be small as the pumping stress is considered identical under baseline and future development conditions. As the pumping volume is a small part of the overall water balance of the aquifer system, it is very unlikely that continued pumping is going to deplete the aquifers and cause non-linearities in the predicted change in groundwater levels. The overall score for the impact on predictions therefore is 'low'.

2.6.2.8.2.11 Length of simulation period

Across the Bioregional Assessment Programme, the simulation period is chosen to be from 2012 to 2102 as discussed in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) and companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). For some parameter combinations and some model nodes this means that the additional drawdown is not realised within the simulation period.

Extending the simulation period is not limited by data as it is about the future, hence the score 'low'. The resources attribute is, however, scored 'high'. To ensure that the additional drawdown is realised at all model nodes for all parameter combinations, would require extending the simulation period with hundreds to even thousands of years. This would impose a sizeable increase in the computational demand and therefore compromise the comprehensive probabilistic assessment of predictions. The technical attribute is scored 'medium'. It is trivial to extend the simulation period in the MODFLOW model. The climate scaling factors used to specify future rainfall and therefore recharge are not available beyond 2100. It is therefore a technical issue in devising a justifiable future climate to assign to the modelling.

The effect on predictions, however, is scored 'low', in line with the theoretical assessment of the relationship between *dmax* and *tmax* presented in submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). It can be shown that any additional drawdown realised after 2102, will always be smaller than the additional drawdowns realised before 2102.

This is in line with the precautionary principle as it means that by limiting the simulation period, the hydrological change will not be underestimated.

2.6.2.8.2.12 Only represent major rivers in groundwater model

Only major, mostly perennial, rivers are represented explicitly in the groundwater model as there is little doubt that these systems interact with the groundwater system. The connection status and level of interaction with the regional groundwater system of ephemeral, smaller streams are less well established. These are not explicitly represented and potential changes in flow rate are not assessed.

The data attribute scores 'high' as there is very little data available on historical flow rates in the higher order streams. The resources attribute also scores 'high' as incorporating this additional level of detail in a regional scale model is very time consuming. The technical component is scored 'medium' as a lot of the dynamics of these smaller features are greatly influenced by very local conditions, beyond the resolution of the grid. Accurately representing these features requires non-trivial upscaling of boundary conditions as pointed out by Brunner et al. (2010).

The overall impact on predictions is scored 'low'. While the reduction in flow in smaller, ephemeral streams cannot be simulated. However, by not representing these surface water features, drawdown is over-estimated as they cannot be off-set by influx from surface water. Where the probability of drawdown is high at the location of an ephemeral stream, a more detailed study is warranted into the local surface water – groundwater dynamics.

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2.6.2.9 Limitations and conclusions

Summary

The groundwater MODFLOW model described in this product is designed for the specific purpose of delivering a probabilistic assessment of the impact of the additional coal resource development on water resources in the Clarence-Moreton bioregion. In its current form, the model is not suited to address any other water management questions without formal re-evaluation of the conceptualisation, parameterisation and boundary conditions. Unlike deterministic models, the stochastic results of this modelling cannot be fully characterised in a single number. Any evaluation or further use of parameter combinations derived in this work or predictions obtained should therefore always be based on their full posterior probability distribution.

The qualitative uncertainty analysis identified the data limitations that have the largest influence on the predictions. These data gaps present the greatest opportunities to reduce predictive uncertainty. The main opportunities lie in increasing the understanding and conceptualisation of the deeper layers, including the aquifer assignment, and in increasing the knowledge base of hydraulic properties of aquifers and aquitards, especially the vertical hydraulic conductivity and storage.

The current model has shown that the potential hydrological change due to coal resource development at model nodes can be deemed to be very minor with a very low probability of exceeding trigger thresholds specified in the NSW aquifer interference policy. Predictions of drawdown 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).

2.6.2.9.1 Data gaps and opportunities to reduce predictive uncertainty

In previous Clarence-Moreton Bioregional Assessment companion products 1.2 (Raiber et al., 2014), 1.3 (Murray et al., 2015), 1.5 (McJannet et al., 2015), 2.1-2.2 (Raiber et al., 2016a) and 2.3 (Raiber et al., 2016b), data and knowledge gaps were highlighted. As discussed in the qualitative uncertainty analysis in Section 2.6.2.8, not all of these data gaps have the same effect on predictions.

The overarching issue that arises through that discussion is the considerable uncertainty in the understanding and conceptualisation of the deeper geological layers.

Seismic data would be of great value to reduce the uncertainty in geometry of the geological model and to identify large-scale fault features. While considerable effort has been invested in the stratigraphic interpretation of existing lithological bore logs to arrive at a unified aquifer assignment, a formal hydrostratigraphic interpretation of new bores would greatly aid in reducing uncertainty in aquifer assignment.

Any groundwater observations that contain information of the flow directions and hydraulic gradients would make the current conceptualisation more robust which would increase the confidence in the model results. Obvious candidate observations are groundwater level measurements of nested or multi-level monitoring bores and environmental tracers.

The knowledge base of hydraulic properties in the deeper layers is very limited in the Clarence-Moreton bioregion. The sensitivity analysis of model predictions highlighted that especially the vertical hydraulic conductivity and storage parameters have a high influence on the model predictions. Any information that can constrain the prior distributions of these parameters will increase the predictability of the groundwater model.

While estimates of recharge and discharge are essential for groundwater management in the bioregion, they are of lesser importance when assessing the change caused by coal seam gas (CSG) development. Additional information would undoubtedly make for a better conceptual model and a groundwater model that can reproduce historical observations more accurately, but would have a very limited potential to reduce the predictive uncertainty of drawdowns and fluxes.

Related to this is the quality of the current groundwater level observations. Analysis of the metadata of the observations highlighted that the horizontal and vertical accuracy of many observation locations is insufficient to be used in formal model evaluation. While this can be addressed by additional quality control in the database in combination with field verification of observation locations, the reduction in predictive uncertainty is limited as the groundwater level observations in the alluvial aquifers cannot constrain the parameters relevant to drawdown predictions.

2.6.2.9.2 Modelling limitations

The qualitative uncertainty analysis in Section 2.6.2.8 lists the major assumptions and model choices that form the basis of the probabilistic assessment of the impact of coal resource development on model nodes related to groundwater in the Clarence-Moreton bioregion. Within the context of the goal of the Bioregional Assessment Programme, the Assessment team deemed these assumptions valid and acceptable. There is no guarantee, however, that these assumptions will hold or be acceptable to address any other water management questions in the region.

The Assessment team therefore cannot recommend to use these models for any other purpose than the evaluation of change caused by CSG extraction without a formal re-evaluation of the suitability of the conceptual model and model assumptions, in line with the *Australian groundwater modelling guidelines* (Barnett et al., 2012).

Input data, model files (including the pre- and post-processing scripts and executables) and results are available at www.bioregionalassessments.gov.au. It is recommended, however, to contact bioregionalassessments@bom.gov.au for detailed information on the groundwater models.

The model is designed within a probabilistic framework. This implies there is not a single parameter combination that provides a ‘best fit’ to observations and a corresponding single set of predictions. The uncertainty analysis does, however, guarantee that the parameter combinations in the posterior parameter distributions honour the observations and general understanding of the groundwater dynamics of the system, within predefined acceptable limits. Any evaluation or further use of both the parameter combinations used in the models or the predictions, need to take into account the full posterior distributions reported in Section 2.6.2.7 and Section 2.6.2.8, or at least a suitable set of moments that describe these distributions.

Subsidence and contaminant transport are beyond the scope of the current stage of the bioregional assessment. Subsidence due to additional coal resource development and solute transport were not simulated as part of the groundwater MODFLOW model.

2.6.2.9.3 Conclusions

A thorough assessment of the existing groundwater models that cover the Richmond river basin revealed that they lacked advanced features such as transient boundaries and formal uncertainty analyses, which are crucial for fulfilling the purposes of the Clarence-Moreton Bioregional Assessment. Hence, they were deemed not to be fit-for-purpose.

The numerical MODFLOW groundwater model that was developed for this Assessment was the first regional groundwater model that covered the Richmond river basin. The conceptualisation of this model was underpinned by a three-dimensional geological model that was purpose-built for the current Assessment. The numerical groundwater model comprised six layers that represent the major types of hydrostratigraphic units prevailing in the Richmond river basin. Transient recharge and river boundaries were implemented in the model over a simulation period of 120 years spanning 1983 to 2102. Available observations were used to constrain the model parameters during the historical period from 1983 to 2012. The MODFLOW Multiple Node Well (MNW) package was adopted to simulate the 2454 non-CSG active bores within the model domain. A total number of 95 CSG extraction wells were simulated in the groundwater model using the MODFLOW Drain package, with a variable conductance that aimed at matching the predicted volumes of extracted water and achieved the target pressure heads.

Although 10,000 parameter combinations were generated for the entire parameter space of the model sequence, only 3,877 were successfully evaluated within the operational constraints of the Assessment. Recharge, drainage conductance and riverbed conductance were found to be the three most sensitive parameters for predicting pressure heads in layer 1. The drain conductance of the CSG wells, the storage coefficient and hydraulic conductivity of layer 6 controlled the amount of water that could potentially be produced from the depressurisation process. As a result, these parameters had a large impact on the drawdown predictions as they greatly influence the stress imposed on the system. Among the 3877 successful model runs, realisation 842 was deemed to be the most representative, with a drawdown prediction that compared well with the Metgasco modelling results. The predicted median change in groundwater level due to the additional coal resource development was less than 0.01 m, with a 95th percentile that did not exceed 1 m. The current model has shown that the overall potential impact of the additional coal resource development can be deemed to be very minor with a very low probability of exceeding trigger thresholds specified in the NSW aquifer interference policy.

Predictions of drawdown can inform the assessment of direct impacts on groundwater-dependent assets, such as groundwater-dependent ecosystems (ecological asset), or groundwater bores used for stock, irrigation and domestic purposes (economic asset). The outputs of the numerical groundwater model can produce contours of the probability for exceeding certain drawdown thresholds. On the other hand, predictions of the exchange fluxes between the surface water and groundwater systems can inform the assessment of indirect impacts on surface water-dependent assets. This flux, which directly affects the baseflow component in surface water features, is input into the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) to quantify changes in relevant hydrological response variable at model nodes associated with surface-water-dependent assets.

The outcomes of the modelling exercise described in this product enables one to assess the level of risk associated with each asset that is potentially impacted either directly or indirectly by the CSG development. These could take the following forms: direct impact on an economic asset is: 'there is a X% chance that Y% of domestic bores in a certain area will have a drawdown of Z m or more'; an indirect impact on a surface-water-dependent asset is: 'there is a X% chance that the number of no-flow days will increase from Y days/year to Z days/year'.

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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.

additional coal resource development: all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012

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 bores and springs

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.

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

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

component: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a coal seam gas (CSG) operation or coal mine. For example, components during the development life-cycle stage of a coal mine include developing the mine infrastructure, the open pit, surface facilities and underground facilities. Components are grouped into life-cycle stages.

conceptual model: abstraction or simplification of reality

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

connectivity: a descriptive measure of the interaction between water bodies (groundwater and/or surface water)

context: the circumstances that form the setting for an event, statement or idea

cumulative impact: for the purposes of bioregional assessments, the total change in water resources and water-dependent assets resulting from coal seam gas and coal mining developments when all past, present and reasonably foreseeable actions that are likely to impact on water resources are considered

dataset: a collection of data in files, in 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).

derived dataset: a dataset that has been created by the Bioregional Assessment Programme

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

discharge: water that moves from a groundwater body to the ground surface or surface water body (e.g. a river or lake)

drawdown: a lowering of the groundwater level (caused, for example, by pumping). In the bioregional assessment (BA) context this is reported as the difference in groundwater level between two potential futures considered in BAs: baseline coal resource development (baseline) and the coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD). Drawdown under the baseline is relative to drawdown with no coal resource development; likewise, drawdown under the CRDP is relative to drawdown with no coal resource development.

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

groundwater system: see water system

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

hydrological response variable: a hydrological characteristic of the system that potentially changes due to coal resource development (for example, drawdown or the annual streamflow volume)

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 landscape class: for bioregional assessment (BA) purposes, an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. They are present on the landscape across the entire BA subregion or bioregion and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of ecosystem assets.

likelihood: probability that something might happen

Monte Carlo simulation: a simulation technique involving random sampling of each probability distribution within the model to produce large number of plausible scenarios. Each probability distribution is sampled in a manner that reproduces the distribution's shape. The distribution of the values calculated for the model outcome therefore reflects the probability of the values that could occur.

permeability: the measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.

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

probability distribution: the probability distribution of a random variable specifies the chance that the variable takes a value in any subset of the real numbers. It allows statements such as 'There is a probability of x that the variable is between a and b'.

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

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

riverbed conductance: a parameter used in the river package of MODFLOW. It is defined as the result of the product of hydraulic conductivity of the riverbed materials and the area (width times the length) of the river in the cell, divided by the vertical thickness of the riverbed materials.

runoff: rainfall that does not infiltrate the ground or evaporate to the atmosphere. This water flows down a slope and enters surface water systems.

sensitivity: the degree to which the output of a model (numerical or otherwise) responds to uncertainty in a model input

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

spring: a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water. Typically, it represents the point at which the watertable intersects ground level.

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

transparency: a key requirement for the Bioregional Assessment Programme, achieved by providing the methods and unencumbered models, data and software to the public so that experts outside of the Assessment team can understand how a bioregional assessment was undertaken and update it using different models, data or software

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.

unconfined aquifer: an aquifer whose upper water surface (watertable) is at atmospheric pressure and does not have a confining layer of low-permeability rock or sediment above it

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

water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

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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