Australian Government

BIOREGIONAL ASSESSMENTS

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

Groundwater numerical modelling for the Galilee subregion

Product 2.6.2 for the Galilee subregion from the Lake Eyre Basin Bioregional Assessment

2018

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.

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Authorship is listed in relative order of contribution.

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Artesian Spring Wetland at Doongmabulla Nature Refuge, Queensland, 2013

Credit: Jeremy Drimer, University of Queensland

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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 in response to likely coal resource development in the Galilee subregion after December 2012. First, the methods are summarised and existing models reviewed, followed by details regarding the development of the groundwater flow model. The product concludes with probabilistic predictions of hydrological change, including uncertainty analysis and a discussion of model limitations, opportunities and conclusions.

A bioregional assessment (BA) considers two potential futures:

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

The difference in results between CRDP and baseline is the change that is primarily reported in a 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.

In the Galilee subregion, there are no coal resource developments in the baseline as there were no commercially operating coal mines as at December 2012. The CRDP includes 14 coal developments and 3 CSG projects. Sufficient information for numerical modelling is available for only 7 of the 14 coal developments. The results reported in this product relate to these seven developments which target the upper Permian coal measures near the central eastern margin of the Galilee subregion: Hyde Park, China Stone, Carmichael, Kevin's Corner, Alpha, China First and South Galilee.

Groundwater modelling for the Galilee subregion follows the companion submethodology M07 (as listed in Table 1) for groundwater modelling. A review of the existing groundwater models identified that only the Galilee Basin hydrogeological (GBH) model (Turvey et al. 2015) was able to simulate the hydrological change of all coal resource developments modelled in the CRDP. This complex numerical model incorporates the whole of the Galilee Basin, and parts of the overlying Eromanga Basin and Cenozoic sediments. It utilises input data from the Galilee subregion BA. While effective at simulating hydrological change, this model requires further refinement to enhance its predictive capacity. The model's complexity and associated computational demand mean that in its current form, it cannot be integrated in the probabilistic uncertainty analysis framework designed for BA as outlined in companion submethodology M09 (as listed in Table 1).

A groundwater analytic element model (referred to as GW AEM) was designed and used specifically for this bioregional assessment to predict changes in groundwater levels at specific model nodes, resulting from the cumulative impact of pumping to dewater mines modelled in the

Galilee CRDP. Estimated groundwater extraction rates from the seven coal projects were included in the numerical modelling to predict changes in groundwater level at 47 model nodes (points in the landscape where water-related impacts on assets are assessed). All mine developments are situated along the eastern margin of the model domain. The GW AEM generated predicted areas of the maximum difference in drawdown between the CRDP and baseline, due to additional coal resource development (*dmax*) and time to maximum change (*tmax*) at the model nodes; these are the key metrics used to assess impacts. Median change in surface water – groundwater flux is also reported.

The GW AEM simulates a simplified hydrostratigraphic model representing the upper Galilee Basin sequence and overlying Cenozoic cover, along the eastern margin of the subregion in the vicinity of CRDP mines. The hydrogeology of the upper Galilee Basin sequence is conceptualised as a series of alternating aquifers and aquitards, outcropping on the Galilee Basin's eastern margin, which gently dip to the west. This sequence comprises the following hydrostratigraphic units, listed in order from youngest to oldest: the Clematis Group aquifer, Rewan Group aquitard, upper Permian coal measures partial aquifer and the Joe Joe Group aquitard. The model excludes the early Jurassic to late Cretaceous Eromanga Basin sequence, which includes the Hutton Sandstone and Hooray Sandstone and Winton-Mackunda formation aquifers. The Cenozoic cover is represented as the top-most layer in the GW AEM.

The only surface water – groundwater interaction included in the model is with the main channel of the Belyando River. In the model, the Belyando River is the only river system identified as a regional discharge area, while its tributaries can be considered maximally losing.

The GW AEM predictions show that model nodes associated with the Clematis Group have a drawdown generally less than 2 m, occurring on or after the end of the simulation period (2102). The impacts are limited to the vicinity of the Carmichael and China Stone proposed developments, which are close to the eastern-most limit of the Clematis Group. Beyond 20 km of the Carmichael and China Stone mine footprints, the probability of exceeding a drawdown of 0.2 m is generally less than 20%.

The predicted *dmax* in the upper Permian coal measures is generally in excess of 5 m throughout the model domain. At a distance of more than 100 km west of the footprints of all mines in the CRDP, the probability of exceeding 5 m drawdown is still in excess of 20%. However, large drawdowns in the upper Permian coal measures are very unlikely to propagate vertically due to the hydraulic characteristics of overlying units.

The median change in surface water – groundwater flux at the end of the simulation period is close to 0.6% of baseflow (noting at times the stream does not flow) at Belyando Crossing, as estimated in companion product 2.1-2.2, with the 5th percentile 0.1% and the 95th percentile close to 2.4%. This flux is integrated into the surface water model to evaluate the effect on different aspects of the total streamflow.

While a formal comparison of the probabilistic outcomes of the GW AEM with the deterministic results of the GBH model is not possible, the GBH results are consistent with the results of the GW AEM and the estimated drawdowns of the GBH are close to the 95th percentile of *dmax* predicted by the GW AEM.

The qualitative uncertainty analysis of the GW AEM assumptions highlights that the assumptions with the highest potential to affect predictions are the implementation of the CRDP, the representation of the Cenozoic and alluvial aquifer system and the conceptualisation of the Belyando River. As an example, the effect of some different conceptualisations for the Cenozoic and alluvial aquifer system on results are detailed as part of the uncertainty analysis.

The main opportunities to improve upon the modelling presented in this product lie in expanding the knowledge base of the shallow aquifer system and the connection status of the river system. Further development of the GBH model and integration of this model in a probabilistic uncertainty analysis framework will allow analysis of several of the simplifying assumptions underpinning the GW AEM which will likely result in more robust and less conservative predictions of hydrological change.

The results from this groundwater modelling are used as inputs in the impact and risk analysis (product 3-4).

Contents

Executive summary ... i

Contributors to the Technical Programme ... x

Acknowledgements ... xii

Currency of scientific results ... xiii

Introduction ... 1

The Bioregional Assessment Programme ... 1
Methodologies ... 3
Technical products ... 5
About this technical product ... 8
References ... 8

2.6.2.1 Methods ... 10

2.6.2.1.1 Background and context ... 10
2.6.2.1.2 Groundwater numerical modelling ... 12
References ... 21
Datasets ... 24

2.6.2.2 Review of existing models ... 25

2.6.2.2.1 Alpha and Kevin's Corner model review ... 29
2.6.2.2.2 Carmichael model review ... 31
2.6.2.2.3 China First model review ... 32
2.6.2.2.4 China Stone model review ... 33
2.6.2.2.5 South Galilee model review ... 34
2.6.2.2.6 Galilee Basin hydrogeological model review ... 35
2.6.2.2.7 Suitability of existing groundwater models ... 43
References ... 45
Datasets ... 47

2.6.2.3 Model development ... 49

2.6.2.3.1 Objectives ... 50
2.6.2.3.2 Hydrogeological conceptual model ... 50
2.6.2.3.3 Design and implementation ... 58
2.6.2.3.4 Model code and solver ... 58
2.6.2.3.5 Geometry and hydrostratigraphy ... 59
References ... 61
Datasets ... 62

2.6.2.4 Boundary and initial conditions ... 63
2.6.2.4.1 Initial conditions ... 63
2.6.2.4.2 Lateral ... 63
2.6.2.4.3 Recharge and evapotranspiration ... 64
2.6.2.4.4 Surface water – groundwater interactions ... 65
References ... 66
Datasets ... 67
2.6.2.5 Implementation of the coal resource development pathway ... 69
2.6.2.5.1 Coal mines ... 69
2.6.2.5.2 Coal seam gas wells ... 71
References ... 71
Datasets ... 72
2.6.2.6 Parameterisation ... 73
References ... 76
Datasets ... 76
2.6.2.7 Observations and predictions ... 77
2.6.2.7.1 Observations ... 77
2.6.2.7.2 Predictions ... 77
2.6.2.7.3 Sensitivity analysis ... 82
References ... 89
Datasets ... 89
2.6.2.8 Uncertainty analysis ... 91
2.6.2.8.1 Quantitative uncertainty analysis ... 91
2.6.2.8.2 Qualitative uncertainty analysis ... 106
References ... 118
Datasets ... 120
2.6.2.9 Limitations and conclusions ... 121
2.6.2.9.1 Data gaps and opportunities to reduce predictive uncertainty ... 121
2.6.2.9.2 Limitations ... 122
2.6.2.9.3 Conclusions ... 123
References ... 124
Glossary ... 126

Figures

Figure 1 Schematic diagram of the bioregional assessment methodology 2

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment 6

Figure 3 Schematic representation of proposed coal resource development operations in the Galilee subregion 13

Figure 4 Points for which drawdown is required to be estimated in the Galilee subregion (see Table 4 for point types) 15

Figure 5 Model sequence for the Galilee subregion 18

Figure 6 Extents of existing groundwater numerical models in the Galilee subregion 29

Figure 7 Cross-section showing the model domain in relation to the Galilee and Eromanga geological basins in the Galilee subregion 52

Figure 8 Overburden thickness to top of upper Permian coal measures and relationship to Eromanga Basin boundary in the Galillee subregion 53

Figure 9 (a) hydrogeological conceptual cross-section, (b) corresponding cross-section of the groundwater analytic element model for the Galilee subregion 56

Figure 10 Lateral and internal boundary conditions and model nodes for the groundwater analytic element model (GW AEM) for the Galilee subregion 64

Figure 11 Time series of drawdown at selected model nodes (a) GAL_021 Carmichael groundwater-dependent ecosystem (GDE) overlying Clematis Group, (b) GAL_037 Doongmabulla Springs and (c) GAL_043 Mellaluka Springs for parameter combination 1980 81

Figure 12 Boxplots of Galilee subregion analytic element model parameter values from the posterior parameter distributions giving rise to *dmax* values less and greater than 0.2m for model node GAL_021 Carmichael groundwater-dependent ecosystem (GDE) overlying Clematis Group 83

Figure 13 Boxplots of Galilee subregion analytic element model parameter values from the posterior parameter distributions giving rise to dmax less than and greater than 50 m for model node GAL_043, Mellaluka Springs 85

Figure 14 Sensitivity indices for all parameter–model node combinations for dmax, grouped per model layer 86

Figure 15 Sensitivity indices for surface water – groundwater flux of the Belyando River for each year of simulation 88

Figure 16 Histograms of posterior parameter distributions 92

Figure 17 Convergence of 5th, 50th and 95th percentile of additional drawdown at selected model nodes of the Galilee subregion 94

Figure 18 Probability of additional drawdown exceeding (a) 5 m in the upper Permian coal measures, (b) 0.2 m in the Clematis Group aquifer and (c) 0.2 m in the Cenozoic and alluvial aquifer 95

Figure 19 (a) additional drawdown (*dmax*) and (b) year of maximum change (*tmax*) at the model nodes associated with the Cenozoic and alluvium hydrostratigraphic unit in the Galilee subregion 97

Figure 20 (a) additional drawdown (*dmax*) and (b) year of maximum change (*tmax*) at the model nodes associated with the Clematis Group hydrostratigraphic unit in the Galilee subregion 99

Figure 21 (a) additional drawdown (*dmax*) and (b) year of maximum change (*tmax*) at the model nodes associated with the upper Permian coal measures hydrostratigraphic unit in the Galilee subregion 101

Figure 22 5th, 50th and 95th percentile of change in surface water – groundwater flux for the Belyando River 102

Figure 23 Contour maps of the 5th, 50th and 95th percentile of additional drawdown (top row) and year of maximum change (bottom row) in the upper Permian coal measures 104

Figure 24 Drawdown in layer 12 (Betts Creek beds formation seam E) in 2058 105

Figure 25 Drawdown in individual coal seams (CS) and interburden (IB) compared to drawdown in a single equivalent layer after 30 years of pumping 110

Figure 26 Comparison of drawdown in an unconfined aquifer due to a constant change in groundwater level of 9.9 m at x=zero metres after 10 years, simulated with an analytic element model (AEM) and a MODFLOW model (MODFLOW) 113

Figure 27 Illustration of alternative conceptualisation in which the constant drawdown boundary in the Cenozoic and Quaternary sediments is removed 115

Figure 28 Boxplots of *dmax* for the original and alternative conceptualisation at (a) GAL_021 Carmichael GDE overlying Clematis Group, (b) GAL_037 Doongmabulla Springs and (c) GAL_043 Mellaluka Springs 116

Tables

Table 1 Methodologies 4

Table 2 Technical products delivered for the Galilee subregion 7

Table 3 Capability requirements of the groundwater numerical modelling approach in the Galilee subregion 14

Table 4 Summary of points for which drawdown due to coal resource development in the Galilee subregion are required 16

Table 5 Summary of available groundwater models within the Galilee subregion 27

Table 6 Model layer thickness and corresponding hydrostratigraphic groupings (after Turvey et al., 2015) 37

Table 7 Stratigraphic units and marker beds used to define subdivision of the upper Permian coal measures 38

Table 8 Steady-state calibration statistics (after Turvey et al., 2015) 40

Table 9 Transient model calibration statistics (after Turvey et al., 2015) 41

Table 10 High level overview of differences and similarities between Galilee Basin hydrogeological (GBH) model and analytic element model approach 45

Table 11 Hydrostratigraphy and corresponding model layers used for the groundwater analytic element model (GW AEM) for the Galilee subregion 60

Table 12 Coal resource development pathway (CRDP) mines included in the groundwater analytic element model (GW AEM) and anticipated groundwater production rates from upper Permian coal measures partial aquifer 70

Table 13 Parameter distributions used for the groundwater analytic element model (GW AEM) for the Galilee subregion 74

Table 14 Model nodes for which drawdown due to coal resource development in the Galilee subregion was calculated with the groundwater analytic element model 79

Table 15 Qualitative uncertainty analysis as used for the Galilee subregion 107

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

Currency of scientific results

The modelling results contained in this product were completed in February 2016 using the best available data, models and approaches available at that time. The product content was completed in November 2017.

All products in the model-data analysis, impact and risk analysis, and outcome synthesis (see Figure 1) were published as a suite when completed.

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 is 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, has undertaken 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.

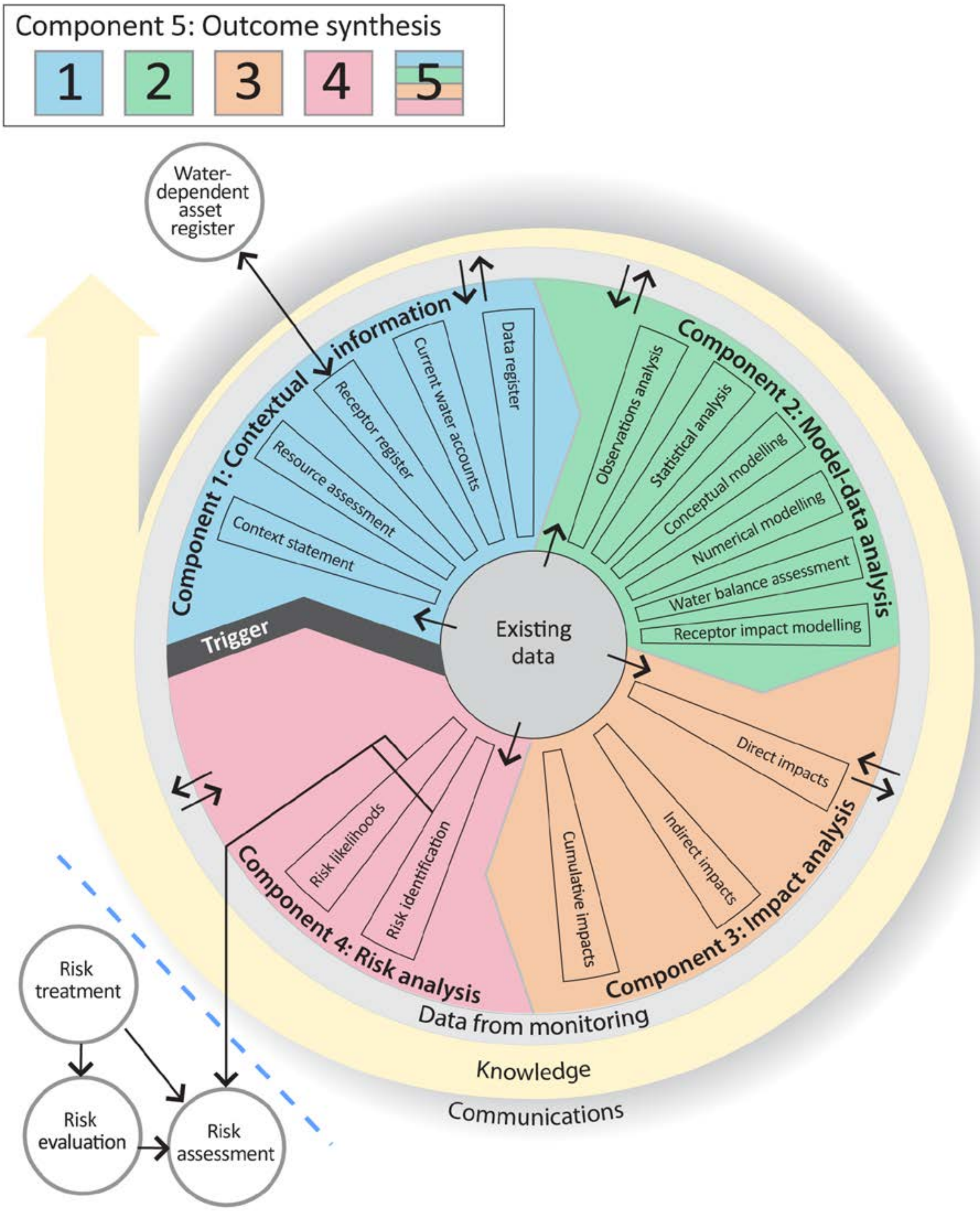


Figure 1 Schematic diagram of the bioregional assessment methodology

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), in the first instance, to 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.

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.

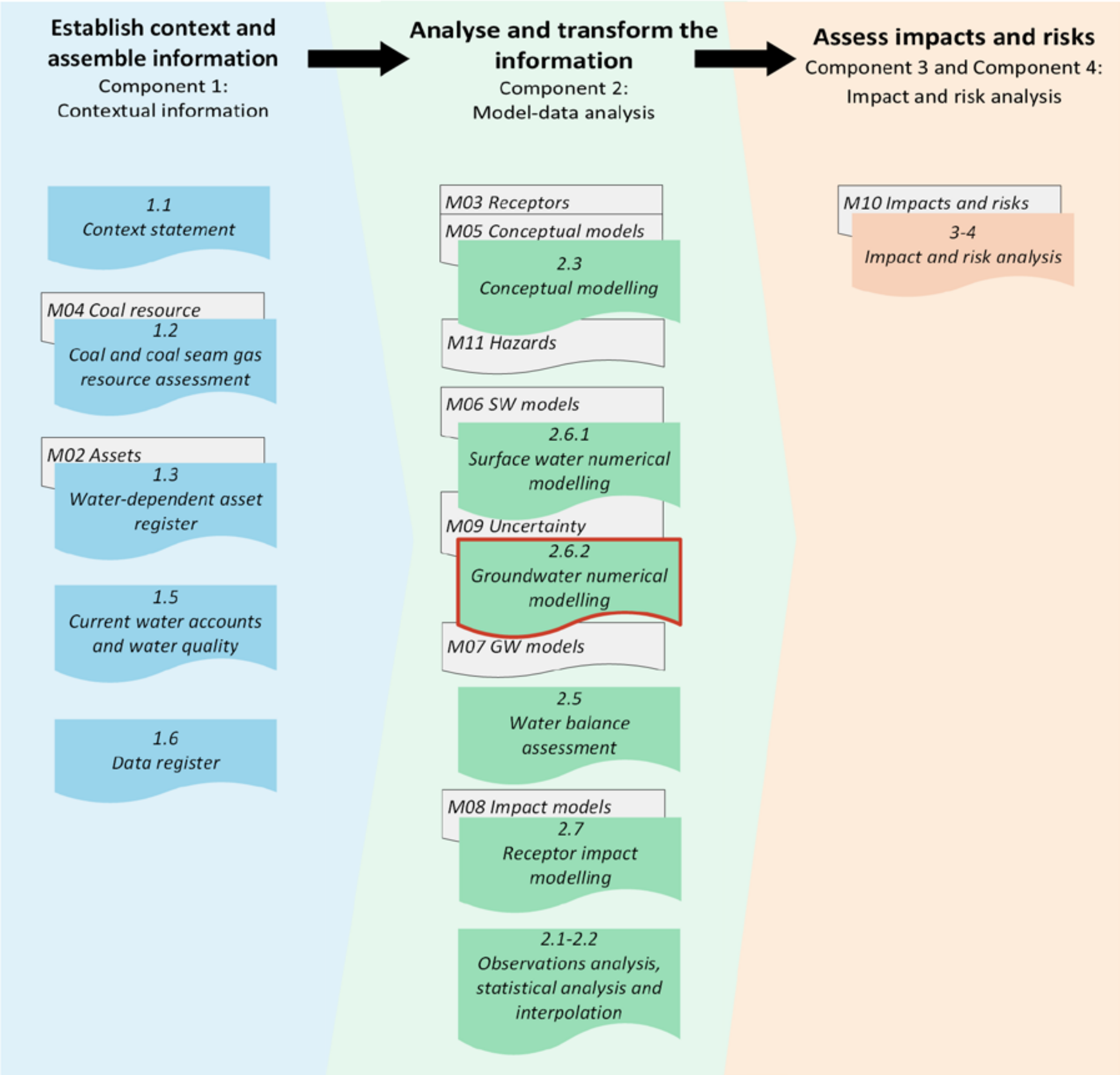


Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Galilee subregion

For each subregion in the Lake Eyre Basin 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 product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical 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 Galilee subregion	1.1	Context statement	2.5.1.1, 3.2	PDF, HTML
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3	PDF, HTML
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4	PDF, HTML, register
	1.5	Current water accounts and water quality	2.5.1.5	PDF, HTML
	1.6	Data register	2.5.1.6	Register
Component 2: Model-data analysis for the Galilee subregion	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	PDF, HTML
Component 3 and Component 4: Impact and risk analysis for the Galilee subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Galilee subregion	5	Outcome synthesis	2.5.5	PDF, HTML

[a]The types of products are as follows:
- 'PDF' indicates a PDF document that is developed by the Lake Eyre Basin 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.

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

About this technical product

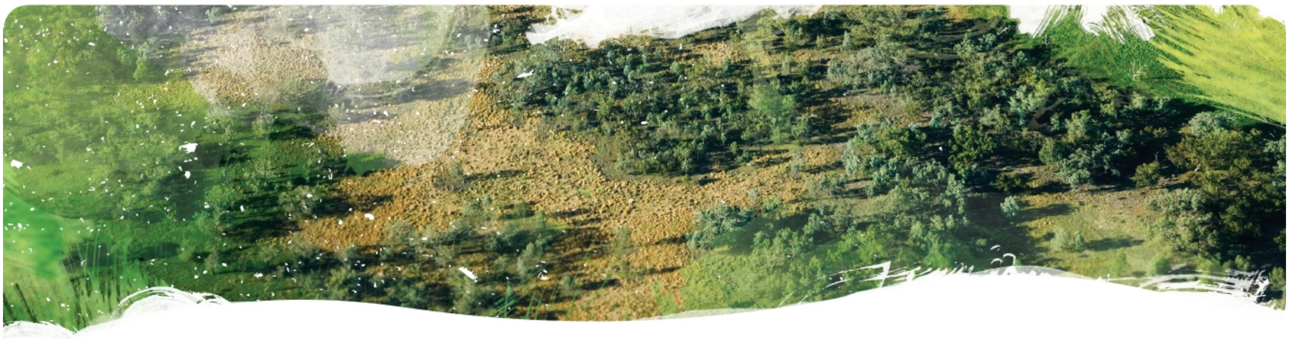
The following notes are relevant only for this technical product.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 140.0° East for the Lake Eyre Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://www.bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). 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.
- 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.

References

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 25 June 2018, 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 25 June 2018, 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 Galilee subregion

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 Galilee subregion.

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

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

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

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

This product reports results for only those developments in the baseline and CRDP that can be modelled. Results generated at model nodes are interpolated to estimate potential hydrological changes for groundwater. Similarly, potential hydrological changes are estimated for surface water in product 2.6.1 (surface water numerical modelling). Product 3-4 (impact and risk analysis) then reports impacts on landscape classes and water-dependent assets arising from these hydrological changes.

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

To probabilistically simulate dewatering of the upper Permian coal measures in the Galilee subregion due to potential large coal mining operations identified in the coal resource development pathway (CRDP), an analytic element groundwater model (referred to as GW AEM) has been developed to estimate drawdown within the upper Permian coal measures and its propagation into the overlying Rewan Group, Clematis Group and Cenozoic cover.

The methods section provides a high-level overview of the conceptualisation, the modelling approach, the interaction with the surface water model and the uncertainty analysis in relation to the other companion products for this subregion and the submethodologies.

2.6.2.1.1 Background and context

The groundwater modelling in bioregional assessments (BAs) 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 CRDP relative to the baseline at specified locations in the landscape to inform the impact and risk analysis reported in product 3-4 (impact and risk analysis).

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 or 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 that changes are additive, which is known as the principle of superposition (Reilly et al., 1987). The biggest implication of this is that the change to the system due to a change in stress is largely independent of current or initial conditions. The most well-known example is the interpretation of a pumping test; the drawdown is only a function of the hydraulic properties of the aquifer, not of the initial conditions.

The principle of superposition enables the modelling to focus on the change in hydrogeological stress and the hydraulic properties, rather than on reproducing historical conditions or predicting future state variables of the system, such as groundwater levels or fluxes.

The probabilistic aspect of the analysis implies that modelling does not provide a single best estimate of the change, but rather an ensemble of estimates based on user-defined probability distributions of input parameters. This allows results to be presented alternatively as a probability of exceeding a threshold drawdown (e.g. 2 m) or as a percentile of drawdown (e.g. 95th percentile).

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

May 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 2.6.2.8.2 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 (e.g. using a wide parameter range when little measured information exists). 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 Galilee subregion (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 products for this subregion 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 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, 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 main geological domains of interest in the Galilee subregion are the Galilee Basin, the Eromanga Basin and the Cenozoic to Quaternary cover sediments and alluvial deposits (refer to companion product 1.1 for the Galilee subregion (Evans et al., 2014)). The Galilee Basin stratigraphic units crop out in the east of the subregion (Figure 3) and contain the main target formations for coal development: Betts Creek beds, Bandanna Formation and Colinlea Sandstone. For BAs these units are collectively known as the upper Permian coal measures. The Rewan Group, Clematis Group and Moolayember Formation separate the upper Permian coal measures from the Jurassic to Cretaceous strata of the Eromanga Basin. The upper Permian coal measures are underlain by the Joe Joe Group. The aquifers hosted in these stratigraphic units are mostly confined and feed several springs as well as providing water to public water supply and stock and domestic bores. The Cenozoic and alluvial sediments, not shown in Figure 3, contain watertable aquifers, some of which are perched (refer to companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a).

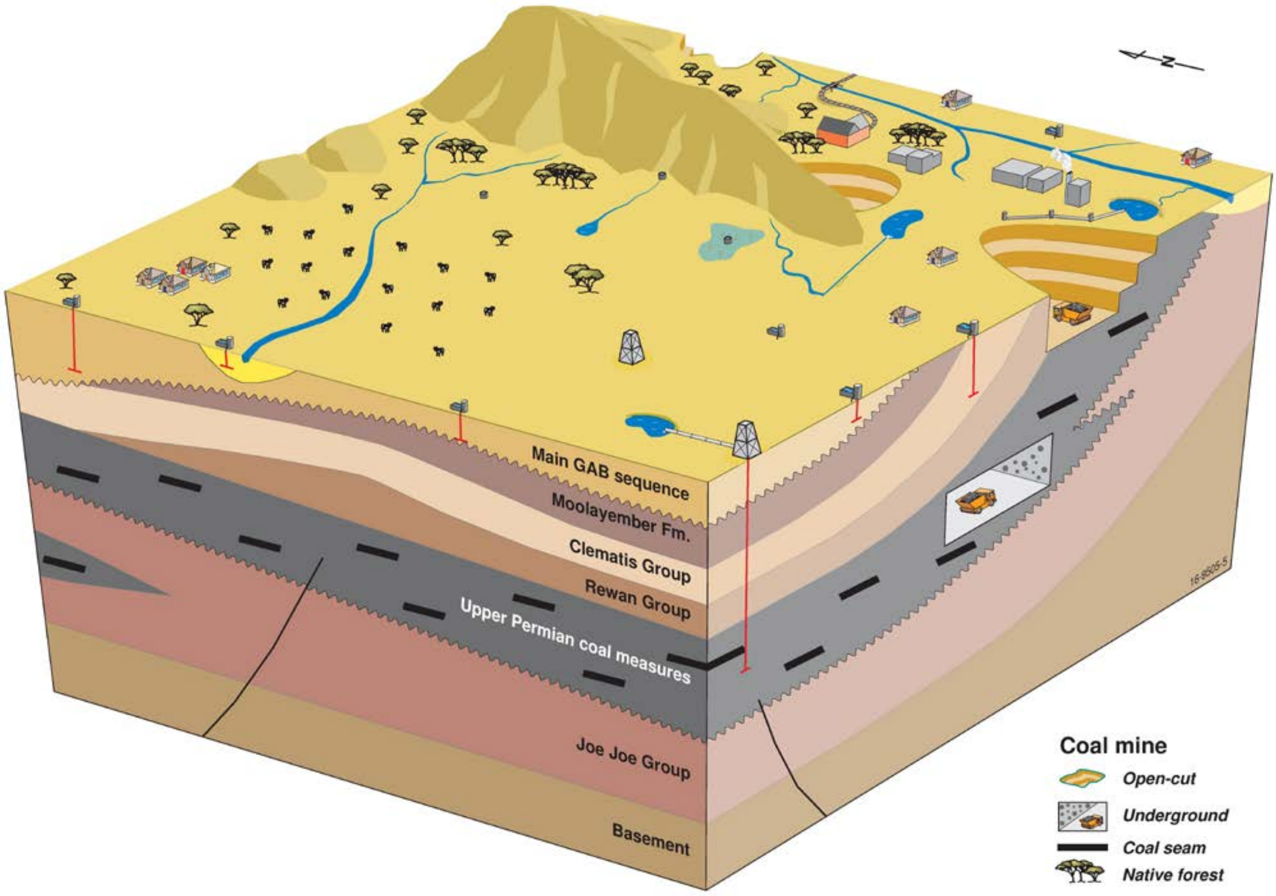


Figure 3 Schematic representation of proposed coal resource development operations in the Galilee subregion

GAB = Great Artesian Basin; Fm = formation
Detailed surface geology is provided in Figure 4.

The coal developments included in the CRDP are all situated in the east of the Galilee Basin due to the proximity of the upper Permian coal measures to the surface (refer to companion product 2.3 for the Galilee subregion (Evans et al., 2018b)). The proposed mining operations are therefore limited to the Belyando river basin, a headwater catchment of the larger Burdekin river basin (companion product 1.1 for the Galilee subregion (Evans et al., 2014)).

The conceptual model for the Galilee subregion indicates that large coal mining operations included in the CRDP will result in dewatering of the upper Permian coal measures in the vicinity of the operations (Figure 3 and companion product 2.3 for the Galilee subregion (Evans et al., 2018b)). This dewatering has the potential to cumulatively impact regional groundwater systems due to lateral and vertical propagation of groundwater level and pressure reductions, both within the upper Permian coal measures and within adjacent hydrostratigraphic units.

Coal mining may potentially affect surface water runoff as rainfall is intercepted by mine workings and therefore no longer contributes to streamflow. Also, coal mining may cause a depressurisation of or drawdown in aquifers interacting with the surface water features, which then indirectly may alter streamflow.

As discussed in detail in Section 2.3.4.1 in companion product 2.3 (Evans et al., 2018b), the CRDP in the Galilee subregion consists of 17 proposed new coal and coal seam gas (CSG) resource development projects. For only seven of these projects is sufficient information available to be included in the modelling (Figure 4). These are all coal projects: Alpha, Carmichael, China First, China Stone, Kevin's Corner, South Galilee and Hyde Park. No CSG developments are included in the modelling.

As outlined in submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016), different model types and model codes are chosen in BA, depending on the specific requirements of each subregion. The main goal of each groundwater model in BA remains, however, to deliver spatially explicit model outputs that are used as inputs to other BA models, including surface water modelling, uncertainty analysis and receptor impact modelling, and to directly evaluate change in water resources. Table 3 lists the criteria a groundwater model in BA needs to satisfy to be considered fit-for-purpose for BA. Beneath the table, these fit-for-purpose criteria are discussed briefly for the numerical modelling approach taken in the Galilee subregion. The remainder of this product describes in greater detail the numerical modelling, and the underlying assumptions and their effect on predictions.

Table 3 Capability requirements of the groundwater numerical modelling approach in the Galilee subregion

Fit-for-purpose assessment criteria	Components
1. Prediction of hydrological response variables	Probabilistic estimates of hydrological change at model nodes
	Integration with receptor impact modelling
	Integration with surface water numerical models
2. Design and construction	Modelling objectives stated
	Model confidence level
	Modelling approach
3. Integration with sensitivity and uncertainty analysis workflow	Formally address uncertainty
	Parameterisation
	Convergence
4. Water balance components	Conceptual model agreement
5. Transparent and reproducible model outputs	Model data repository
	Model code and executables
	Pre- and post-processing scripts

2.6.2.1.2.1 Prediction of hydrological response variables

The objective of the numerical modelling undertaken as part of a BA is to probabilistically assess hydrological changes arising from coal resource development at water-dependent assets and model nodes (see companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016)). The groundwater and surface water modelling predicts changes in hydrological response variables, the hydrological characteristics of the system or landscape class that potentially change due to coal resource development. These hydrological response variables are the input for receptor impact models that will evaluate how the change in hydrology and hydrogeology results in a change in the economic, social or ecological value of assets.

The model is required to estimate drawdowns caused by the coal resource developments outlined in the modelled CRDP at model nodes in the upper Permian coal measures, the Clematis Group and the Cenozoic and Quaternary cover sediments. Figure 4 shows the locations of these points and their hydrostratigraphic unit. Table 4 conveys the same information, together with a short description of each point, its water source and the model layer the point is assigned to.

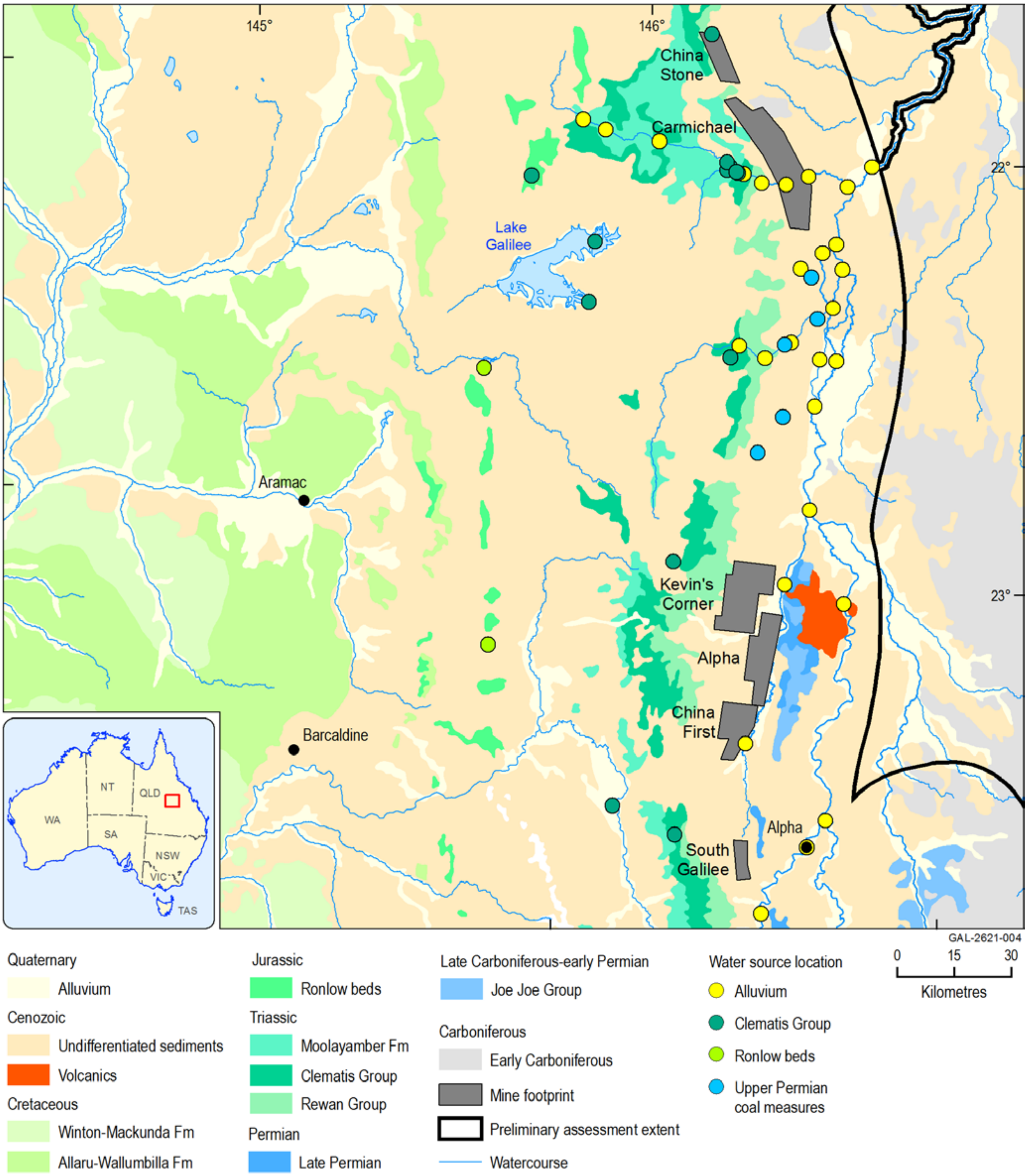


Figure 4 Points for which drawdown is required to be estimated in the Galilee subregion (see Table 4 for point types)

Data: Bioregional Assessment Programme (Dataset 1)

Table 4 Summary of points for which drawdown due to coal resource development in the Galilee subregion are required

	Alluvium	Ronlow beds	Clematis Group	Upper Permian coal measures	Total
GDE	26	0	4	0	**30**
GW licence	0	0	3	2	**5**
Monitoring bore	0	0	1	0	**1**
Spring	0	2	4	3	**9**
TWS	1	0	1	0	**2**
Total	**27**	**2**	**13**	**5**	**47**

GDE = groundwater-dependent ecosystem; GW licence = groundwater extraction licence; TWS = town water supply

Model nodes were positioned to represent one or more identified water-dependent assets, such as clusters of groundwater bores, groundwater-dependent ecosystems, stream confluences and river reaches.

Most model nodes are located in the alluvium, the majority of which are associated with groundwater-dependent ecosystems with one model node assigned to a town water supply. The Ronlow beds, which are part of the Eromanga Basin, have two model nodes associated with springs. There are 13 model nodes associated with the Clematis Group and they include groundwater-dependent ecosystems, licensed groundwater extractions, monitoring bores, springs and the Jericho town water supply. The upper Permian coal measures have five model nodes, which are two groundwater extraction licences and three springs. There are no model nodes associated with the main aquitard units in the modelling domain, such as the Rewan Group, as the groundwater model used in this assessment (an analytic element model) does not provide estimates of drawdown for aquitards.

The hydrological response variables for groundwater are drawdown (*dmax*) and year of maximum change (*tmax*) at model nodes, where drawdown is defined as the difference in groundwater level between the baseline and CRDP, due to additional coal resource development.

For surface water, nine hydrological response variables are defined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) at 61 nodes along the stream network (companion product 2.6.1 for the Galilee subregion (Karim et al., 2018)).

Changes in the groundwater system can propagate to changes in the surface water system, which means that simulating the change in hydrological response variables at the various model nodes necessitates the development of an integrated surface water – groundwater modelling approach. The groundwater and surface water, however, operate at very different spatial and temporal scales. The surface water obviously is bound to river channels and floodplains. Streamflow is very responsive to individual rainfall events, requiring at least a daily temporal resolution to capture its ephemeral nature. Groundwater dynamics in the alluvial and Cenozoic deposits are mostly local and controlled through interactions with surface events, such as high rainfall or flooding (Section 2.1.3.2.2 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)). Capturing this dynamic in a numerical model necessitates at a minimum a monthly resolution.

The deeper hydrogeological units hosted in the Eromanga and Galilee basins are much more extensive, both horizontally and vertically. The groundwater dynamics are very slow. In the outcrop zones of the units, there are indications that groundwater levels are influenced by recharge events. In the deeper, confined parts of the hydrogeological units there is no indication that groundwater dynamics are affected by recharge and discharge processes. Simulating groundwater flow in the deeper hydrogeological units requires a spatially extensive model, but a high temporal resolution is not essential.

While fully coupled surface water – groundwater model codes are available (e.g. Hydrogeosphere, Brunner and Simmons, 2012), their use was not deemed to be justified within BA due to the high data requirements for parameterisation and due to operational constraints. The latter relates mainly to the general numerical instability of such models and long run times which would severely limit a probabilistic uncertainty analysis that requires the models to be evaluated 100s of times with vastly different parameter sets.

For the Galilee subregion, a pragmatic coupling of two models was developed, consisting of a regional groundwater model to simulate the change to the groundwater systems of the subregion and a rainfall-runoff model to simulate the change to the surface water systems of the subregion (Figure 5). The individual models have different spatial and temporal resolution which requires a set of customised processing steps to up or downscale model data to allow the models to be linked.

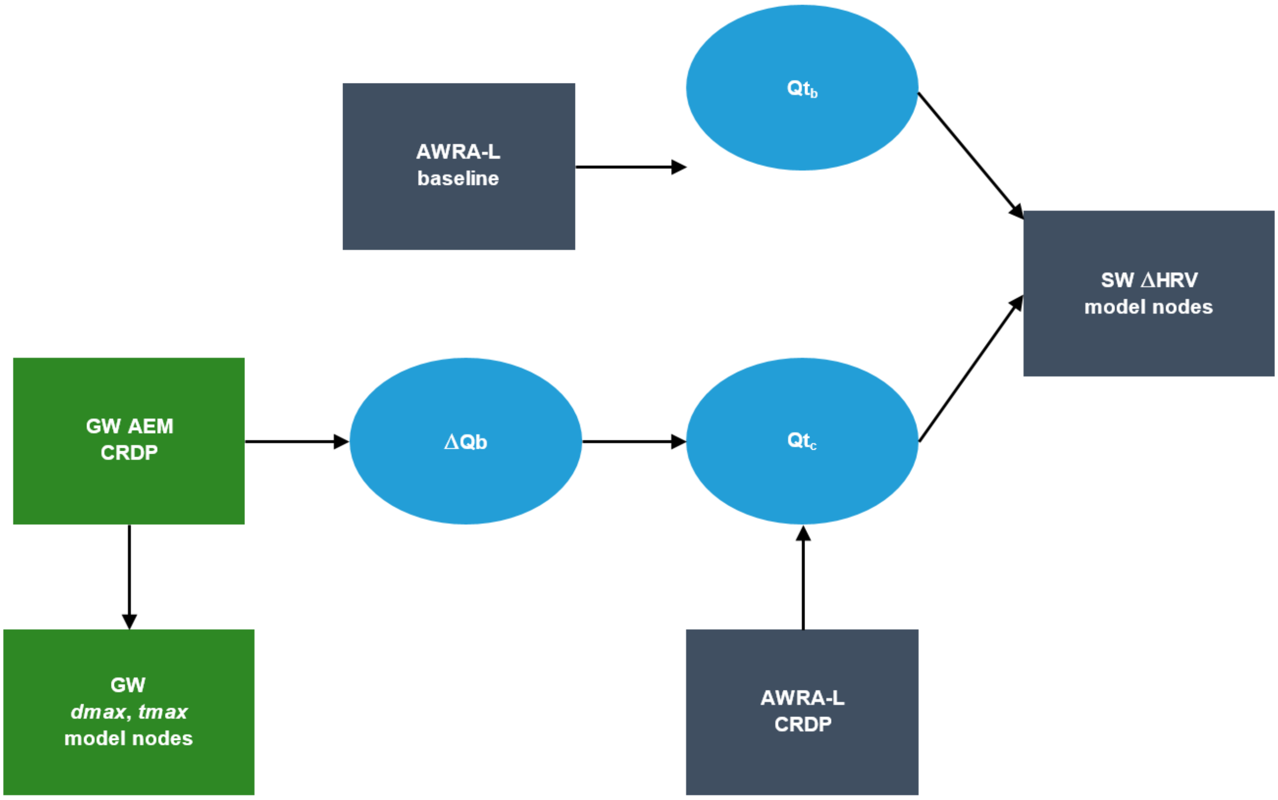


Figure 5 Model sequence for the Galilee subregion

AWRA-L = rainfall-runoff model; *dmax* = maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs results, obtained by choosing the maximum of the time series of differences between two futures; GW = groundwater; GW AEM = regional groundwater analytic element model; ΔHRV = change in hydrological response variable; *tmax* = year of maximum change; ΔQb = change in surface water – groundwater interaction flux; Qt_b = total streamflow baseline; Qt_c = total streamflow coal resource development pathway (CRDP); SW = surface water

The regional groundwater model is an analytic element model (referred to as GW AEM), designed to simulate the change in drawdown at the points shown in Figure 4 and the change in surface water – groundwater flux. As there is no coal resource development under baseline conditions, the drawdown and change in surface water – groundwater flux due to coal development is zero. There is therefore no need for a separate baseline conditions run for the groundwater model. The change in surface water – groundwater flux simulated with the CRDP run of the analytic element model, $\Delta Qb(t)$, is taken into account in the Australian Water Resources Assessment landscape model (AWRA-L) surface water model generated streamflow. The change in a number of hydrological response variables is modelled at the model nodes. The simulation of river management or routing of streamflow through the river network with a river model is not necessary as the salient features of streamflow can be simulated solely with a rainfall-runoff model (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

The AWRA-L baseline run simulates streamflow at surface water model nodes without any active mines. The AWRA-L CRDP run simulates streamflow at the surface water model nodes incorporating the effect of approved open-cut and underground coal mines in the CRDP. The total surface water streamflow under CRDP, Qt_c, is obtained as:

$$Qt_c = \max(0, Qt_b - Qt_c - \Delta Qb) \quad (1)$$

where $Qt_b$is the total surface water flow under baseline and ΔQb is the change in surface water – groundwater flux between baseline and CRDP computed by the groundwater model.

Due to the ephemeral nature of the river system and the difference in temporal resolution between the groundwater model and the surface water model it is possible that the change in surface water – groundwater flux is larger than the total available streamflow. Streamflow under those conditions is reduced to zero. This would typically occur during periods of low flows driven by baseflow. Any further loss of baseflow due to mine dewatering may result in the river running dry. Note that many of the smaller creeks and rivers are maximally losing. The surface water – groundwater flux for such systems is independent of the groundwater level and can therefore not be affected by drawdown.

The time series of Qt_b and Qt_c are summarised in the nine hydrological response variables to highlight different aspects of the hydrograph. These hydrological response variables will inform the receptor impact models for the model nodes associated with surface water.

2.6.2.1.2.2 Design and construction

According to the *Australian groundwater modelling guidelines* (Barnett et al., 2012), it is essential to design and construct the groundwater model in function of clearly stated objectives and to provide a model confidence level. The objective of the modelling is explicitly stated in the previous section. The model confidence level is an a priori categorisation of a groundwater model to reflect its predictive capability in function of the model complexity, prediction timeframe and data availability. As clarified in submethodology M07 (Crosbie et al., 2016), the groundwater models in the Bioregional Assessment Programme are all classified as level 1, the lowest level, as they are required to make predictions of unprecedented stresses at time frames longer than periods with data available to constrain the model.

The objectives of the modelling are not to simulate the state of groundwater in the future under baseline and coal resource development conditions, but to quantify the difference between those two futures. This is a very important nuance to the modelling objectives as it enables a number of simplifying assumptions based on the principle of superposition (Reilly et al., 1987). The principle of superposition means that for linear systems, the solution to a problem involving multiple inputs (or stresses) is equal to the sum of the solutions to a set of simpler individual problems that form the composite problem. To simulate the effect of change in stress, such as depressurisation and dewatering for coal resource development, it is therefore sufficient to only know the change in stress. It is not necessary to know the initial conditions in the aquifer or the other fluxes and stresses, provided these do not change due to the change in stress (Barlow and Leake, 2012).

The principle of superposition underpins most of the pumping test interpretations (Kruseman and de Ridder, 1994); aquifer parameters are inferred from the change in stress (pumping rate) and change in groundwater level (drawdown).

The principle of superposition is only valid for linear systems (i.e. systems where the response to a change in stress is proportional to the change in the stress). In other words, where a doubling of stress will result in a doubling of the response. In groundwater flow dynamics this condition is satisfied for confined aquifers. Unconfined aquifers are not strictly linear, as the transmissivity depends on the saturated thickness. Reilly et al. (1987) and Rassam et al. (2004) do show, however, that the concepts are still valid for mild violations of the linearity conditions. The assumption most likely to be violated when simulating dewatering of an unconfined aquifer is that the transmissivity is no longer constant as the saturated thickness decreases during dewatering. Singh and Atkins (1985) provide an overview of different analytic solutions that take into account this change in transmissivity in the context of mine dewatering. From these equations it is apparent that not accounting for changing transmissivity will lead to under estimating drawdowns in the vicinity of the mine. At greater distances from the mine, however, drawdowns will be overestimated. This is consistent with the interpretation of pumping tests, where high transmissivity results in a large, but shallow cone of depression, while a low transmissivity results in a small, but deep cone of depression (Kruseman and de Ridder, 1994). Barlow and Leake (2012) discuss the conditions for which analytical solutions are valid in the context of surface water – groundwater interaction. The principle of superposition is not valid if the connection status changes due to the stress (e.g. if the river changes from losing or gaining connected to losing disconnected). When the surface water and groundwater system is connected, the change in surface water – groundwater flux is proportional to the change in groundwater level. When the system becomes disconnected, the system is maximally losing and the flux is no longer proportional to the groundwater level (Lamontagne et al., 2014).

As such, the concept of superposition can be implemented in any groundwater modelling code, see, for example, Leake et al. (2008). The analytic element modelling code, implemented through TTim version 0.3 (Bakker, 2015), for this regional model is chosen because the scripted nature of the modelling code lends itself very well to automated changing of all aspects of the model, required for the sensitivity and uncertainty analysis (Bakker and Kelson, 2009). Another advantage is that due to the grid-independent nature of the analytic element method, the resolution of the results is not dependent on the grid discretisation as is the case for finite difference or element models. Outputs can thus be generated at any arbitrary locations within the modelling domain.

Further technical details of the conceptualisation, parameterisation and implementation are documented in the following sections of this product for the groundwater modelling and in companion product 2.6.1 for the Galilee subregion (Karim et al., 2018) for surface water modelling.

2.6.2.1.2.3 Integration with sensitivity and uncertainty analysis workflow

Companion submethodology M09 (as listed in Table 1) (Peeters et al., 2016) discusses in detail the propagation of uncertainty through numerical models in BAs. The workflow outlined in this product is tailored to numerical models with long run times and where observations of the groundwater system can be used to constrain the model parameters.

The analytic element model for the Galilee subregion has a very short run time and, because only the change in the system is simulated and not the state variables, it is not possible to use state observations, such as fluxes and groundwater levels, to constrain the model parameters through Approximate Bayesian Computation Markov chain Monte Carlo sampling of prior parameter ensembles.

These ensembles capture the range of each parameter that is deemed likely, based on the available local information and international literature. This is discussed in greater detail in the parameterisation section (Section 2.6.2.6).

The uncertainty analysis then consists of a direct sampling of these ensembles of parameter values with the analytic element model to arrive at an ensemble of predictions of additional drawdown, year of maximum change and change in surface water exchange flux.

2.6.2.1.2.4 Water balance components

A secondary objective of the numerical models is to inform the water balance assessment (companion product 2.5). The AWRA-L model produces surface water estimates of the water balance under baseline and coal resource development futures and can therefore be used in that assessment. The analytic element model, however, only simulates the change in stress due to coal resource development. Its model output therefore has no information on other components of the regional water balance such as recharge or lateral exchange fluxes.

2.6.2.1.2.5 Transparent and reproducible model outputs

An over-arching requirement of the BAs is for all model outputs to be transparent and reproducible.

The model files, including the pre- and post-processing scripts and executables, will be made available through the BA data repository.

As the evaluation of the model chain is a highly automated and scripted process, it is possible to reproduce the results reported in this document using the scripts and executables in the repository, provided the computational resources are available. Scripting the modelling process has the added advantage that it minimises the risk of human error in the data analysis.

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2.6.2.2 Review of existing models

Summary

Five numerical groundwater models have been prepared by mine proponents to assess the impacts of proposed coal mine development in the Galilee subregion. These are for Alpha and Kevin's Corner, Carmichael, China First, China Stone, and South Galilee coal projects. Most of these models simulate the impact of only one or two mines. These models are not suited for the Galilee subregion bioregional assessment (BA) as they are relatively local in scale, have varying model configurations, and are not readily available for the Bioregional Assessment Technical Programme.

The Galilee Basin hydrogeological (GBH) model is a regional numerical groundwater model that encompasses the whole of the Galilee subregion. It has been recently developed as part of a joint project between the Queensland Government and Australian Government. This complex numerical model incorporates the whole of the Galilee Basin, and parts of the overlying Eromanga Basin and Cenozoic sediments. It utilises input data compiled and generated for this BA. The predictive runs from the transient model utilises the modelled coal resource development pathway (CRDP) developed as part of this BA.

Within the operational constraints of the Bioregional Assessment Programme, it was not possible to use the GBH model in the stochastic analysis required for the probabilistic assessment of modelled groundwater change. A stochastic analysis includes ensuring numerical stability over the entire plausible range of parameter values and evaluating the model hundreds to thousands of times.

This review focuses on both local and regional-scale groundwater models developed to simulate the groundwater impacts of coal mining development in the Galilee subregion. The main goal of the review is to evaluate if any of the existing models can be used in their current form for the purpose of the BA numerical modelling or if they can be modified to suit this purpose. The requirements for BA numerical models are listed in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). These requirements do not only cover the horizontal and vertical extent of the model domain, but more importantly include stability criteria to ensure the model is suitable for stochastic analysis.

A secondary aim of the review is to provide an overview of the different conceptualisations and parameterisations of the groundwater system. This information, where suitable, will be used in the BA numerical modelling. In addition to that, the hydrological change predicted by these models will provide a frame of reference for comparison of the model results of the BA modelling.

Five groundwater numerical models have been prepared in the Galilee subregion to assess the potential for local to sub-regional hydrological changes associated with groundwater extraction by coal mines. Bleakley et al. (2014) undertook a review of five numerical groundwater models developed for proposed coal mines within the Galilee Basin. At the time that this report was prepared there were a number of proposed mines which had not yet advanced to the environmental impact statement (EIS) stage, and therefore had not yet developed groundwater models for the region surrounding their tenement. As mining projects progress it is likely that more data will become available and characterisation and calibration of groundwater models will improve.

The models reviewed by Bleakley et al. (2014) related to the Alpha, Carmichael, China First, Kevin's Corner, and South Galilee coal projects. Subsequent to Bleakley et al. (2014), a draft EIS became available for the China Stone Coal Project, which is being developed by MacMines Austasia Pty Ltd (Hansen Bailey, 2015). As of November 2015, the list of proposed coal mining developments for which a numerical groundwater model exists is as follows:

- Alpha and Kevin's Corner
- Carmichael
- China First (Galilee Coal)
- China Stone
- South Galilee.

Impacts on groundwater at Alpha and Kevin's Corner have been considered in a single model investigating the cumulative impact to groundwater levels. The South Galilee model extent includes the China First Coal Project, and groundwater extraction for both the South Galilee Coal Project and China First Coal Project are included in the model. Kevin's Corner and Alpha coal projects are also represented in the South Galilee model as boundary conditions. The Carmichael model considers only the impacts from the Carmichael Mine. The tenement boundaries and the extent of associated models are shown in Figure 6 and Bleakley et al. (2014). Table 5 summarises some basic features of the current groundwater models developed within the subregion.

A regional numerical groundwater model that encompasses the whole of the Galilee subregion has recently been developed as part of a joint project between the Queensland Government and Australian Government. The aim of this regional numerical groundwater model was to investigate groundwater flow systems in the Galilee subregion and estimate cumulative impacts from coal resource development. Further detail on the regional model is outlined in Turvey et al. (2015) and Table 5.

All the models were calibrated in a steady-state simulation, and results of the steady-state models were used as input for the transient models used to predict drawdowns during mining. Details and results of each model are discussed below.

Table 5 Summary of available groundwater models within the Galilee subregion

Groundwater model	Model area	Cell size	Predictive model time frame	Number of model layers	Model code used	Takes into account impacts from nearby mines?	Coupled to surface water model?	Treatment of induced permeability through fractures	Report
Alpha and Kevin's Corner	100 km × 45.6 km	100 m × 200 m	30 years mining operations, 300 years post mining	11	MODHMS	Yes, semi-cumulative[a]	Yes – for post-mining stage an integrated groundwater and surface water model is used to simulate recovery of groundwater levels	Hydraulic properties are constant through time – no increase in permeability is induced by fracturing associated with longwall mining	URS (2012a), URS (2012b)
Carmichael	108 km × 93 km	50 m to 1 km	59 years mining operations, 196 years post mining	12	MODFLOW-SURFACT	No	No – surface water represented as boundary conditions	Fractured zone above underground mines assigned increased vertical hydraulic conductivity	GHD (2013)
China First	120 km × 130 km	100 m to 1 km	34 years mining operations, 200 years post mining	11	MODFLOW-SURFACT	Yes, semi-cumulative[a]	No – surface water represented as boundary conditions	Fractured zone above underground mines assigned increased vertical hydraulic conductivity	Merrick and Alkhatib (2013)
China Stone	85 km × 75 km	75 m × 75 m in mine area, up to 500 m × 500 m at extremities	50 years mining operations, 200 years post mining	18	MODFLOW-SURFACT	Yes, semi-cumulative[a]	No – surface water represented as boundary conditions	Fractured zone above underground mines assigned increased vertical hydraulic conductivity	AGE Pty Ltd (2015)
South Galilee	73 km × 65 km	50 m to 1 km	48 years mining operations, 100 years post mining	7	MODFLOW-SURFACT	Yes, semi-cumulative[a]	No – surface water represented as boundary conditions	Fractured zone above underground mines assigned increased vertical hydraulic conductivity	RPS Aquaterra (2013)

Groundwater model	Model area	Cell size	Predictive model time frame	Number of model layers	Model code used	Takes into account impacts from nearby mines?	Coupled to surface water model?	Treatment of induced permeability through fractures	Report
Galilee Basin hydrogeological model	299,400 km^2	150 m to 10 km	2012–2220. According to the CRDP this covers 6 years pre-mining, a total mining period of 56 years, and post mining period of 152 years	13	MODFLOW-USG	Yes, cumulative. Includes all mines in the modelled CRDP	No	Fractured zone above underground mines assigned increased vertical hydraulic conductivity. Extent of fracturing above a longwall determined using the Ditton Model (Ditton and Merrick, 2014)	Turvey et al. (2015)

CRDP = coal resource development pathway

[a]Semi-cumulative refers to superposition of model drawdown estimates with adjacent model drawdown outputs.

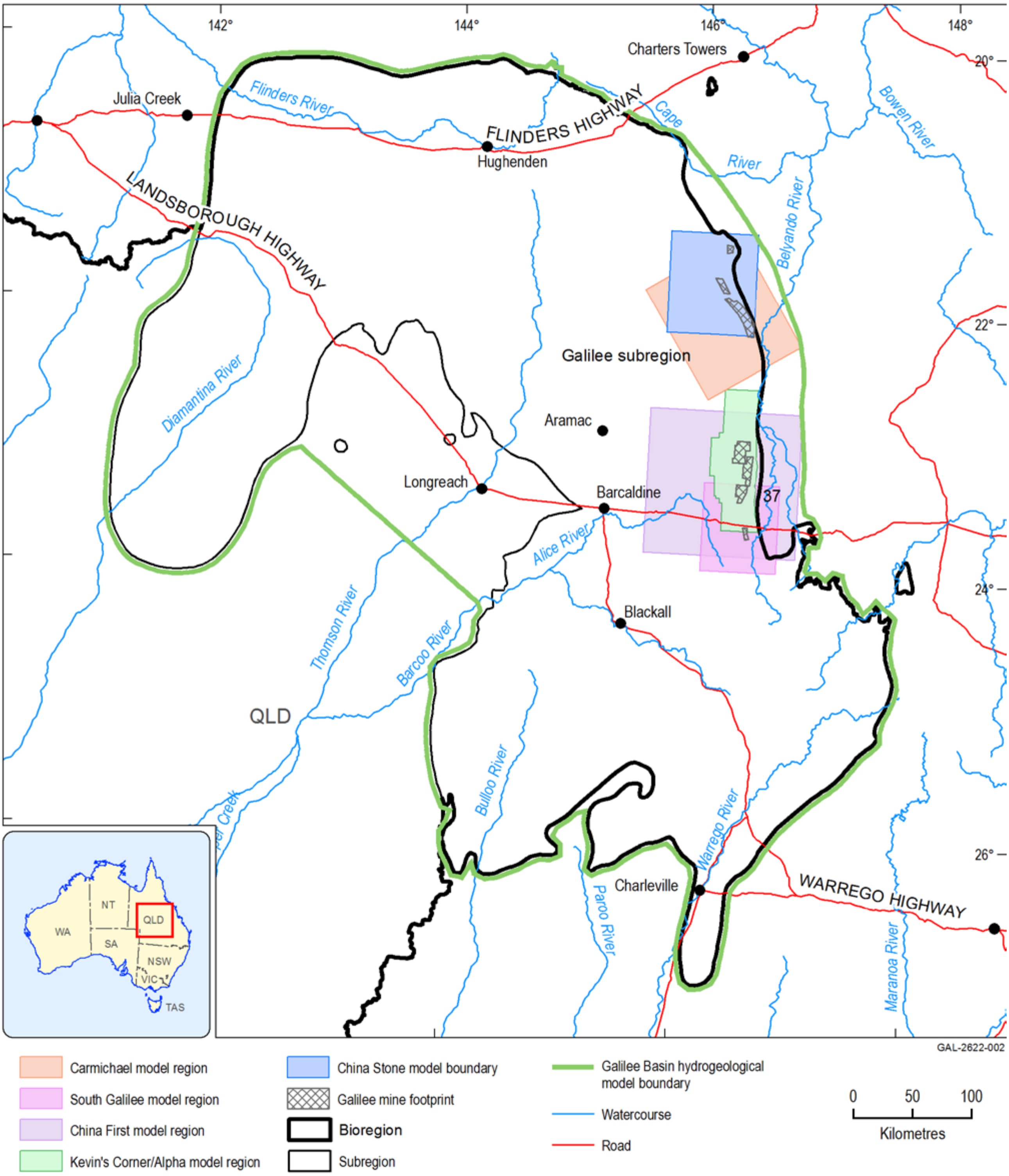

Figure 6 Extents of existing groundwater numerical models in the Galilee subregion

Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.2.1 Alpha and Kevin's Corner model review

URS (2012a, 2012b) and PB Pty Ltd (2012) provide summaries of the history of groundwater model development for the Alpha and Kevin's Corner coal projects. For this report the model referred to here is the groundwater assessment model as detailed in URS (2012a, 2012b). The groundwater assessment model was utilised for the prediction of groundwater inflows, changes to groundwater levels, and to assess potential impacts to bores and environmental assets (URS, 2012b) for the Alpha and Kevin's Corner coal projects. The groundwater assessment model has three major components: a steady-state regional-scale model that includes the Alpha and Kevin's Corner coal projects; a local-scale transient model that focuses on the Alpha test pit; and the predictive inflow into the mine simulations, which utilised the regional-scale model framework. Increases in conductivity caused by fracturing due to stress release following tunnelling above longwall panels in the Kevin's Corner Mine were applied to the C seam and CD interburden. Changes in recharge due to storage of mine waste rock in open-cuts, which is done as part of progressive open-cut rehabilitation, were not included.

The steady-state groundwater assessment model and predictive inflow simulations cover an area of some 118.5 km × 45.6 km and is comprised of 100 m × 200 m asymmetrical cells in the mine areas with coarser-scale cells outside the mine areas. The transient groundwater assessment model was a local-scale model developed as a subdomain of the steady-state model, with 20 m × 20 m grid cells focused on the Alpha test-pit area.

The model contains 11 layers. The Cenozoic units, Moolayember Formation, and Clematis Group are all grouped into the uppermost model layer. This is not ideal as the Moolayember Formation regional aquitard is grouped with the underlying and overlying aquifers. As a result the model cannot simulate vertical flow between these units. Layers 2 and 3 represent the Rewan Group. Layers 4 to 10 represent the upper Permian coal measures, while model layer 11 represents the Joe Joe Group.

Constant-head boundaries were assigned to the southern and northern edges of the modelling domain. The western model boundary coincides with the Great Dividing Range and is assigned as a no-flow boundary (URS, 2012b), as was the contact between the Colinlea Sandstone and Joe Joe Group. It was assumed that the model edges are far enough away from the mine that no mine dewatering induced water level drops will occur at the edge of the model domain for the duration of simulated mining in the model.

A uniform recharge value of 0.037 mm/year was applied across the model area to shallow aquifers in alluvium only as there did not appear to be any correlation between rainfall events and groundwater level fluctuations in the underlying upper Permian coal measures (URS, 2012a).

This local-scale transient model utilised various datasets collated during dewatering of the Alpha test pit for a transient calibration while the steady-state regional-scale model was calibrated using groundwater level measurements taken prior to commencement of dewatering of the Alpha test pit. For the predictive groundwater inflow simulations, calibrated hydraulic conductivities were obtained from the steady-state regional model while calibrated storativity values were utilised from the local-scale transient groundwater model. Sensitivity and uncertainty analyses were undertaken utilising calibrated parameters for both steady-state and transient model runs.

From the predictive groundwater inflow simulation runs, the best-case estimate for the amount of cumulative groundwater inflow into the mines for both projects ranged from 2.13 to 8.4 GL/year over a 30-year period. Predictive groundwater simulations run out for 300 years.

The groundwater inflow simulations overall predict minimal drawdowns for groundwater in the alluvium, as the shallow aquifers are not hydraulically connected to deeper groundwater systems. Localised drawdowns in alluvium may occur if groundwater is within 100 m of the open-cut. Regional groundwater flow patterns would not be markedly altered by the final Alpha and Kevin's Corner mine voids. The risk of induced groundwater flow towards the mines from the overlying Clematis Group and Great Artesian Basin (GAB) aquifers is considered small.

2.6.2.2.2 Carmichael model review

GHD Pty Ltd (2013) reports on the numerical model for the Carmichael Mine. Some basic parameters are outlined in Table 5. The highest grid resolution, in the location of open-cut mine pits and underground mines, is 50 m. This coarsens toward the margins of the model to a maximum cell size of 1 km. The model contains 3,318,470 active cells. It contains 12 layers and has a transient modelling time of 196 years (Bleakley et al., 2014). The mining phase of the transient modelling run was from 2013 to 2071, with recovery phase post mining running out to 2209.

The Permian and Carboniferous rocks are represented in the model by five layers. Four model layers represent main resource seams (AB and D), interburden and overburden to the AB seam. The lowermost layer incorporates the relatively low permeability Joe Joe Group, as well as the lower sections of the Colinlea Sandstone, which includes the E and F coal seams (Bleakley et al., 2014).

Surface water bodies in the model domain are mapped as ephemeral in the Bureau of Meteorology's Australian Hydrological Geospatial Fabric, and were essentially represented as drain cells in the model; river stand height and riverbed elevation are given the same value, meaning water may flow into the river as baseflow, but not from the river to an aquifer as leakage. Riverbed conductance values were assigned with the intention of making them high enough that flow from aquifers to surface water was controlled by the aquifer properties rather than by the riverbed conductance (GHD Pty Ltd, 2013). Underground mines and open-cut mine pits are represented by drain cells.

General-head boundaries (GHBs) are assigned to the outer edge of the active cells in the model. Outflow was simulated on the east boundary with GHB in the Cenozoic (Tertiary) units, and inflow was simulated on the north and west boundaries with GHB in the Triassic and Permian geologic units, and in the south with GHB in the Cenozoic units. No GHBs were assigned to the top model layer (Quaternary alluvium), as discharge from this unit is expected to be primarily through baseflow to surface water bodies (GHD Pty Ltd, 2013).

Initial long-term mean rainfall recharge rates were estimated using recharge–runoff modelling techniques. Recharge rates were refined during the calibration process by allowing them to vary automatically between 0.5 and 5.0 mm/year. This assisted with obtaining the best agreement between observed and modelled water levels. Recharge was enhanced near major streams to simulate stream interactions with shallow groundwater in alluvium.

Predicted near-surface impacts of the model include drawdown in the alluvium to the east of the mining area greater than 2 m, and drawdowns up to 1 m along the Carmichael River corridor (GHD

Pty Ltd, 2013). This contrasts with drawdown at depth in the coal seams that are being targeted for mining, which is in excess of 300 m during the mining phase.

The model predicted a drawdown during the operational phase of up to 10 m along the western boundary of the model, where the Dunda beds, Clematis Group (Sandstone) and/or the Moolayember Formation are mapped as outcrop.

Of particular importance is the potential impact on springs that are situated close to the predicted cone of drawdown. The closest of these is the Doongmabulla Springs complex, which is thought to source water from the Clematis Group aquifer. In this instance the predicted drawdown was 0.5 m to 0.19 m (GHD Pty Ltd, 2013).

Subsequent to the initial model run, the model was re-run with a range of GHB scenarios at the western boundary to address conditions on the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) Approval and was subject to an independent peer review.

2.6.2.2.3 China First model review

Merrick and Alkhatib (2013) provide details on the China First (Galilee Coal) groundwater model as part of the China First supplementary Environment Impact Statement.

Some basic parameters for the steady-state model are outlined in Table 5. Model cell size was of 100 m over the mine areas, coarsening to a maximum of 1 km at the model boundaries. This model extent was made sufficient enough so as to be able to report on: drawdown and recovery relating to the China First Coal Mine only; cumulative drawdown and recovery by China First Coal Mine and the adjacent Alpha Coal Project, but not the South Galilee Coal Project, as drawdown data relating only to South Galilee Coal Project (and not incorporating other nearby mines) could not be obtained; and assessment of potential impacts to GAB aquifers and springs.

The model contains 11 layers and has a transient runtime of 200 years, of which 30 years represents the mining period. The uppermost model layer represents alluvium and regolith. Layers 2 and 3 represent the regolith, Moolayember Formation, Clematis Group and Rewan Group. Layers 4 to 10 detail the various hydrostratigraphic units in the upper Permian coal measures while Layer 11 is the Joe Joe Group. The grouping of all geological units above the Rewan Group into a single model layer compromises the ability of the model to resolve changes in groundwater level in individual units above the Rewan Group, such as in the Clematis Group or in the Cenozoic deposits.

General-head boundaries are assigned to the model domain edges, to simulate inflow from the west and outflow to the east and north-east. All surface water bodies were represented using the MODFLOW River package. Unlike the DRAIN package, the RIVER package allows for both flow into streams (discharge) and out of streams (recharge). Water depths varied from 0 to 2 m based on the size and flow regime of the stream (Merrick and Alkhatib, 2013). Natural springs, open-cut mines, and underground mines were represented as drain cells. In the open-cut and underground mine areas, as mining progressed, the predictive model was able to incorporate changes to recharge, hydraulic conductivity and storage.

Rainfall-recharge values for the model were: alluvium, 1.1 mm/year; Clematis Group-Warang Sandstone, 30 mm/year; Rewan Group and Dunda beds, 6.7 mm/year; and Bandanna Formation, 1 mm/year. Recharge from rivers and creeks totalled 30 ML/day.

Over the life of China First Coal Mine the cumulative aggregate inflows for the open-cuts averaged 2.6 GL/year, and for underground development, 23.1 GL/year. The groundwater modelling predicts that the GAB springs and GAB aquifers are unlikely to be impacted. For some streams it was predicted that leakage to shallow aquifers would increase by up to 1.1 ML/day. Once the mine is closed, predictive modelling suggests that groundwater levels would substantially recover, with only minor groundwater sinks being permanently developed within the immediate vicinity of the mine voids.

Post-mining groundwater levels are simulated by running the model for 200 years with no mining stresses. Groundwater levels recover to levels slightly below pre-mining groundwater levels over the duration of the simulation. Different behaviour is observed in shallow and deep aquifers: groundwater levels in deep aquifers are seen to recover rapidly for approximately 50 years, followed by slower, incomplete recovery to the end of the simulation (200 years); shallow groundwater levels decline for the first 60 years due to drainage through fractures created by mining into the deep aquifers, then recover in concert with the deep aquifer groundwater levels. Permanent lowering of the watertable is predicted over the mine footprint.

2.6.2.2.4 China Stone model review

AGE Pty Ltd (2015) reports on the details of the numerical model for the proposed China Stone Coal Mine. Model dimensions and runtimes are outlined in Table 5. The model consists of 18 layers. Model layers 1 and 2 represent Quaternary and Cenozoic sediments, and if present regolith material. Model layer 3 represents the Ronlow beds, while layers 4 to 8 represent the Galilee Basin sequence from Moolayember Formation down to the base of the Rewan Group. Model layers 9 to 17 represent the upper Permian coal measures while the Joe Joe Group is represented by layer 18.

All model boundaries except the base of the model were set as general-head boundaries. Variable diffuse recharge rates were applied across the model domain and were dependent on the surface geology. They ranged from 0.08 ML/day (outcrop areas of Rewan Group and upper Permian coal measures) up to 1.13 ML/day (Clematis Group outcrop). The model included fracture zones developing as the result of longwall mining in the upper Permian coal measures, which were conservatively assumed to propagate through the entire thickness of overlying strata into the Clematis Group.

Major drainage features incorporated into the model had varying vertical riverbed conductance ranging from 0.0038 m/day (Lake Buchanan) up to 9.6 m/day (Carmichael River) (riverbed conductance is defined as $C = K \times W \times L / M$, where K is hydraulic conductivity of the streambed material, W is stream width, L is length of the stream, and M is thickness of stream layer).

The steady-state calibration utilised an observed water level measurement from 127 bores. Many of the water level measurements were taken when the area was experiencing drought conditions, a result being that monitoring did not record any significant changes to water levels. Thus a transient calibration was not considered to be useful with data at hand. Changes to hydraulic conductivity due to cracking above underground mine longwall panels was incorporated into the transient model as were changes to recharge and hydraulic properties due to storing waste rock in areas of open-cuts where mining was complete. An estimate of cumulative impacts from both the China Stone and Carmichael mines was also carried out.

During the 50 years that mining operations were simulated in the model, total groundwater inflows were calculated to be up to 20 ML/day, although the overall mean could be in the order of 4 to 8 ML/day. Up to 33 m drawdown may occur in the Clematis Group (where it is saturated) in the vicinity of the northern underground mine workings. However, drawdown impacts diminish away from mine areas to less than 1 m within 5 km of proposed mine workings. Groundwater levels in Cenozoic sediments are likely to be drawn down immediately east of the southern open-cut mine areas. Cumulative drawdown in Cenozoic sediments post closure of the mine may be up to 10 m near mine areas but decreases to around 1 m, 10 km east of the mine tenement areas.

2.6.2.2.5 South Galilee model review

RPS Aquaterra (2012) and RPS Aquaterra (2013) provide details on the South Galilee groundwater model. The model presented in RPS Aquaterra (2013) is a revision of the original model as outlined in RPS Aquaterra (2012), thus model details presented here are derived from RPS Aquaterra (2013). However, RPS Aquaterra (2012) contains much of the background information for the model.

Some basic parameters for the steady-state model are outlined in Table 5. The South Galilee model area includes the China First Coal Project area. It has a variable cell size of 50 m in the mining tenement, and 1 km at the model boundaries.

The model contains seven layers. The uppermost model layer represents the Quaternary and Cenozoic material. Model layer 2 represents the Moolayember Formation, Clematis Group and the Rewan Group. Model layer 3 represents the primary coal resource. Model layers 4 to 6 represent the other coal seams, interburden and underburden. Model layer 7 represents the Joe Joe Group. Including the Moolayember Formation in model layer 2, which otherwise represents aquifers, partial aquifers, and coal resources, is likely to affect the ability of the model to predict impacts on shallow groundwater levels in the Quaternary and Cenozoic material resulting from changes in deeper groundwater levels.

The northern, western and much of the eastern boundaries for the models were designated as general-head boundaries. An exception to this was the western boundary of the Rewan Group (model layer 3) and Joe Joe Group (model layer 8), which were designated as no-flow boundaries as they represent aquitards. Other areas, including the southern boundary were designated no-flow boundaries (RPS Aquaterra, 2013).

Recharge was applied to the model only where alluvium was present at the surface, or where the Clematis Group outcropped. Alluvium was assigned a recharge rate of 2.75 mm/year (or 0.5% rainfall), Cenozoic (called Tertiary in the model) 5.5 mm/year (1% rainfall) and the Clematis Group was assigned recharge of 13.75 mm/year (2.5% rainfall).

Surface water bodies were represented with the MODFLOW River package, allowing flow both from aquifers to streams and from streams to aquifers. River stages were set at 5 m below the river bank elevation. The riverbed of Native Companion Creek was set at 1 m below the river stage. All other surface streams had the riverbed set at 0.1 m below the river stage. This arrangement allows a low level of constant leakage to occur from surface water to groundwater (RPS Aquaterra, 2012), however most of the streams in the model domain are ephemeral.

Mining-induced fracturing was simulated in the transient model by allowing for changes in conductivity over time to occur as mining progresses in model cells that represent mine areas. Some parts of the China First Coal Mine areas were incorporated into the model so as to investigate cumulative impacts from the China First and South Galilee coal projects (RPS Aquaterra, 2013). The model was run for 100 years to simulate groundwater recovery post mining.

Predicted mine inflows range from 2 to 8 GL/year, which equates to 5 to 23 ML/day (RPS Aquaterra, 2013) with a total cumulative inflow volume of 187 GL over life of mine. A sensitivity analysis on the effects of faulting on the Rewan Group was undertaken by increasing the permeability of the Rewan-Dunda layer to simulate the potential interconnectivity effect due to faulting and fracturing. The analysis showed that the model was not sensitive to drastic changes to hydraulic conductivity in the Rewan Group. This implied that the presence of faults in the Rewan Group would not significantly increase inflows to the mine. The cumulative model runs suggest that there will be minimal impacts to the Alpha town water supply. Cumulative drawdown in the Clematis Group aquifer during mining was in the order of 3 to 5 m, which is considered to be overly conservative as a result of the Clematis Group aquifer being lumped with the Rewan Group aquitard in the model.

2.6.2.2.6 Galilee Basin hydrogeological model review

A regional numerical groundwater model of the Galilee Basin – here referred to as the Galilee Basin hydrogeological (GBH) model – has been developed utilising data and interpretation undertaken for the Galilee subregion by the Assessment team. The model was jointly funded by the Commonwealth Department of the Environment's Office of Water Science and the Queensland Government. A consultant – HydroSimulations – was engaged to produce a calibrated and stress-tested transient numerical groundwater flow model capable of simulating the cumulative impacts of proposed coal mining developments. The GBH model was built over a 2.5 month period. The following summaries are based on a detailed description of the GBH model, provided in Turvey et al. (2015).

Input data for the model was compiled as part of this assessment for the Galilee subregion. Companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a) provides detail on data used as input to the GBH. These data include: the geological model of the Galilee subregion, potentiometric surfaces for aquifers in the subregion, and recharge volumes, among other datasets. The GBH model was built utilising the new MODFLOW-USG platform and AlgoMesh, which uses flexible meshes to allow refinement around key features while maintaining a reasonable cell count for computational efficiency. The GBH model consists of an unstructured grid (except for mines) consisting of 1.93 million cells ranging in size from 150 m to 10 km and covers an area of 299,400 km^2. A cell size of 165 m to 250 m is used around modelled mines. Modelling was carried out in three stages, resulting in steady-state, transient and predictive simulations. Mines simulated in the transient model are: China First, Kevin's Corner, Carmichael, South Galilee, China Stone, Hyde Park and Alpha. These are mines that comprise the modelled CRDP, as outlined in companion product 2.3 for the Galilee subregion (Evans et al., 2018b).

The GBH model consists of 13 layers representing the major hydrostratigraphic units present within the subregion (Table 6). In many cases, individual model layers represent multiple stratigraphic units that are grouped based on similar hydraulic properties.

Table 6 Model layer thickness and corresponding hydrostratigraphic groupings (after Turvey et al., 2015)

Model layer	Hydrostratigraphic unit	Classification	Mean thickness (m)	Maximum thickness (m)	Calibrated horizontal hydraulic conductivity (Kh) (m/day) (same for steady-state and transient calibration)	Specific storage (Ss) (transient calibration) (1/m)	Specific yield (Sy) (transient calibration) (%)
Layer 1	Cenozoic	Unconfined aquifer	11	66	$1.00x10^{0}$ (regolith) /$3.00x10^{1}$ (Cenozoic)	$1.00x10^{-3}$	$1.00x10^{-1}$ (Cenozoic) /$1.00x10^{-2}$ (regolith)
Layer 2	Winton-Mackunda formations	Unconfined to semi-confined aquifer	61	782	$2.57x10^{-1}$	$1.00x10^{-2}$	$1.00x10^{-2}$
Layer 3	Allaru/Toolebuc/ Wallumbilla formations (Rolling Downs Group aquitard)	Aquitard	166	756	$3.04x10^{-4}$	$5.00x10^{-4}$	$1.00x10^{-2}$
Layer 4	Cadna-owie Formation/Hooray Sandstone/Gilbert River Formation/ Ronlow beds	Confined aquifer	52	289	$1.72x10^{-1}$	$5.00x10^{-4}$	$1.00x10^{-2}$ (east) /$8.00x10^{-3}$ (west)
Layer 5	Westbourne/Adori/ Birkhead formations (Injune Creek Group)	Aquitard	67	423	$1.26x10^{-4}$	$5.00x10^{-4}$	$8.00x10^{-3}$
Layer 6	Hutton Sandstone/Boxvale Sandstone /Precipice Sandstone	Confined aquifer	60	381	$1.27x10^{-1}$ (east) /$7.59x10^{-1}$ (west)	$5.00x10^{-4}$	$1.50x10^{-2}$ (east) /$7.00x10^{-3}$ (west)
Layer 7	Moolayember Formation	Aquitard	85	706	$2.26x10^{-1}$	$1.00x10^{-4}$	$7.00x10^{-3}$
Layer 8	Warang-Clematis Group	Confined aquifer	56	573	$1.96x10^{0}$ (east) /$4.02x10^{0}$ (west)	$1.00Ex10^{4}$	$1.50x10^{-2}$ (east) /$6.00x10^{-3}$ (west)
Layer 9	Rewan Group (includes Dunda beds)	Aquitard	88	474	$3.00x10^{-4}$	$1.00x10^{-7}$	$5.00x10^{-3}$
Layer 10	Top Bandanna Formation to base of B Seam (BC1)	Partial aquifer	50	416	$1.30x10^{-1}$	$1.00x10^{-6}$	$1.00x10^{-2}$
Layer 11	Base B Seam to Top of E seam (BC2)	Partial aquifer	29	65	$7.40x10^{-1}$	$1.00x10^{-6}$	$8.00x10^{-3}$
Layer 12	Top of E seam to base of Colinlea Sandstone (BC3)	Partial aquifer	25	223	$2.50x10^{0}$	$1.00x10^{-6}$	$1.00x10^{-2}$

Model layer	Hydrostratigraphic unit	Classification	Mean thickness (m)	Maximum thickness (m)	Calibrated horizontal hydraulic conductivity (Kh) (m/day) (same for steady-state and transient calibration)	Specific storage (Ss) (transient calibration) (1/m)	Specific yield (Sy) (transient calibration) (%)
Layer 13	Joe Joe Group/Drummond Basin sediments/crystalline basement	Aquitard	602	1916	$8.77x10^{-5}$ (Joe Joe Group) /$2.00x10^{-3}$ (Drummond Basin) /$2.00x10^{-5}$ (crystalline basement)	$1.00x10^{-7}$	$7.00x10^{-3}$

Mean thickness and maximum thickness figures are from Table 3-1 in Turvey et al. (2015).

Significant vertical hydraulic gradients exist through the upper Permian coal measures. For this reason the upper Permian coal measures were modelled as three layers (layers 10, 11 and 12). From top to bottom these sub-units are informally designated BC1, BC2 and BC3. The partitioning was done on the basis of approximately similar groundwater pressures existing in each sub-unit (Table 7). The upper Permian coal measures are designated as a partial aquifer because of low hydraulic conductivity (variable Kh values, but less than 0.2 m/day).

Table 7 Stratigraphic units and marker beds used to define subdivision of the upper Permian coal measures

Sub-unit	Formation	Marker bed
BC1	Bandanna Formation / Blackwater Group	Top Bandanna Formation to base B seam
BC2	Peawaddy Formation / Black Alley Shale / Colinlea Sandstone (upper)	Base B seam to base DE Sandstone
BC3	Colinlea Sandstone (lower)	Top E seam to base Colinlea

Major rivers within the subregion are represented in the model using the MODFLOW River package and are assumed to be connected to the groundwater system. Rivers modelled include: Carmichael River, Belyando River, Native Companion Creek, Alpha Creek, Aramac Creek, Thomson River, Flinders River, Diamantina River, Barcoo River, Warrego River, and Blackwater Creek.

Groundwater discharges from 121 springs are simulated in the model using the MODFLOW River package (head-dependent boundary conditions) by setting the stage and bed elevation of the river cells to be equal, allowing one-way flow (discharge from groundwater) only. The River package allows for the specification of spring – discharge observation points where the fluxes from these river cells are functions of the calculated groundwater level and assigned conductance. Major springs represented include Doongmabulla, Mellaluka, Edgbaston, Coreena and Corinda springs. Based on limited data available from the Queensland springs database, the major springs were assigned flows greater than 100 m^3/day; all other springs modelled were limited to less than 100 m^3/day.

Long-term mean recharge rates used in the model are based on chloride mass balance estimates reported in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a). Estimated recharge rates vary from a low of 0.1 mm/year, for the Joe Joe Group, to a high of 5 mm/year for Cenozoic alluvial deposits.

It is considered that no lateral groundwater inflow or outflow occurs along the eastern margin of the Galilee subregion. Consequently, no boundary condition is assigned to the eastern edge of all model layers. In contrast, general-head boundaries are applied along the western boundary of the model to the aquifer model layers 2, 4 and 6, representing the regional hydraulic gradient and communication with aquifers outside of the model domain.

Existing groundwater extraction is represented in the model using the MODFLOW Well package. For steady-state simulations the mean recorded artesian well discharge between 1983 and 2012 was applied to be consistent with the data used for calibration. For the historical transient model the actual annual discharge rate values were used, while predictive model runs used a constant flow rate of 895 ML/day, which represents estimated total daily extraction for the year 2012.

Turvey et al. (2015) noted that bore discharge estimates provided may be inaccurate and that for some bores there is uncertainty about the source aquifer. As a result it is possible that well stresses are misapplied in the model. To compensate, variable bore discharge rates have been applied during model simulation to prevent incorrectly assigned discharge rates from drying out cells in low conductivity layers, causing model instability.

Mine dewatering for the seven mines included in the predictive model is simulated using the MODFLOW Drain package. The package integrates the proposed mine plan location, timing, depth and method of extraction. Open-cut mine pits are assumed to be the full thickness of the relevant target coal seams. Drain cells are progressively added to the transient model to simulate extraction of mine panels over time.

Longwall mine induced fracturing is simulated using the MODFLOW-USG Time-Variant Materials package. Hydraulic parameters are changed with time in the goaf and overlying fracture zones during extraction of each longwall panel.

2.6.2.2.6.1 Steady-state calibration

Steady-state calibration was assessed against water levels corrected for temperature and salinity to ensure comparability with MODFLOW predictions which do not take account of density variation.

Calibration statistics for the steady-state simulation are shown in Table 8. Predictions within ±10 m of target levels were distributed evenly across the model domain, however a tendency remains to under predict water levels in the west and over predict water levels in the east. An area of significant over prediction (>50 m) occurs within layers 11 and 12 at the south-east of the model. Target residuals at the southern group of mines (Kevin's Corner, Alpha, China First and South Galilee) are relatively good, with an overprediction of approximately 13 m being the most significant discrepancy. However, at Carmichael, particularly north of the Carmichael River, significant model overpredictions of up to 38 m occur within the coal seam layers. No data were available for calibration at either China Stone or Hyde Park mines at the time of model development.

Table 8 Steady-state calibration statistics (after Turvey et al., 2015)

Statistic	Value
Residual mean (m)	5.71
Absolute residual mean (m)	17.62
Residual standard deviation (m)	23.27
Sum of squares (m^2)	339,911
Root mean square (RMS) error (m)	23.94
Minimum residual (m)	–100.00
Maximum residual (m)	119.28
Number of observations	593
Range in observations (m)	506
Scaled RMS error	4.6%
% Targets within ±10 m	43
% Targets within ±25 m	73

Turvey et al. (2015) includes a comparison of simulated potentiometric surface contours derived from the steady-state calibration and contours interpreted from observed water levels for companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a). Turvey et al. (2015) found that there is general agreement between the pattern of the Eromanga Basin modelled surfaces and interpreted surfaces. A comparison of model layers 1 and 2 and interpreted surfaces for the Cenozoic and Winton and Mackunda formations shows differences in elevation generally less than 20 m and similar inferred flow directions. A comparison between the model layer 4 surface and the interpreted surface for the Hooray Sandstone showed modelled elevations 10 to 30 m below the interpreted surface and similar inferred flow directions. These properties are the same for the comparison between the model layer 6 surface and the interpreted surface for the Hutton Sandstone.

The discrepancies between the modelled Galilee Basin units (model layers 8, 10, 11 and 12) and interpreted surfaces are more variable with a general pattern of under prediction of modelled water levels over most of the model domain and over prediction of modelled water levels toward the eastern boundary of the subregion where aquifers outcrop. However, inferred flow directions are generally similar for both modelled and interpreted surfaces.

The general underestimation of modelled water levels in the location of some springs is likely to account for predicted spring flows that are less than observed flows. The total modelled spring flow under estimates reported flow by around one order of magnitude.

Calibration to baseflow was not undertaken due to uncertainty in available baseflow records.

The water balance for the steady-state simulation indicates that just under half of the recharge to groundwater is from direct rainfall recharge, with an approximately equal contribution from river leakage and inflow along model boundaries accounting for the remaining portion of inflow. Losses from the system in order of magnitude are: evapotranspiration; groundwater extraction; discharge to rivers and springs; followed by groundwater outflow along model boundaries. All but two rivers in the model (Thomson and Diamantina rivers) act as net losing systems overall.

2.6.2.2.6.2 Transient calibration

Manual transient calibration was carried out for the period January 1998 to December 2012. Due to the limited data available for transient calibration, steady-state *Kh* and *Kv* values were not varied and only variation in storage parameters (*Ss* and *Sy*) was allowed. High specific storage (*Ss*) values were required to prevent excessive drawdown due to well extraction over the calibration period. For the transient simulation, groundwater recharge rates were varied using a series of recharge factors for the period 1983 to 2011 derived from the Australian Water Resources Assessment landscape model (AWRA-L) in order to scale steady-state recharge values to derive a transient recharge dataset. Recharge estimates for the period 2012 to 2014 were derived using the Penman-Grindley recharge model (Finch, 1994).

Calibration statistics for the transient simulation are shown in Table 9.

Table 9 Transient model calibration statistics (after Turvey et al., 2015)

Statistic	Value
Residual mean (m)	5.72
Absolute residual mean (m)	11.31
Residual standard deviation (m)	15.87
Sum of squares (m^2)	156,240
Root mean square (RMS) error (m)	16.85
Minimum residual (m)	–33.01
Maximum residual (m)	52.42
Number of observations	550
Range in observations (m)	260
Scaled RMS error	5.9%
% Targets within ±10 m	64
% Targets within ±25 m	89

The transient model mass balance indicates that the majority of water that enters the model does so via a combination of river leakage and rainfall recharge. Regional groundwater flow into the model, via general-head boundaries, is approximately double that of outflow. Over the calibration period there was a net loss in storage suggesting a depleting resource.

2.6.2.2.6.3 Predictive runs

Two predictive model runs were simulated and run out to the year 2220 in order to allow for sufficient simulation of the water level recovery phase.

The first predictive model run for the GBH model represents a baseline which consists of existing groundwater use without groundwater extraction due to coal mining (Turvey et al., 2015). For BA, the baseline is defined as a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012 (see Section 2.3.4 in companion product 2.3 (Evans et al., 2018b) for further detail). As of December 2012, there were no operational coal mines or CSG fields in the Galilee subregion (Evans et al., 2018b). Hence, the first predictive run of the GBH model represents the coal resource development baseline defined for this assessment.

The second predictive model run includes the seven coal mines that comprise the modelled CRDP (see Section 2.3.4.1 in companion product 2.3 (Evans et al., 2018b) for detail) and represents the cumulative drawdown of these potential coal mining operations. Additional stresses to those imposed on the baseline predictive model run include: a progressive excavation and associated dewatering of the seven open-cut and longwall mines; progressive development of fracture zones above underground mines and associated changes in permeability; and progressive placement of fill in open-cut mines to end of mine life using modified hydraulic parameters and recharge.

2.6.2.2.6.4 Limitations – Galilee Basin hydrogeological model

The GBH model is a complex regional groundwater model produced in a very short time period and within a limited budget. Upon completion, a number of limitations and issues have been identified by the contractors – HydroSimulations – and reviewers from Queensland Government, Office of Water Science and relevant project and discipline leads from the Bioregional Assessment Technical Programme. The limitations noted by various reviewers include:

- The ability of the model to simulate impacts to the unconfined Cenozoic aquifer – model layer 1 – is limited. Predictive model runs did not show any impact to model layer 1, particularly in the vicinity of open-cut mine pits. It would be expected that drawdown and dewatering of Cenozoic units would occur adjacent to mine pits which penetrate and expose the Cenozoic units. Turvey et al. (2015) suggested that certain options within the MODFLOW-USG code do not allow the model to represent negative pressures (i.e. dry cells representing unsaturated conditions). This means that an artificial head is maintained at the base of each layer, which may result in under prediction of the magnitude of drawdown within each cell. This will have had particular implication for impacts predicted in model layer 1, essentially resulting in water being held at the base of model layer 1 for the entire model simulation and resulting in negligible reported drawdown within this layer.
- Combining several hydrogeological units into a single model layer means that accurate representation of real-world groundwater levels for all members of the GAB and Galilee Basin units cannot be produced. This is a particular issue for the upper Permian coal measure layers (model layers 10, 11 and 12), where bulk hydraulic conductivity parameters applied to the model representing coal seam layers are higher than those of the interburden layers (that are not included). Additionally, no vertical hydraulic conductivity variation exists within the bulked layers. As discussed in Section 2.6.2.8.2.4, combining hydrogeological layers together can be justified when conservatively estimating drawdowns. The lumping of hydrogeological layers, however, can result in biased parameter estimates if local groundwater level observations are used to constrain the aggregated hydraulic parameters. Another potential issue is that mine dewatering rates will be over-estimated as the

aggregated unit will be dewatered in the model, rather than just the mined interval. Such an overestimate can be considered conservative and therefore justified. It will contribute to discrepancies between estimated pumping rates between models, further complicating comparisons between model results.

- The representation of losing and gaining streams in the GBH model is suited to predict the hydrological change due to coal resource development. However, in a deterministic aquifer simulator such as the GBH model, incorrectly specified surface water – groundwater boundary conditions is a large source of conceptual model uncertainty. This may bias parameter estimates and therefore bias predictions. Debate exists about the representation of the Thomson, Alice, Carmichael and Belyando rivers as losing streams. Initial assessments done for companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a) suggests these streams could be predominantly gaining. Section 2.6.2.9.1 identifies the large potential of improving the characterisation of the connection status of the river network to reduce predictive uncertainty.
- Queensland Government reviewers noted issues with some of the input data, in particular the boundary definitions for some model layers (e.g. the Rewan Group) and the accuracy of some well flow rates. There is a possibility that over extraction of groundwater from the model due to erroneous input well flow rate data has resulted in calibrated hydraulic conductivities and storage properties being too high. Anomalously high hydraulic conductivities and storage properties are likely to result in increased mine inflows and greater resultant drawdowns.
- Limited data were available for calibration; most data collected were of single-point observations over a period of 30 years. Therefore, reliability of the data is unknown as long-term trends were not able to be analysed. Section 2.6.2.9.1 highlights the need for additional field data collection.
- Limited formal sensitivity analysis has been carried out due to the short model development time frame and agreed scope for the project. It is therefore difficult to clearly indicate which parameters are controlling calibration, inflows and predicted impacts.
- The GBH model input data does not include more recent groundwater data that became available after the release of the groundwater modelling report for China Stone Coal Project. Extra data in AGE Pty Ltd (2015) would refine the results of the steady-state and transient models in the vicinity of China Stone and Carmichael coal projects.

2.6.2.2.7 Suitability of existing groundwater models

The mine-scale numerical groundwater models developed by proponents in the Galilee subregion are deterministic models developed for the purpose of assessing the impact of a single mining development. While the relatively small scale of these models allows for higher resolution in cell size and parameter variability, treating each coal resource development in isolation will not account for the possibility of cumulative impacts on the groundwater system.

Several of the mine-scale models have attempted to account for cumulative impacts using the principal of superposition. That is, where the drawdown contours of two models overlap, the total drawdown in that area is calculated by summing the drawdown predicted by the overlapping models. This is a straightforward way of accounting for cumulative impacts, but is relatively simple, and does not account for the more complex impacts that multiple coal projects may have on local to regional groundwater systems, such as local changes in groundwater flow direction, reductions in subsurface flow volumes, or changes to recharge volumes and distribution. The way mine-scale models clump the Galilee Basin and Eromanga stratigraphic sequences varies from model to model. Ideally, all coal resource development should be represented in a single numerical groundwater model to accurately simulate the combined impact they will have on both local and regional-scale groundwater flow systems.

While the mine-scale models outlined in previous sections show good correlation between observed and predicted groundwater levels, in many cases the data available for calibration only covers a short time period, for many bores this is less than five years. In predicting water levels decades or centuries into the future this places a great deal of significance on data representing a small part of a complex system.

The groundwater models built by the mine proponents (Alpha and Kevin's Corner, Carmichael, China First, China Stone and South Galilee coal projects) can provide some degree of guidance at a semi-regional scale on cumulative impacts but for reasons stated above, as well as issues surrounding the availability of models for use in the Bioregional Assessment Programme, these models are not suitable to use in this analysis of the Galilee subregion.

The Galilee Basin hydrogeological model (Section 2.6.2.2.6) encompasses the whole Galilee subregion and the second predictive run of the transient model (Section 2.6.2.2.6.3) incorporates the Galilee subregion's modelled CRDP. This model does take into account regional complexities as well as changes to hydraulic properties as mining progresses in mine areas. However, model limitations (Section 2.6.2.2.6.4) suggest that further refinements would improve the model's outputs and its predictive capacity. Also, as outlined in Section 2.6.2.1, BA modelling methodology takes a probabilistic approach in order to provide an estimate of uncertainty for modelling results. Due to long model runtimes of the GBH model (around 20 hours for a single evaluation) and concerns regarding the numerical stability, it was not considered suitable for BA use without additional investment in model development. This was not possible within the time frame of the Galilee subregion BA.

As described in the following sections there are other approaches to groundwater modelling that can determine cumulative drawdown with estimates of uncertainty within reasonable time frames. Results from these types of models can be used to inform and improve complex regional numerical groundwater models such as the GBH model.

As indicated in Section 2.6.2.1, the analytic element model method is chosen for this study. Table 10 gives a high level overview of the differences and similarities between the GBH model and the analytic element model approach. The section numbers indicated where the model is discussed in this product. The assumptions and limitations of this alternative modelling approach are discussed in the context of the predictions in Section 2.6.2.8.2.

Table 10 High level overview of differences and similarities between Galilee Basin hydrogeological (GBH) model and analytic element model approach

	GBH	Analytic element model	Section
Output	groundwater levels, mine drainage rates, surface water – groundwater flux, spring flow for no development and CRDP conditions	change in groundwater levels and surface water – groundwater flux	2.6.2.7
Solver type	finite volume	analytic element	2.6.2.3.4
Uncertainty analysis	none – deterministic model	stochastic	2.6.2.8.1
Geometry	geological model	simplified	2.6.2.3.5
Boundary conditions	no change in river stage, recharge rates, stock and domestic pumping rates and spring drainage levels between no development and CRDP	no change in river stage, recharge rates, stock and domestic pumping rates and spring drainage levels between no development and CRDP	2.6.2.4
Implementation CRDP	specified drainage level	specified pumping rate	2.6.2.5
Hydraulic properties	uniform in space, variable in time in vicinity of mines	uniform in space and time	2.6.2.6
Calibration	deterministic – single optimum	none – stochastic parameter sets are not constrained by historical observations	2.6.2.8.1
Sensitivity analysis	limited, one-at-a-time	comprehensive, global	2.6.2.7.3

CDRP = coal resource development pathway

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2.6.2.3 Model development

Summary

The objective of groundwater modelling undertaken as part of bioregional assessments (BAs) is to assess the cumulative impacts of coal resource development on water-dependent assets.

The groundwater analytic element model (GW AEM) is designed to predict changes in groundwater level at specific model nodes, resulting from the cumulative impact of pumping for mine dewatering within the upper Permian coal measures of the Galilee subregion.

The Galilee subregion is host to three groundwater systems, which generally operate independently but in some places are hydraulically connected. The three systems in order from youngest to oldest are:

1. Cenozoic aquifers
2. layered Mesozoic aquifers and aquitards of the Eromanga Basin (Great Artesian Basin)
3. layered Permo-Triassic aquifers and aquitards of the Galilee Basin.

The GW AEM simulates a simplified hydrostratigraphic model representing the upper Galilee Basin sequence and overlying Cenozoic cover along the eastern margin of the subregion, in the vicinity of coal resource development pathway (CRDP) mines. The model excludes the early Jurassic to late Cretaceous Eromanga Basin sequence comprising the Hutton Sandstone and Hooray Sandstone and aquifers in the Winton-Mackunda formations. Inclusion of these formations in the model is only warranted if sizeable drawdowns are predicted in the underlying Clematis Group.

For this groundwater model the analytic element methodology is selected (Bakker, 2013) using the open-source implementation available in TTim (Bakker, 2015). This grid-independent, flexible groundwater methodology allows a comprehensive uncertainty analysis for a fraction of the computational cost of such an analysis with a finite-difference model.

The groundwater system is implemented as an alternating sequence of aquifers and aquitards, represented by seven model layers. Changes in groundwater level and flow are only simulated for the aquifers. The model layers are horizontal, with constant thickness. The top of the model is set to an arbitrary level of zero metres and the total nominal thickness of the simulated sedimentary column is 600 m.

The model calculates a time series of the change in groundwater level within the upper Permian coal measures and aquifers above, resulting from groundwater discharge associated with coal resource developments identified in the CRDP.

2.6.2.3.1 Objectives

As stated in Section 2.6.2.1, the objective of the numerical modelling undertaken as part of a BA is to probabilistically assess hydrological changes arising from coal resource development at water-related assets. The main objectives of the groundwater model therefore are (i) to provide the drawdown due to additional coal resource development (additional drawdown) at the model nodes (Section 2.6.2.1, Figure 4 and Table 4), and (ii) to estimate the change in surface water – groundwater flux to propagate to the surface water models (companion product 2.6.1 for the Galilee subregion (Karim et al., 2018a)).

In addition to the additional drawdown at the model nodes, probabilistic maps of the drawdown under the baseline coal resource development (baseline), the coal resource development pathway (CRDP) and the difference between the two will be provided.

There is no model node for which changes in water balance are considered to be the hydrological response variable. Therefore, while changes in water balance are not an objective of the modelling, probabilistic estimates of changes in the surface water – groundwater flux are discussed. A more comprehensive discussion on the water balance of the Galilee subregion is presented in companion product 2.5 (Karim et al., 2018b).

2.6.2.3.2 Hydrogeological conceptual model

A detailed description of the hydrogeology of the Galilee subregion is provided in companion product 2.3 (Evans et al., 2018b). Figure 7 shows a geological cross-section of the Galilee Basin while Figure 9a shows a conceptual cross-section of the model domain.

The Galilee subregion is host to three groundwater systems, which generally operate independently but in some places are hydraulically connected. The three systems in order from youngest to oldest are:

1. Cenozoic aquifers
2. layered Mesozoic aquifers and aquitards of the Eromanga Basin (Great Artesian Basin, GAB)
3. layered Permo-Triassic aquifers and aquitards of the Galilee Basin.

The early Jurassic to late Cretaceous Eromanga Basin sequence constitutes most of the cover overlying the Galilee Basin (Figure 10 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)). The Eromanga Basin includes a significant portion of the layered aquifers and aquitards of the GAB. The boundary of the Eromanga Basin sequence occurs along the west of the Great Divide, approximately 25 to 55 km west of the nearest CRDP mines. The main aquifers of this sequence within the Galilee subregion are listed in order from youngest to oldest:

- The partial aquifer in the Winton-Mackunda formations partially outcrops over much of the western portion of the Galilee subregion and hosts a regional watertable groundwater flow system. This aquifer supplies a large number of shallow bores within the subregion. The Winton-Mackunda partial aquifer is separated from the underlying Hooray Sandstone aquifer by the Allaru Mudstone and Wallumbilla Formation, which form part of the regionally extensive Rolling Downs Group aquitard of the GAB. However, these units are locally considered a partial aquifer near their eastern boundary where they supply low-yielding shallow sub-artesian bores.

- The Hooray Sandstone and equivalents is the main artesian aquifer of the GAB and extends over the entire Galilee Basin from west of the Great Divide. Nearly half of the flowing artesian bores overlying the Galilee Basin are screened in this aquifer. The Hooray Sandstone is separated from the underlying Hutton Sandstone aquifer by the Injune Creek Group leaky aquitard.
- The Hutton Sandstone aquifer is a confined GAB-wide artesian aquifer, extending over the entire Galilee Basin from west of the Great Divide. The number of artesian bores screened in this aquifer is similar to that in the Hooray Sandstone aquifer, and accounts for nearly half of the flowing artesian bores overlying the Galilee Basin. The Hutton Sandstone aquifer directly overlies and is in contact with the upper unit of the Galilee Basin – the Moolayember Formation aquitard over most of the subregion.
- The Precipice Sandstone aquifer is the basal aquifer of the Eromanga Basin sequence. This aquifer is located in the south of the subregion, pinching out to the south of the CRDP mines. The Precipice Sandstone aquifer is separated from the Hutton Sandstone aquifer by the Evergreen Formation aquitard.

The edge of the Eromanga Basin coincides with the eastern outcrop extent of the Hutton Sandstone. Along this boundary, overburden thickness (strata lying above the upper Permian coal measures) is in the order of 400 to 600 m, in the vicinity of the southern CRDP mines, and reaches as much as 1000 m west of the northern CRDP mines (Figure 7 and Figure 8).

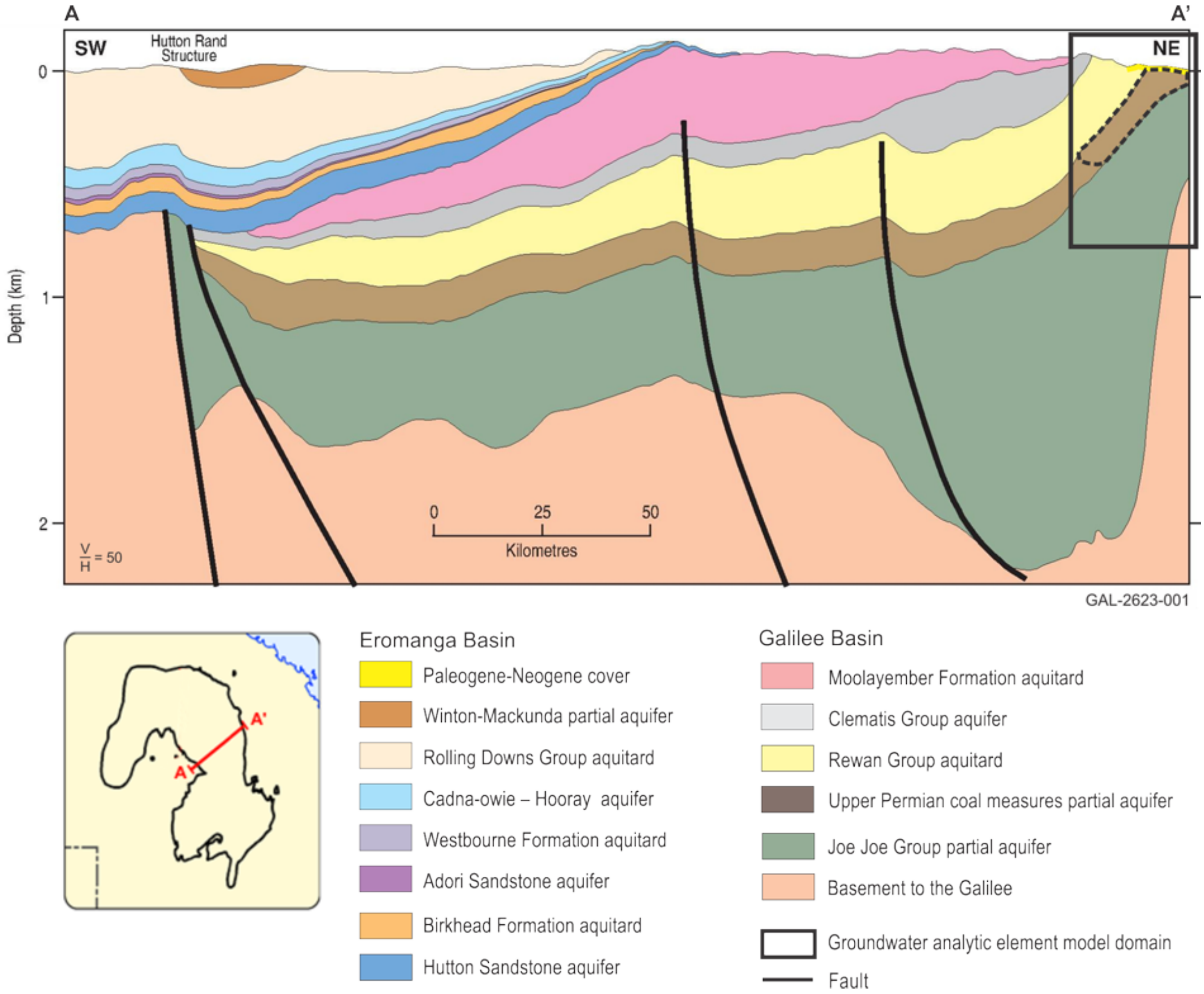

Figure 7 Cross-section showing the model domain in relation to the Galilee and Eromanga geological basins in the Galilee subregion

Paleogene-Neogene cover exaggerated; black dashes are a schematic representation of potential coal development

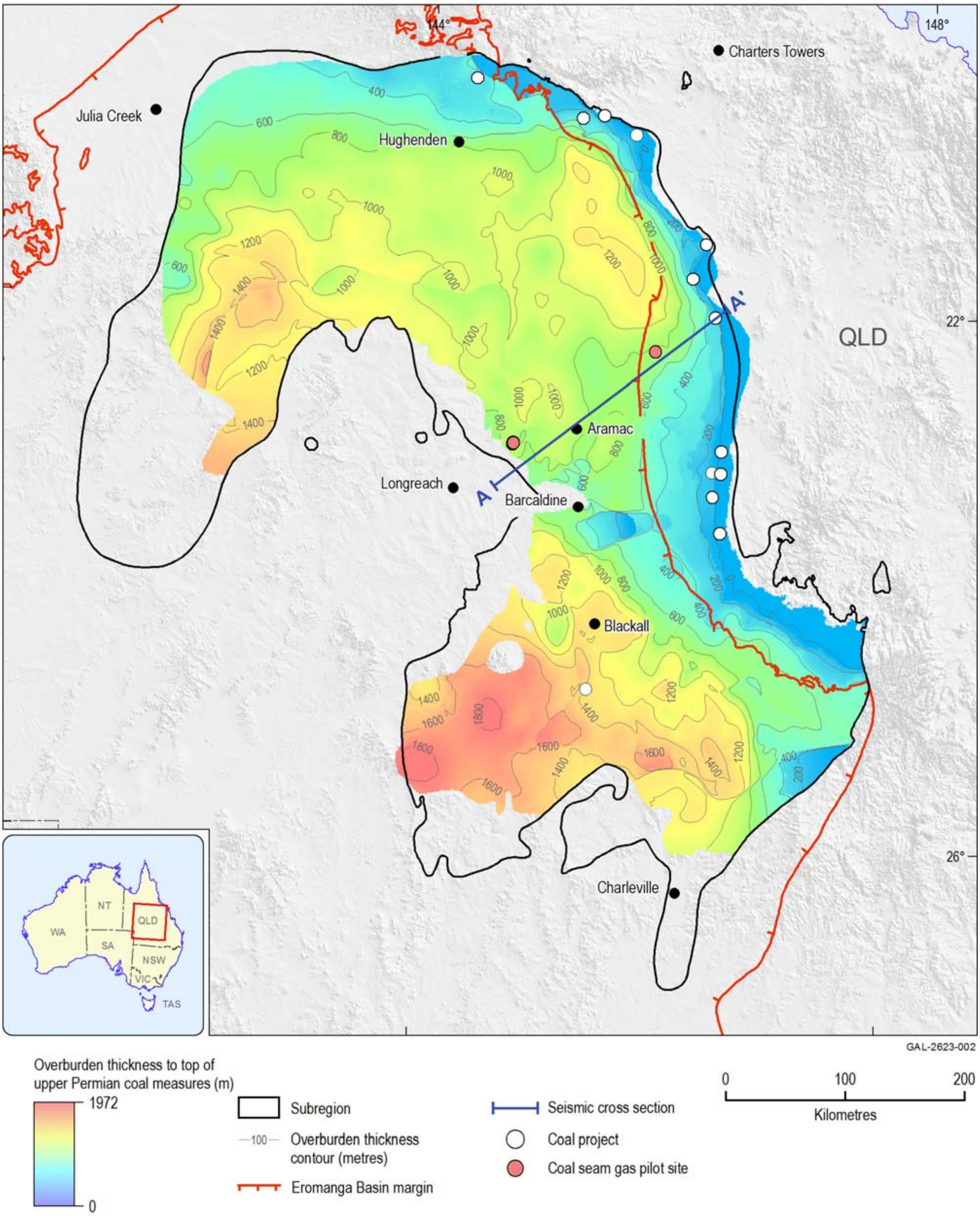

Figure 8 Overburden thickness to top of upper Permian coal measures and relationship to Eromanga Basin boundary in the Galillee subregion

Data: Bioregional Assessment Programme (Dataset 1)

The upper sequence of the Galilee Basin groundwater system is the main focus of the groundwater model. The hydrogeology of the upper Galilee Basin is conceptualised as a series of alternating aquifers and aquitards, outcropping on the basin's eastern boundary and gently dipping to the west. This sequence comprises the following aquifers, listed in order from youngest to oldest:

- The Clematis Group aquifer (includes Warang Sandstone in the north of the subregion) is the main regional aquifer in the Galilee Basin. This aquifer outcrops in some areas near CRDP mines. Recharge to the Clematis Group groundwater flow system is via rainfall in outcrop areas and leakage from underlying and overlying aquifers. The Clematis Group aquifer naturally discharges as baseflow to the Carmichael River and to the Doongmabulla Springs. The Moolayember Formation aquitard to a large extent separates the Clematis Group from the overlying GAB units across much of the basin, but is absent approaching the western margins of the Galilee Basin. Here the Hutton Sandstone aquifer is in direct contact with the Clematis Group aquifer (Figure 7).
- The upper Permian coal measures form a partial aquifer consisting of alternating layers of coal and porous sandstone. Coal seams within this unit are the target of mining operations, where they approach the surface, east of the Great Divide. There are seven named seams separated by interburden sandstones, ranging from the A seam in the Bandanna Formation at the top of the Betts Creek beds, to the F seam in the Colinlea Sandstone at the base, with the upper split in the D seam referred to as DU or D1, and the lower split called DL or D2. The coal seams are highly variable in thickness ranging from 0.1 m for the E seam at Kevin's Corner to 18 m for the A seam at Carmichael (data from Bleakley et al., 2014). The mean thickness of the coal seams is about 3 m. The thickest total accumulation of coal occurs at Carmichael with a total thickness of 39 m; the thinnest accumulation is at South Galilee where the total coal thickness is considerably less (14.5 m). The interburden sandstones are thicker than the coal seams, with the thickest being the BC interburden. This unit ranges in thickness from 60 m at Carmichael to 90 m at Kevin's Corner, Galilee and South Galilee (Bleakley et al., 2014). The coal seam most favoured by the mining companies is the D seam because of its low ash content. The Rewan Group separates the upper Permian coal measures from the overlying Clematis Group aquifer and forms a tight aquitard within the Galilee Basin sequence. Although the upper part of the Rewan Group (which is known as the Dunda beds) is generally regarded as more permeable than the rest of this unit (see companion product 2.1-2.2 (Evans et al., 2018a) for further details), the current lack of information about the regional extent and thickness of the Dunda beds meant that it could not be included as a specific unit within the groundwater model.
- The Joe Joe Group is the basal aquitard of the Galilee Basin, reaching in excess of 1000 m in thickness. This unit varies in hydraulic character, acting as a leaky aquitard in the north-eastern and central-eastern zone of the basin at the top of the sequence, due to the Aramac Coal Measures, and at the base of the sequence due to the Lake Galilee Sandstone. Elsewhere the unit is considered a tight aquitard.

The aquifers of the Eromanga and Galilee basins are unconformably overlain by a thin veneer of Cenozoic deposits which comprise Quaternary alluvial deposits, associated with streams, and older Cenozoic sediments. In some cases, these directly overlie the upper Permian coal measures. The potentiometric surface of the Cenozoic aquifers indicates that these sediments comprise a local groundwater flow system with a strong relationship with the surface drainage system of the major rivers, such as the Belyando River (see companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)).

As outlined in Section 2.3.2.1 in companion product 2.3 for the Galilee subregion (Evans et al., 2018b), the majority of rivers in the Galilee subregion have prolonged periods of low flow. During wet periods, river flows and flooding may recharge the alluvial aquifers. Groundwater stored in these aquifers may return to river baseflow or, if at shallow enough levels, be used as a water source for vegetation in riparian zones and on floodplains in dry periods. Groundwater discharging to rivers can prolong river flow during periods of low rainfall. Eventually, however, once groundwater levels fall below the base of the river channel, baseflow will cease.

Groundwater models are by necessity a simplification of the reality, designed to capture the salient features of the hydrogeological system relevant to the objectives of the modelling. The modelling for the BAs focuses on assessing the change to the groundwater system due to coal resource development rather than on reproducing and simulating the current and future state of the groundwater system (see submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016)). This allows the groundwater system to be simplified into the conceptual cross-section shown in Figure 9a, which subsequently is translated into an analytic element model (Figure 9b). The next section briefly introduces the main features of the implementation of the conceptual model into the groundwater model. The remainder of the product provides a more detailed discussion on the rationale and justification of these model choices.

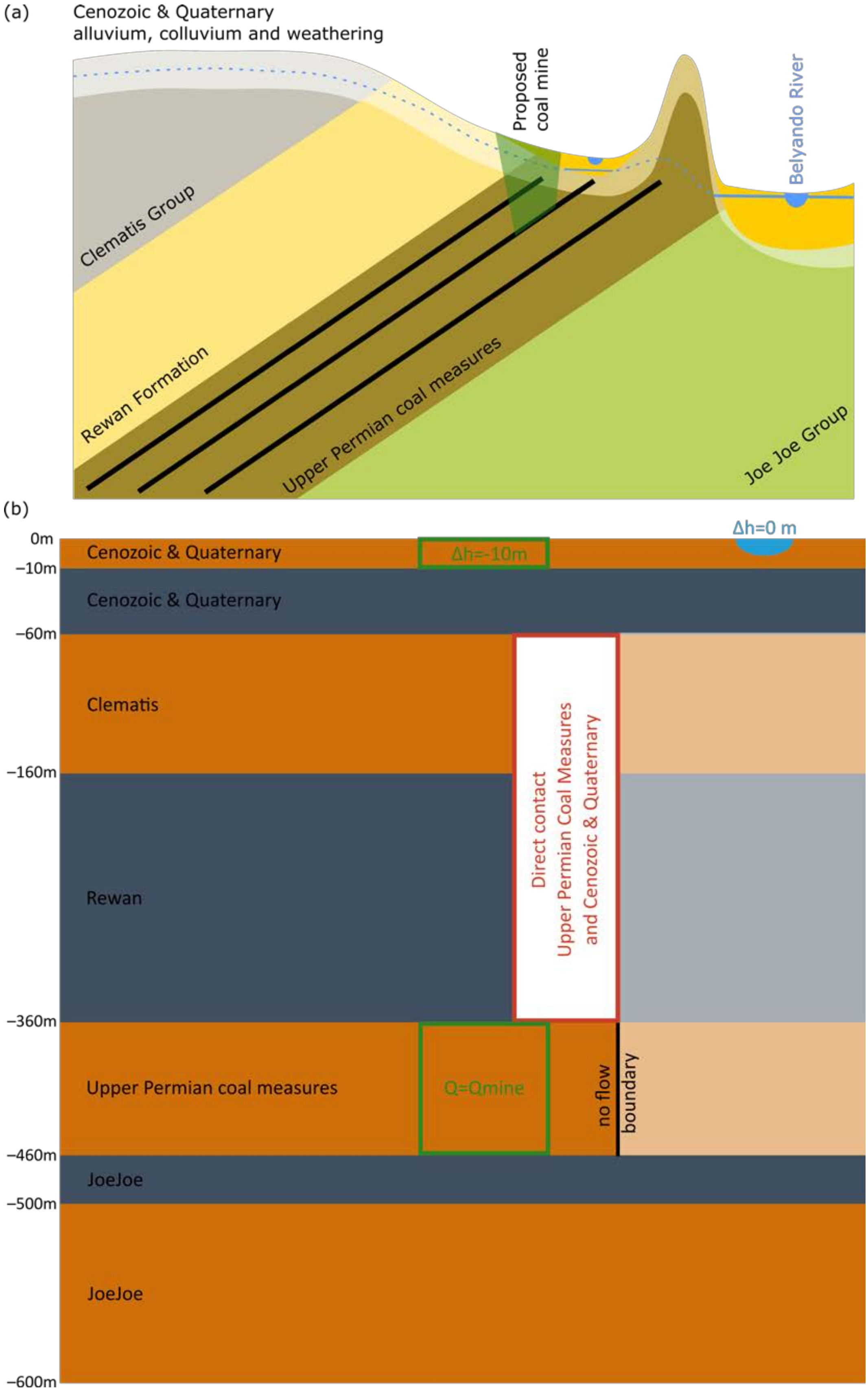

Figure 9 (a) hydrogeological conceptual cross-section, (b) corresponding cross-section of the groundwater analytic element model for the Galilee subregion

In (b) aquifers are in dark orange, aquitards in dark grey. Green colours indicate stresses related to coal mining. Blue indicates surface water groundwater interaction. Q is the mine dewatering pumping rate. Δh is the change in groundwater level.

In the GW AEM, the hydrostratigraphy is implemented as an alternating sequence of aquifers and aquitards of infinite extent, constant thickness and uniform hydraulic properties. The details of the hydrostratigraphy as implemented in the model are provided in Section 2.6.2.3.5 and Table 11. The Cenozoic and alluvial cover is conceptualised to consist of a basal zone of low-permeability sediments, representing the Cenozoic weathering that resulted in a kaolinised weathering profile (see Section 1.1.3.2.3 in companion product 1.1 (Evans et al., 2014)) and an upper zone of highly permeable sediments representing unconsolidated colluvial and alluvial sediments.

The model excludes the early Jurassic to late Cretaceous Eromanga Basin sequence comprising the Hutton Sandstone and Hooray Sandstone and Winton-Mackunda Formation aquifers. The low-permeability Moolayember Formation separates the Eromanga Basin sequence from the Clematis Group aquifer. Any hydrological change in the Eromanga Basin sequence therefore will be smaller than the change simulated in the Clematis Group aquifer. This assumption of not simulating the change in the Eromanga Basin sequence is only justified if the simulated change in the Clematis Group aquifer is sufficiently small. The results presented in section 2.6.2.8.1 indicate that this is the case. Note that in the conceptualisation shown in Figure 9, hydraulic change in the layer representing the Clematis Group can occur via two pathways. Firstly, drawdown in the upper Permian coal measures can vertically propagate through the Rewan Group and result in drawdown in the Clematis Group. A second pathway is for drawdown in the Cenozoic and alluvial cover to propagate laterally and subsequently vertically propagate downwards into the Clematis Group.

At the eastern edge of the outcrop area of the upper Permian coal measures, a no-flow boundary is assigned. The location of this boundary is shown in Figure 10 (Section 2.6.2.4). Where the upper Permian coal measures subcrop under the Cenozoic and alluvial cover, a direct hydraulic connection between the upper Permian coal measures and the Cenozoic and alluvial cover is simulated (Figure 10 in Section 2.6.2.4), with a leakage proportional to the product of the vertical hydraulic conductivity of the Cenozoic sediments and the thickness of the kaolinised weathering profile. This thickness is nominally set to 50 m (see Section 2.6.2.3.5 and Table 11). This conceptualisation recognises that while locally there will be limited overburden covering the coal measures, there will always be an impedance to flow between coal measures and colluvial and alluvial sediments.

The pumping rates reported by mining companies (see companion product 2.3 for the Galilee subregion (Evans et al., 2018b)) are assigned to the mine footprints in the upper Permian coal measures. These pumping rates are based on local-scale modelling by the mining companies, which integrates greater local geological detail than available in the regional geological model (see companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)) and more detailed mine development plans. By applying these locally derived pumping rates, local detail and information can be integrated into the regional-scale model. In the Cenozoic aquifer, a constant drawdown of 10 m is assigned to the mine footprints. This drawdown represents the direct and complete dewatering of the Cenozoic and alluvial deposits with a nominal saturated thickness of 10 m. Further details on the implementation of the CRDP are provided in Section 2.6.2.5.

The potentiometric surface of the Cenozoic sediments indicates that the alluvial system of the Belyando River can be considered to be a regional discharge feature with groundwater levels underneath the Belyando River controlled by the local interaction between river stage and groundwater evaporation. The Belyando River channel is therefore assigned a constant drawdown of zero metres as the groundwater level underneath the Belyando River channel is unlikely to change due to coal mining activity. The location of this boundary is shown in Figure 10 in Section 2.6.2.4, and a more detailed discussion of the boundary and initial conditions is provided in Section 2.6.2.4.

2.6.2.3.3 Design and implementation

Unlike classical cellular groundwater models, analytic element models are grid-independent (Bakker, 2013). Their resolution is determined by the discretisation of the internal boundary elements, the points, lines and polygons representing groundwater level or flux boundaries. One of the key advantages of this approach is the flexibility regarding time stepping and spatial locations for outputting the calculated metrics. In the temporal domain it is necessary to define stress periods (i.e. periods in which the stresses and boundary conditions are constant), but it is not necessary to temporally discretise into time steps. This means the solution to groundwater flow equations can be evaluated at arbitrary points and times.

Yearly stress-periods are chosen as this corresponds to the temporal resolution of the available mine pumping rates. As the analytic element model is only simulating the change due to coal resource development, the simulation period starts in 2018, the earliest date mine pumping rates are available, and ends in 2102, as specified in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). The submethodology also illustrates that the stochastic approach guarantees that the drawdown is not under estimated (Crosbie et al., 2016, p. 30).

2.6.2.3.4 Model code and solver

For this groundwater model the analytic element methodology is selected (Bakker, 2013) using the open-source implementation available in TTim (Bakker, 2015). The groundwater flow equations are solved based on the representation of internal boundary conditions, points, lines or polygons where constant groundwater level, constant flux or flux dependence on groundwater level is imposed. The resulting groundwater flow equations can be evaluated at arbitrary points in space and time. The solution is therefore independent of a spatial and temporal discretisation of the model domain and time into grid and time steps.

For finite-difference or finite-element groundwater models, the computational time is dominated by the number of grid cells and the number of time steps. The computational effort for the GW AEM is split between the time needed to solve the groundwater equations, which is related to the complexity of the representation of the internal boundaries, and the time needed to evaluate these equations at the required model nodes and times. In this case, a single evaluation of the transient analytic element model takes about 15 minutes.

2.6.2.3.5 Geometry and hydrostratigraphy

2.6.2.3.5.1 Hydrostratigraphy

The groundwater system is implemented as an alternating sequence of aquifers and aquitards, represented by seven model layers. Groundwater level and flow will only be simulated for the aquifers. The flow between two successive aquifers will be controlled by the hydraulic gradient between them and the hydraulic properties assigned to the aquitard separating both aquifers. A summary of the hydrostratigraphic units simulated by the GW AEM and their corresponding model layers are shown in Table 11. Companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a) provides further detail on the thickness and distribution of the various hydrostratigraphic units outlined in Table 11.

The layer representing Cenozoic sediments is an equivalent to layers representing 'Tertiary sediments' in the mine-scale groundwater models (see Section 2.6.2.2). The Cenozoic aquitard layer represents the weathering that occurred in the early Cenozoic and resulted in a kaolinised weathering profile (see Section 1.1.3.2.3 in companion product 1.1 (Evans et al., 2014)).

Unlike in most mine-scale hydrogeological numerical models, the upper Permian coal measures are simulated as a single aquifer layer. Simulating the individual seams was deemed not justified as the data are not available to establish their presence and thickness throughout the entire model domain and because the pumping rates reported by mining companies do not provide sufficient detail to partition the pumping between the different seams. In Section 2.6.2.8.2.4 it is shown that this approach leads to an underestimate of drawdown in the coal seam, but over estimates drawdown at the base of the Rewan Group aquitard.

Although there are no model nodes associated with the Joe Joe Group, it is included in the numerical model as the cone of depression in the upper Permian coal measures can propagate into this hydrostratigraphic unit. The Joe Joe Group is separated into two layers, an upper aquitard and an aquifer. The upper aquitard represents the impedance to flow between the upper Permian coal measures and the Joe Joe Group due to coal interburden layers. The Joe Joe Group aquifer is assigned a nominal thickness of 100 m to recognise that it is very unlikely that the entire Joe Joe Group is acting as a vertically homogeneous aquifer contributing evenly to groundwater flow. Representing the entire formation thickness would result in a very high transmissivity and storage. This would provide the model with a source of water that is unlikely to be mobilised and therefore representing the entire thickness would lead to an underestimate of drawdown.

Table 11 Hydrostratigraphy and corresponding model layers used for the groundwater analytic element model (GW AEM) for the Galilee subregion

Unit name	Hydrogeology	GW AEM layer	GW AEM layer thickness (m)	Comments
Quaternary alluvium	Unconfined aquifer	Model layer 1 – aquifer	10	Generally high permeability and high recharge; in many places the alluvial aquifer is highly interactive with surface waters
Cenozoic sediments	Semi-confined aquifer	Model layer 2 – aquitard	50	Lower permeability unit receiving less recharge than alluvial aquifer, and saturated zone may not be laterally continuous
Clematis Group	Confined aquifer	Model layer 3 – aquifer	100	Variable yields of generally fresh sub-artesian groundwater; some areas of artesian pressures are evident in western portions of the aquifer
Rewan Group	Regional aquitard	Model layer 4 – aquitard	200	Regional aquitard that separates the upper Permian coal measures from overlying sequences in the Galilee Basin; generally of low permeability. The upper and slightly more permeable part of the Rewan Group (i.e. the Dunda beds) is not explicitly represented in the GW AEM due to insufficient data on its extent and thickness at the regional scale of the assessment.
Upper Permian coal measures	Partial aquifer	Model layer 5 – aquifer	100	Significant aquifer with vertical hydraulic gradients existing between some coal seams and interburden sandstones; hydrostratigraphic sequence is heterogeneous
Joe Joe Group	Basal aquitard of the Galilee Basin	Model layer 6 – aquitard	40	Leaky aquitard at top of and base of sequence in the north-eastern and central eastern zone of the basin; generally a tight aquitard elsewhere; Joe Joe Group split into two layers for the GW AEM to assist computation
		Model layer 7 – aquifer	100	

2.6.2.3.5.2 Model geometry

The model layers are of infinite lateral extent, horizontal, with constant thickness (Figure 9b). The top of the model is set to an arbitrary level of zero metres and the total thickness of the simulated sedimentary column is 600 m.

The geological cross-section in Figure 7 does indicate that the hydrostratigraphic units in the Galilee Basin dip towards the west, basin-inwards, and that the thickness of these units is variable. The change in a confined groundwater system depends on the transmissivity of the aquifers and leakage of aquitards. Changes in slope and thickness are therefore only important insofar that they affect transmissivity and leakage. As detailed in the parameterisation section of this product (Section 2.6.2.6), all uncertainty regarding the transmissivity and leakage is transferred to the uncertainty in the hydraulic conductivity. Section 7.1 in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016) discusses in greater detail how the assumption of uniform hydraulic parameters in combination with the stochastic approach will not lead to an underestimate of drawdown.

The Cenozoic and alluvial deposits are not continuous, have a high variability in thickness and are unconfined. Despite the assumption that the layer is of uniform thickness and of infinite extent is not an entirely accurate representation of reality, it is justified as it will lead to an overestimate of the extent of the hydrological change. It will be possible for the groundwater model to predict drawdown in locations beyond the boundary of the Cenozoic cover, where these sediments, in fact, are not present. Within the boundaries of the Cenozoic cover, however, the magnitude of drawdown potentially is under estimated. The boundaries of the Cenozoic cover can be thought of as impermeable boundaries, and pumping close to impermeable boundaries will lead to larger drawdowns than when these boundaries are not present (Kruseman and de Ridder, 1994).

This conceptualisation of the Cenozoic cover is nevertheless considered justified as it will lead to an overestimate of the number of model nodes that are potentially affected, although locally drawdown will be under estimated.

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2.6.2.4 Boundary and initial conditions

Summary

Analytic element modelling is grid independent and by default assumes aquifers and aquitards are of infinite extent. This offers great flexibility in generating output at any desired location and obviates the need to explicitly specify lateral boundary conditions as is the case for finite-difference or element codes. The eastern extents of the upper Permian coal measures and of the Clematis Group are, however, explicitly represented as no-flow boundaries.

The model directly simulates the change due to coal resource development. The initial conditions, the initial change, is zero in every model layer as currently no coal resource developments are active.

At the regional scale, coal resource development does not alter recharge. No change in recharge is therefore simulated.

The river network is considered ephemeral and disconnected. This implies that the surface water – groundwater flux is not dependent on the position of the watertable. As this flux will not change due to drawdown, these streams are not represented. The Belyando River, however, is considered as a regional discharge feature. The river stage in the Belyando River is dominated by runoff in the Belyando river basin. The river is, therefore, represented as a specified head boundary, where a change in groundwater level equal to zero is imposed in the Belyando River channel.

2.6.2.4.1 Initial conditions

The groundwater model is directly simulating the change to the system, not the state of the system. As there were no commercially producing coal resource developments in the Galilee subregion at the end of 2012, the change in the system at that time is zero. The initial conditions (i.e. the initial change in groundwater level) therefore are equal to zero in all aquifers.

2.6.2.4.2 Lateral

Analytic element modelling is grid independent and by default assumes aquifers and aquitards are of infinite extent. The eastern boundary of the upper Permian coal measures is implemented as a no-flow boundary in the model (Figure 10).

The direct contact between the upper Permian coal measures and the Cenozoic/alluvium aquifer is implemented as a linear feature in the groundwater analytic element model (GW AEM) in the centre of the area where upper Permian coal measures subcrop underneath the Cenozoic and Quaternary cover sediments. The linear feature allows groundwater levels in the upper Permian coal measures to locally equilibrate with groundwater levels in the Cenozoic/alluvium aquifer through a conductance term which represents the Cenozoic aquitard. In effect, this means groundwater extraction in the upper Permian coal measures can propagate directly to the Cenozoic/alluvium aquifer layer.

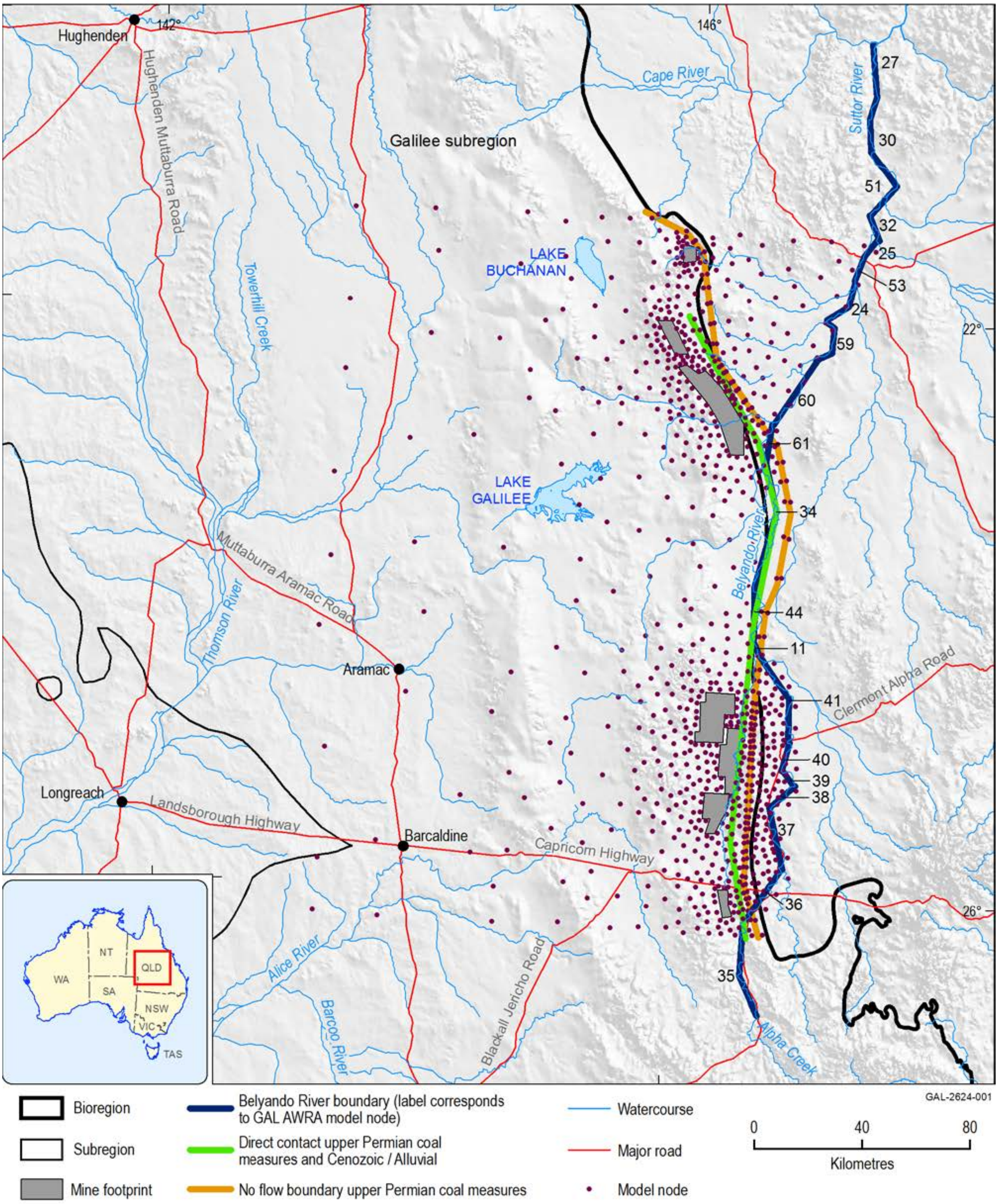

Figure 10 Lateral and internal boundary conditions and model nodes for the groundwater analytic element model (GW AEM) for the Galilee subregion

AWRA = Australian Water Resources Assessment; GAL = Galilee subregion
Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.4.3 Recharge and evapotranspiration

Recharge and evapotranspiration were not included in the regional GW AEM. In this modelling approach, only the change in the system due to coal resource development is simulated. At the regional scale, coal resource development does not change land use or rainfall patterns. The change in recharge and evapotranspiration due to coal resource development is thus zero and therefore not included in the model. It is noted that at the local, mine development scale, the change in land use will result in a change in recharge and evapotranspiration, especially after mining ceases. This is beyond the resolution and scope of the modelling. A more detailed discussion on this rationale and the effect on predictions is provided in the qualitative uncertainty analysis in Section 2.6.2.8.

2.6.2.4.4 Surface water – groundwater interactions

Surface water – groundwater interactions are represented as a linear feature in the GW AEM to which a constant groundwater level of zero metres is assigned. The linear feature consists of line segments approximating the main channel of the Belyando River (Figure 10). The line segments correspond to the stream reaches used in the surface water modelling (see companion product 2.6.1 for the Galilee subregion (Karim et al., 2018)).

The Belyando River receives some baseflow from shallow aquifers, as indicated in the potentiometric surface for the Cenozoic sediments in Section 2.1.3.3.2 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018). This groundwater discharge occurs either as a baseflow contribution to the Belyando River or through direct evapotranspiration by vegetation. This means the groundwater levels underneath the Belyando River system are mostly controlled by the riverbed elevation and the extinction depth of evapotranspiration, provided the Belyando River remains a regional discharge location.

The other rivers and creeks in the model domain are not considered to be discharge locations for regional groundwater flow and are not represented in the analytic element model. These ephemeral streams, when flowing, are likely to be losing streams – that is, they could locally recharge the alluvial aquifer. For the majority, they will be losing disconnected – that is, the loss rate is independent of the groundwater level in the aquifer (Brunner et al., 2009). In that case, any change in the groundwater level due to coal resource development will not affect the surface water – groundwater interaction flux. Not representing these streams will result in a conservative estimate of the drawdown as the simulated drawdown cannot be compensated by an increase in the water flux entering the aquifer through the stream. However, wherever drawdown is simulated under creek beds, local information needs to be sought to establish the connection status of the creek at that location to evaluate the potential change in surface water – groundwater flux.

For the Belyando River, any drawdown simulated in the Cenozoic/alluvium aquifer will not result in a drawdown underneath the Belyando River, but it will result in a reduction in the surface water – groundwater flux. The change in surface water – groundwater flux thus simulated is subtracted from the total streamflow for that stream segment calculated by the Australian Water Resources Assessment landscape model (AWRA-L) (see companion product 2.6.1 (Karim et al., 2018)). As pointed out in the methods section (Section 2.6.2.1) in Equation (1), the minimum resulting streamflow is zero.

This implementation of the river boundary results in an overestimate of the reduction in surface water – groundwater flux, as it comprises both the change in baseflow and groundwater evapotranspiration. It does this only locally, however, as in the immediate vicinity of the river channel drawdowns are under estimated.

The Carmichael River receives baseflow through discharge from the Clematis Group aquifer as well as through outflow from the Doongmabulla Springs complex, which is also sourced from the Clematis Group aquifer. Any change in the flow rate of these springs therefore has the potential to change the baseflow contribution to the Carmichael River. Previous modelling, such as Turvey et al. (2015) indicates that these changes are very small. The change in baseflow in the Carmichael River due to changes in spring flow rates is not simulated explicitly or incorporated in the AWRA-L model. This assumption is only valid if the changes in spring flow rate are very small. The Doongmabulla Springs complex is therefore included in the model to quantify the change and verify this assumption. Further discussion about the conceptual understanding of the Doongmabulla Springs complex is provided in companion product 3-4 (Lewis et al., 2018) for the Galilee subregion.

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2.6.2.5 Implementation of the coal resource development pathway

Summary

Groundwater extraction from seven of the mines included in the coal resource development pathway (CRDP) for the Galilee subregion has been explicitly modelled by the groundwater analytic element model (GW AEM).

Anticipated groundwater production rates for mines were obtained from relevant environmental impact statements and applied to digitised polygons that represent the active mine working areas. To simulate dewatering of alluvial sediments proximal to mine pits, a constant head of –10 m was applied along the boundary of each mine footprint, representing complete dewatering of the Cenozoic and alluvial deposits.

The Galilee subregion CRDP consists of 17 proposed new coal and coal seam gas (CSG) resource development projects (see companion product 2.3 for the Galilee subregion (Evans et al., 2018b)). Of these, only seven coal resource developments included in the modelled CRDP are incorporated into the GW AEM as they had sufficient information for modelling (Table 12). As there are no baseline coal resource developments in the Galilee subregion, the CRDP is defined only by the additional coal resource developments.

2.6.2.5.1 Coal mines

No developments were included in the baseline coal resource development (baseline), which is a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012. Most mine inflow rates were obtained from relevant environmental impact statements (EIS). Where applicable to the coal development, mine inflow rates outlined in EIS incorporate changes that may occur to aquifer parameters under post-mining fractured conditions.

Anticipated groundwater production rates for CRDP mines included in the GW AEM are outlined in Table 12. For two coal mine developments (Hyde Park and China Stone), groundwater production rates had to be estimated from proposed coal yields and assumed hydraulic conditions (Table 12) as relevant data were not available at the time of writing.

Table 12 Coal resource development pathway (CRDP) mines included in the groundwater analytic element model (GW AEM) and anticipated groundwater production rates from upper Permian coal measures partial aquifer

Coal project	Decade	Production rate (ML/d)	Source
Hyde Park	2018–2028	1.5	Rates estimated from coal yield and assumed hydraulic conditions
	2028–2038	3	Rates estimated from coal yield and assumed hydraulic conditions
	2038–2048	3	Rates estimated from coal yield and assumed hydraulic conditions
China Stone	2018–2028	8.1	Rates estimated from coal yield and assumed hydraulic conditions
	2028–2038	13.5	Rates estimated from coal yield and assumed hydraulic conditions
	2038–2048	13.5	Rates estimated from coal yield and assumed hydraulic conditions
Carmichael	2018–2028	12.3	GHD (2013)
	2028–2038	13.7	GHD (2013)
	2038–2048	14.3	GHD (2013)
	2048–2058	13.4	GHD (2013)
	2058–2068	6.6	GHD (2013)
	2068–2078	1.8	GHD (2013)
Kevin's Corner	2018–2028	7	URS (2012)
	2028–2038	8.7	URS (2012)
	2038–2048	9.5	URS (2012)
Alpha	2018–2028	5.3	URS (2012)
	2028–2038	5.3	URS (2012)
	2038–2048	5.3	URS (2012)
China First (Galilee)	2018–2028	27.2	Merrick and Alkhatib (2013)
	2028–2038	63	Merrick and Alkhatib (2013)
	2038–2048	70	Merrick and Alkhatib (2013)
South Galilee	2018–2028	17.3	RPS Aquaterra (2013)
	2028–2038	24.7	RPS Aquaterra (2013)
	2038–2048	24.7	RPS Aquaterra (2013)

Data: Bioregional Assessment Programme (Dataset 1)

The coal mines are represented in the GW AEM as polygons, which outline the boundary of the mine working area (Figure 4 in Section 2.6.2.1). The mine working area represents the combined footprint of open-cut and underground mine areas that are active during one of the decadal modelling time periods (Table 12). For each mine working area, relevant pumping rates were applied to the polygon boundary.

For Kevin's Corner, Alpha, Galilee and South Galilee coal projects, polygons that represent their mine working areas were digitised from mine scheduling maps in their respective supplementary environmental impact statements (Table 12).

For Carmichael and China Stone coal projects, the mine scheduling maps were not readily available at the time of building the GW AEM, so these were approximated using mine tenement boundaries.

Hyde Park, while an advanced and active development project, has (as of December 2015) not submitted an environmental impact statement for consideration by state government agencies. However, maps outlining mine scheduling are available and these were used to generate the mine working area polygons utilised in the model.

Where Cenozoic sediments were conceptualised to overlie a mine working area, a constant change in head of –10 m was applied at the edge of the mine working footprint, from the start of mining. All of the mines listed in Table 12 have an open-cut component in which the Cenozoic cover, if present, will be removed as part of the overburden. This creates a permanent drainage of the Cenozoic sediments, even after mining operations cease. There are insufficient data available to specify the drawdown in the Cenozoic cover at the edge of the mine footprint individually. Based on the thickness and potentiometric surface of the Cenozoic cover sediments (Section 2.1.2.2.5 and Section 2.1.3.3.2 in companion product 2.1-2.2 for the Galilee subregion (Evans et al. 2018a)), the constant specified drawdown of 10 m is a representative value of the saturated thickness of cover sediments at the mine locations.

2.6.2.5.2 Coal seam gas wells

No coal seam gas (CSG) projects were included in the groundwater analytic element model as CSG projects in the Galilee subregion are not sufficiently advanced; therefore, sufficient data on development parameters such as pumping rates are not available as of January 2016.

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2.6.2.6 Parameterisation

Summary

The hydraulic properties of the groundwater analytic element model (GW AEM) are chosen to be lognormally distributed (with the exception of the specific yield of the Cenozoic and alluvial cover aquifer, which is normally distributed).

The means of the distributions are based on those documented in Bleakley et al. (2014). Bleakley et al. (2014) contains hydraulic field test data, core test data and calibrated model parameters obtained from mining proponent reports, produced as part of the environmental impact statement assessment process.

The standard deviations are chosen such that the interquartile range covers at least one order of magnitude.

Table 13 lists the parameter distributions used in the GW AEM for the Galilee subregion for sensitivity and uncertainty analysis. The analytic element modelling code TTim (Bakker, 2015) requires for aquifer layers to specify horizontal hydraulic conductivity (*Kh*) and specific storage (*Ss*) (for confined aquifers) or specific yield (*Sy*) (for unconfined aquifers). Aquitard layers require specification of vertical hydraulic conductivity (*Kv*) and specific storage (*Ss*).

In finite-difference groundwater modelling codes such as MODFLOW (Harbaugh et al., 2000), the vertical flow between model layers is controlled by the equivalent vertical hydraulic conductivity, computed based on the vertical hydraulic conductivity assigned to the model layers. In the analytic element groundwater code as implemented for the Galilee subregion, vertical flow between aquifers is controlled by the vertical hydraulic conductivity assigned to the interspersed aquitard. It is therefore not necessary to specify vertical hydraulic conductivity to aquifer layers or horizontal hydraulic conductivity to aquitard layers.

For most of the hydraulic properties of the hydrostratigraphic units, insufficient data are available to empirically establish a formal probability distribution. Some local information on aquifer properties is available from various technical reports. For example, Harrington et al. (2012) provides a preliminary review of the available data in the region, while Bleakley et al. (2014) is a more comprehensive summary of currently available hydraulic property information relevant to the Galilee Basin. Bleakley et al. (2014) contains hydraulic field test data, core test data and calibrated model parameters obtained from mining proponent reports, produced as part of the environmental impact statement assessment process. This product is, therefore, the main source to establish the ranges of hydraulic properties in the GW AEM.

Each parameter is assumed to be lognormally distributed, in line with international literature on distributions of hydraulic properties (Carrera et al., 2005). The specific yield of the alluvial hydrostratigraphic unit is the only parameter that is not transformed. The means of the distributions are based on those documented in Bleakley et al. (2014). In some cases, the specific storage values used are not exact matches to those provided in Bleakley et al. (2014) but are conservative estimates selected for modelling purposes (see source notes in Table 13).

The standard deviation is chosen such that the interquartile range, the range between the 25th and 75th percentile, approximately covers at least an order of magnitude. To illustrate the resulting range, Table 13 lists the mean of the distribution as well as the 5th, 50th and 95th percentile of the distribution (based on 10,000 samples). Although the ranges are based on the limited local information, they correspond well to ranges reported in international literature, such as in Batlle-Aguilar et al. (2016). No covariance between parameters is specified as no reliable information is available locally or in international literature. Not specifying covariance will result in conservative predictions as unlikely parameter combinations (e.g. high conductivity and low storage) are retained in the parameter distributions used in the uncertainty analysis.

Table 13 Parameter distributions used for the groundwater analytic element model (GW AEM) for the Galilee subregion

Parameter name	Description	Units	Trans-formation	Mean	[5th, 50th, 95th] percentile (based on 10,000 samples)	Source
Kh_Alluvium	Horizontal hydraulic conductivity of Cenozoic and alluvial aquifer	m/d	Log10	0.99	[0.18, 1.00, 5.37]	Bleakley et al. (2014) – field test data. Maximum reported value
Sy_Alluvium	Specific yield of Cenozoic and alluvial aquifer	%	None	0.10	[0.07, 0.10, 0.13]	Bleakley et al. (2014) – calibrated model value used in Carmichael modelling (literature value for Sy)
Kv_Alluvium	Vertical hydraulic conductivity of Cenozoic aquitard	m/d	Log10	0.01	[1.91×10^{-3}, 0.01, 0.05]	Assumed value based on Bleakley et al. (2014) – Kh field test data. Minimum reported value for alluvium and tertiary units
Kh_Clematis	Horizontal hydraulic conductivity of Clematis Group aquifer	m/d	Log10	2.99	[0.56, 3.03, 15.6]	Bleakley et al. (2014) – field test data. Minimum reported value
Ss_Clematis	Specific storage of Clematis Group aquifer	1/m	Log10	1.85×10^{-6}	[3.46×10^{-7}, 1.85×10^{-6}, 9.76×10^{-6}]	Assumed value based on Bleakley et al. (2014) – calibrated model value. Very low value (will yield larger drawdowns), corresponds to max Storativity of ~1×10^{-3}
Kv_Rewan	Vertical hydraulic conductivity of Rewan Group aquitard	m/d	Log10	8.96×10^{-6}	[1.69×10^{-6}, 8.91×10^{-6}, 4.90×10^{-5}]	Bleakley et al. (2014) – core test data. Minimum recorded value

Parameter name	Description	Units	Trans-formation	Mean	[5th, 50th, 95th] percentile (based on 10,000 samples)	Source
Ss_Rewan	Specific storage of Rewan Group aquitard	1/m	Log10	3.59×10^{-7}	[6.85×10^{-8}, 3.56×10^{-7}, 1.90×10^{-6}]	Assumed value based on Bleakley et al. (2014) – calibrated model value. Very low value (will yield larger drawdowns), corresponds to Storativity of ~1×10^{-4}
Kh_BCB	Horizontal hydraulic conductivity of upper Permian coal measures aquifer	m/d	Log10	0.10	[0.02, 0.10, 0.52]	Assumed value based on Bleakley et al. (2014) – field test data high values
Ss_BCB	Specific storage of upper Permian coal measures aquifer	1/m	Log10	1.89×10^{-6}	[3.61×10^{-7}, 1.89×10^{-6}, 1.03×10^{-5}]	Assumed value based on Bleakley et al. (2014) – field test data. Corresponds to Storativity of ~2×10^{-4} – within range of observed values
Kh_JoeJoe	Horizontal hydraulic conductivity of Joe Joe Group aquifer	m/d	Log10	1.51×10^{-4}	[2.77×10^{-5}, 1.52×10^{-4}, 7.86×10^{-4}]	Assumed values based on Bleakley et al. (2014) – core test data. Represents both lower upper Permian coal measures and Joe Joe Group, mid-range values
Kv_JoeJoe	Vertical hydraulic conductivity of Joe Joe Group aquitard	m/d	Log10	1.72×10^{-4}	[3.18×10^{-5}, 1.73×10^{-4}, 7.86×10^{-4}]	Assumed values based on Bleakley et al. (2014) – core test data. Represents both lower upper Permian coal measures and Joe Joe Group, mid-range values
Ss_JoeJoe	Specific storage of Joe Joe Group aquifer	1/m	Log10	1.00×10^{-6}	[1.90×10^{-7}, 9.99×10^{-7}, 5.32×10^{-6}]	Assumed value based on Bleakley et al. (2014) – field test data. Corresponds to Storativity of ~1×10^{-4}

Data: Bioregional Assessment Programme (Dataset 1)
All parameters are considered to be normally distributed.

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2.6.2.7 Observations and predictions

Summary

The regional groundwater analytic element model (GW AEM) is not designed to reproduce historical conditions and can therefore not be constrained by historical observations.

A set of 47 model nodes were selected for which the drawdown (*dmax*) – the maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development – and year of maximum change (*tmax*) were calculated. In addition to this set, more than 500 model nodes were defined for which time series of drawdown for each hydrostratigraphic unit was recorded and stored.

The results of the sensitivity analysis indicate that the most important parameters affecting the drawdown at a model node are the hydraulic properties of the hydrostratigraphic unit in which the model node is located.

2.6.2.7.1 Observations

The GW AEM is designed to simulate the change in the groundwater system due to coal resource development directly, not to simulate historical conditions in the Galilee sedimentary basin. Comparison with historical observations of groundwater pressure or fluxes is therefore not possible or warranted. Fitting a complex model to a limited observation dataset that is not designed to inform such exercise, but designed to monitor water resources, will lead to biased parameter estimates which subsequently will lead to biased model predictions (Doherty and Welter, 2010). In this light, the unconstrained suite of parameters employed here are conservative and less prone to bias.

2.6.2.7.2 Predictions

The model is designed to estimate drawdowns caused by the coal resource developments in the modelled CRDP at specified locations in the upper Permian coal measures, the Clematis Group and the Cenozoic and Quaternary cover sediments. These model nodes are presented in Figure 4 and Table 4 in Section 2.6.2.1. Table 14 conveys the same information, together with a short description of each model node, its water source and the model layer the model node is assigned to.

As outlined in Table 14, the water source for two model nodes is interpreted to be the Ronlow beds (part of the GAB). Conceptually, it is unlikely there could be measureable drawdown impacts to aquifers in the Ronlow beds due to its distance from coal resource development areas and the presence of a thick aquitard (the Moolayember Formation) between the Ronlow beds and the underlying Clematis Group. To test this hypothesis, some model nodes, for which the water source is the Ronlow beds, are incorporated into the model. For the sake of model simplicity and for minimising model runtimes, the decision was taken to attribute these model nodes to the Clematis Group. The reasoning being that, the probability of a measurable impact in the Ronlow beds will always be less than the probability of measurable impact in the underlying Clematis Group at these particular model nodes. A similar approach was also taken for model nodes associated with wetlands and streams underlain by the Moolayember Formation (e.g. Lake Galilee).

For one of the model nodes listed in Table 14, it is not deemed justified to estimate drawdown with the analytic element model. This is model node GAL_041, the Alpha town water supply. The town water supply sources water from the Belyando alluvium, which is only connected to the Galilee Basin via the Joe Joe Group. This part of the alluvium and the connection is not well represented in the analytic element model and drawdown at the Alpha town water supply is therefore not simulated.

In addition to the model nodes listed in Table 14 and Figure 4, drawdown is also calculated for each model layer at the model nodes indicated in Figure 10. These model nodes are distributed throughout the model domain with a higher density around areas of high potential hydraulic gradients (i.e. the coal mines and no-flow boundary).

Table 14 Model nodes for which drawdown due to coal resource development in the Galilee subregion was calculated with the groundwater analytic element model

ID	Easting	Northing	Description	Water source	Model layer
GAL_001	453657.9	7471715	Sandy Creek Belyando confluence / Sandy Creek GDE	Alluvium	0
GAL_002	467416.3	7391929	Native Companion Creek / Alpha Creek confluence, Native Companion Creek GDE	Alluvium	0
GAL_003	453168.4	7366093	Alpha Creek upstream of Alpha, Alpha Creek GDE	Alluvium	0
GAL_004	465511.3	7448484	Native Companion Creek GDE	Alluvium	0
GAL_005	449398.1	7451778	Sandy Creek GDE	Alluvium	0
GAL_006	443960.9	7409432	Sandy Creek	Alluvium	0
GAL_007	451739.7	7498689	Belyando River GDE just upstream of Fiery Creek anabranch	Alluvium	0
GAL_008	451700	7510913	Fiery Creek GDE anabranch	Alluvium	0
GAL_009	455986.2	7511072	Belyando River GDE	Alluvium	0
GAL_010	453565.3	7524605	Dunda Creek GDE / Fiery Creek GDE confluence	Alluvium	0
GAL_011	454795.6	7534884	Belyando River GDE	Alluvium	0
GAL_012	443564	7514485	Dunda Creek GDE	Alluvium	0
GAL_013	430030.6	7512183	Dunda GDE overlying Clematis Group	Alluvium	0
GAL_014	437055.3	7509603	Dunda GDE overlying Rewan Group	Alluvium	0
GAL_015	452414.4	7541155	Belyando GDE	Alluvium	0
GAL_016	449040.9	7538496	Belyando GDE anabranch	Alluvium	0
GAL_017	443802.2	7533932	Belyando tributary drainage line	Alluvium	0
GAL_018	453564.2	7556466	Carmichael – Belyando GDE confluence	Alluvium	0
GAL_019	437371.7	7555196	Carmichael GDE at confluence of two anabranches	Alluvium	0
GAL_020	430942.3	7554878	Carmichael GDE overlying Dunda beds subcrop	Alluvium	0
GAL_021	425756.4	7556783	Carmichael GDE overlying Clematis Group	Alluvium	0
GAL_022	421999.3	7558212	Dyllingo Creek near Moolayember Formation subcrop	Clematis Group	1
GAL_023	443060.2	7557895	Carmichael River GDE at subregion boundary	Alluvium	0
GAL_024	459411.5	7562340	Belyando River GDE	Alluvium	0
GAL_025	402631.8	7562670	Dyllingo Creek GDE near Clematis Group subcrop	Alluvium	0
GAL_026	388212	7563993	Dyllingo Creek GDE near Clematis Group / Moolayember Formation subcrop	Alluvium	0
GAL_027	382060.4	7565978	Dyllingo Creek GDE near Ronlow beds subcrop	Alluvium	0
GAL_028	413175.5	7591908	China Stone near Clematis Group outcrop	Clematis Group	1

ID	Easting	Northing	Description	Water source	Model layer
GAL_029	389025	7518959	Lake Galilee wetlands (underlain by Moolayember Formation)	Clematis Group	1
GAL_030	388892.6	7534713	Lake Galilee wetlands (underlain by Moolayember Formation)	Clematis Group	1
GAL_031	441970.2	7513781	Cluster of groundwater licences in Betts Creek beds	Upper Permian coal measures	2
GAL_032	449673.4	7521390	Cluster of groundwater licences in Betts Creek beds	Upper Permian coal measures	2
GAL_033	427963.3	7508796	Cluster of groundwater licences in Clematis Group	Clematis Group	1
GAL_034	428043.8	7383876	Cluster of groundwater licences in Clematis Group / Dunda beds	Clematis Group	1
GAL_035	419180.2	7454256	Cluster of groundwater licences in Clematis Group / Dunda beds	Clematis Group	1
GAL_036	369975.8	7549910	Springnv38_Desert – source possibly Ronlow beds	Clematis Group	1
GAL_037	421384.5	7557193	Doongmabulla springs	Clematis Group	1
GAL_038	424294.9	7556829	Doongmabulla springs	Clematis Group	1
GAL_039	363390.3	7498810	Spring107A. Ronlow beds source	Ronlow beds	1
GAL_040	373047.6	7427372	Spring114. Ronlow beds source	Ronlow beds	1
GAL_041	463268.9	7384570	ALPHA TWS environs	Alluvium	NA
GAL_042	410776.3	7389482	JERICHO TWS environs	Clematis Group	1
GAL_043	446766.4	7532055	Mellaluka springs	Upper Permian coal measures	2
GAL_044	421085.9	7559288	Doongma spring_Burdekin_51	Clematis Group	1
GAL_045	438099	7484976	Hector spring_Burdekin_84	Upper Permian coal measures	2
GAL_046	443606.8	7494960	Albro springs_Burdekin_85	Upper Permian coal measures	2
GAL_047	423823.8	7557007	H202 Clematis Group monitoring bore	Clematis Group	1

GDE = groundwater-dependent ecosystem; TWS = town water supply; the topmost layer in the groundwater model is assigned '0'; NA indicates drawdown at model node could not be simulated. Potential hydrological change at this location will be discussed qualitatively in companion product 3-4 (impact and risk analysis) for the Galilee subregion.
Data: Bioregional Assessment Programme (Dataset 1); Bioregional Assessment Programme (Dataset 2)

The GW AEM calculates a time series of the change in groundwater level due to coal resource development. As initial conditions in each model layer are set equal to zero metres, this change in groundwater level corresponds to the drawdown. Figure 11 shows an example of these time series. For each model node, only the drawdown (*dmax;* the maximum difference in drawdown between the CRDP and baseline, due to additional coal resource development) and year of maximum change (*tmax*) are recorded and stored. Figure 11 illustrates how these values are calculated.

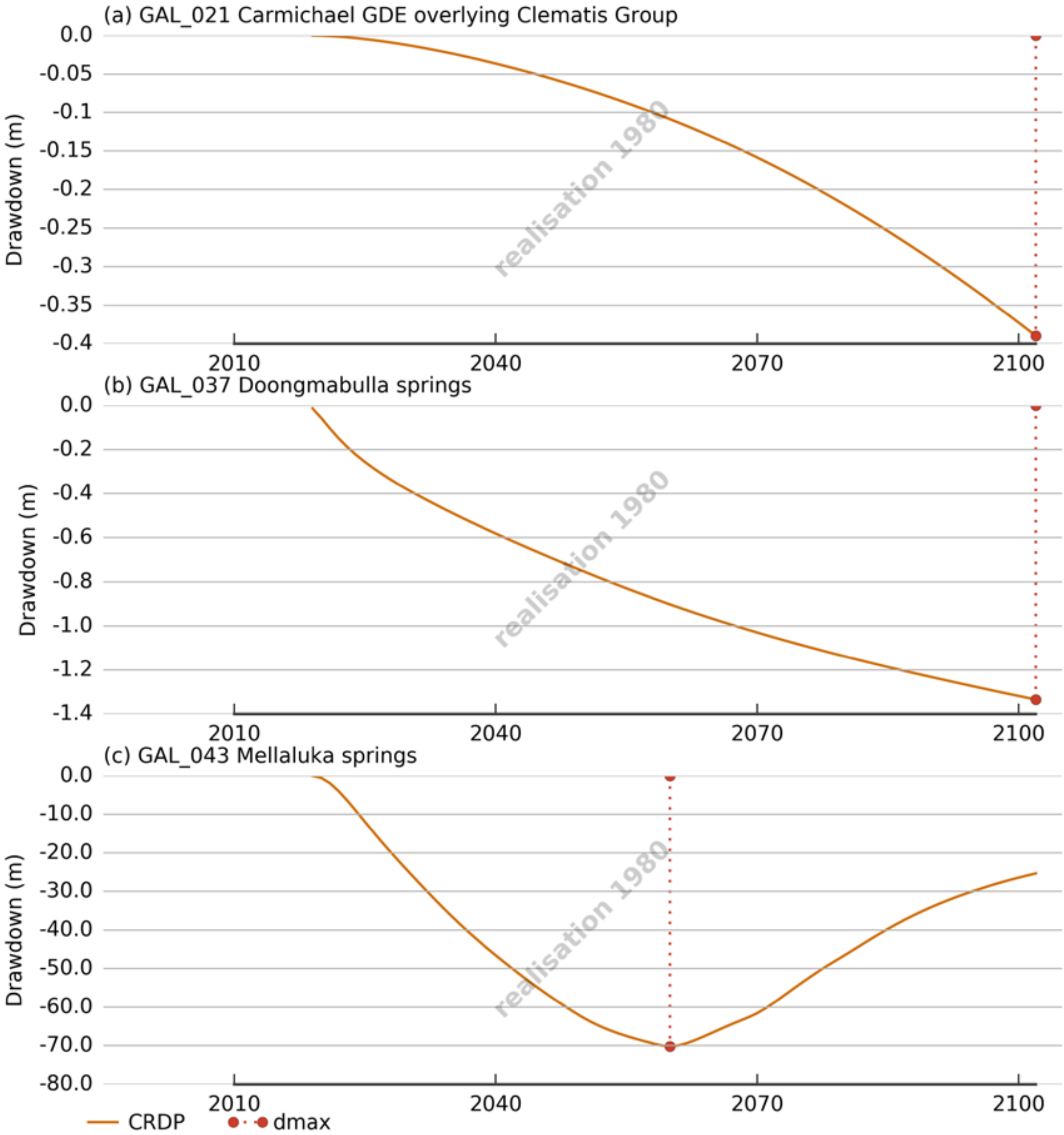

Figure 11 Time series of drawdown at selected model nodes (a) GAL_021 Carmichael groundwater-dependent ecosystem (GDE) overlying Clematis Group, (b) GAL_037 Doongmabulla Springs and (c) GAL_043 Mellaluka Springs for parameter combination 1980

dmax = maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development
CRDP = baseline + additional coal resource development
Data: Bioregional Assessment Programme (Dataset 1)

The graphs in Figure 11 show the results of parameter combination number 1980 of the 10,000 parameter combinations of the groundwater model that have been evaluated for the uncertainty analysis (Section 2.6.2.8). For this parameter combination, the drawdown is only realised within the simulation period in the upper Permian coal measures.

In the remaining sections of this product, the results of the modelling will always be presented as summary statistics of the resulting predictive distributions, such as the median *dmax* value or the probability that *dmax* exceeds a pre-specified threshold.

2.6.2.7.3 Sensitivity analysis

Section 2.6.2.8 provides a comprehensive description of the parameter combinations used for the uncertainty analysis and how these are derived from the initial values presented in Table 10. This section examines the effect of parameters on predictions in order to identify the most influential parameters.

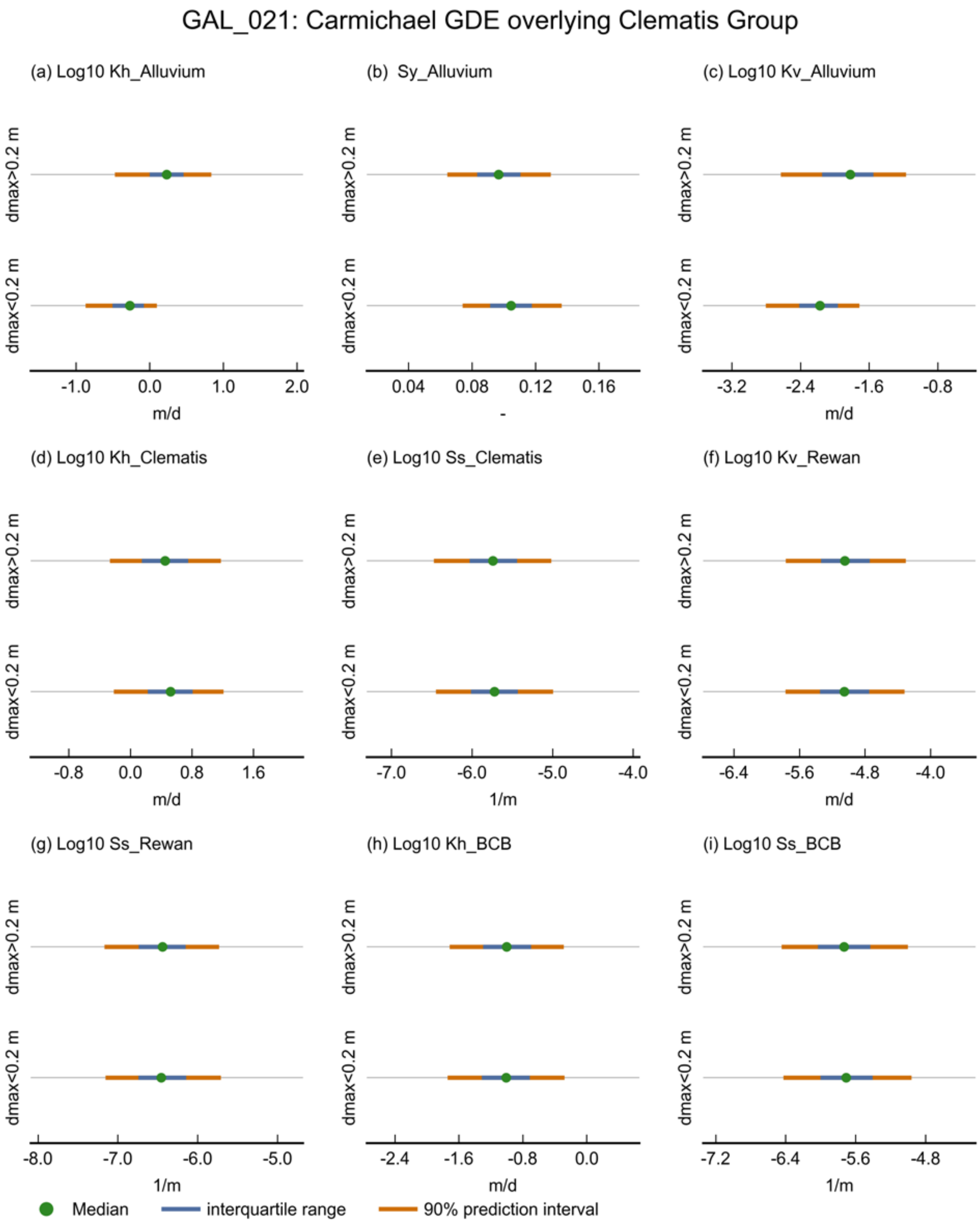

Figure 12 Boxplots of Galilee subregion analytic element model parameter values from the posterior parameter distributions giving rise to *dmax* values less and greater than 0.2m for model node GAL_021 Carmichael groundwater-dependent ecosystem (GDE) overlying Clematis Group

Each dot represents a model evaluation. The red lines indicate the median of the *dmax* values in the parameter range spanned by the red line segment.

dmax = maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development

CRDP = baseline + additional coal resource development

Data: Bioregional Assessment Programme (Dataset 1)

Figure 12 shows the variation of the drawdown at model node GAL_021, the Carmichael groundwater-dependent ecosystem (GDE) overlying Clematis Group sediments, in the alluvium west of the Carmichael Coal Project in function of the GW AEM parameters. From this plot it is apparent that drawdown is mostly influenced by the hydraulic properties of the alluvium. The horizontal hydraulic conductivity appears to be the dominant parameter. This is a clear indication that the simulated drawdown at this model node is a propagation of the drawdown in the alluvium rather than a vertical propagation of the drawdown in the upper Permian coal measures via the Rewan Group aquitard (see Figure 9 and discussion in Section 2.6.2.3.2). Note that the propagation of drawdown from the Cenozoic and alluvium to the Clematis Group hinges on the assumption that the Cenozoic and alluvium are a continuous aquifer.

Figure 13 provides a similar plot for model node GAL_043, Mellaluka Springs. The dominant parameters affecting *dmax* are the vertical hydraulic conductivity of the alluvium and the specific storage of the upper Permian coal measures hydrostratigraphic unit. Lower storage values mean that for the same pumping rate more drawdown is realised. An increase in the vertical hydraulic conductivity of the alluvium allows for drawdown to be compensated by inflow from the Cenozoic and alluvium.

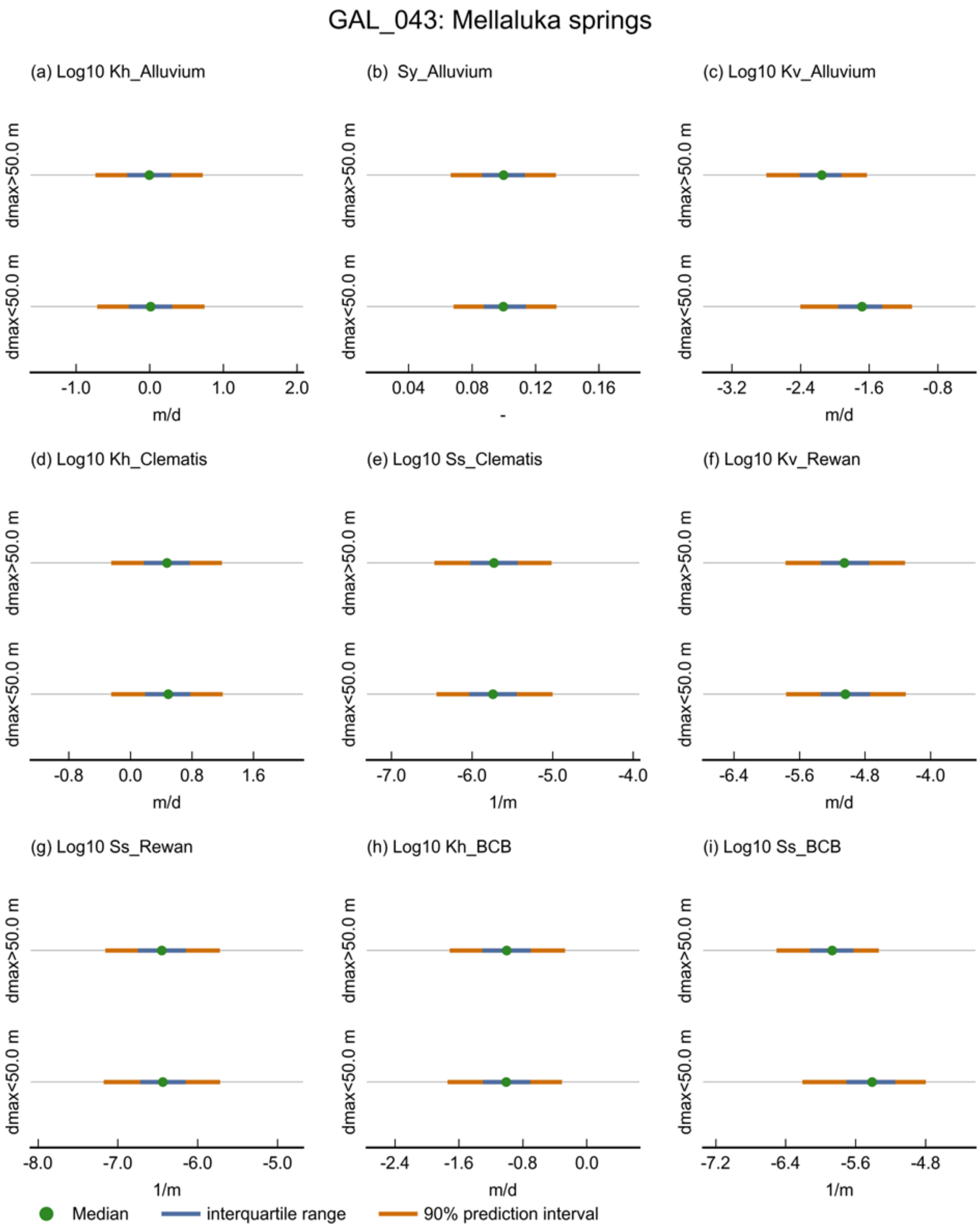

Figure 13 Boxplots of Galilee subregion analytic element model parameter values from the posterior parameter distributions giving rise to dmax less than and greater than 50 m for model node GAL_043, Mellaluka Springs

Each dot represents a model evaluation. The red lines indicate the median of the *dmax* values in the parameter range spanned by the red line segment.

dmax = maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development

CRDP = baseline + additional coal resource development

Data: Bioregional Assessment Programme (Dataset 1)

A similar graphical analysis of these relationships for each model node is beyond the scope of the product. Figure 14 shows the sensitivity index of *dmax* for each parameter–model node combination, calculated with the density-based sensitivity index introduced by Plischke et al. (2013). Larger values of the sensitivity index indicate higher sensitivity of the prediction to the parameter.

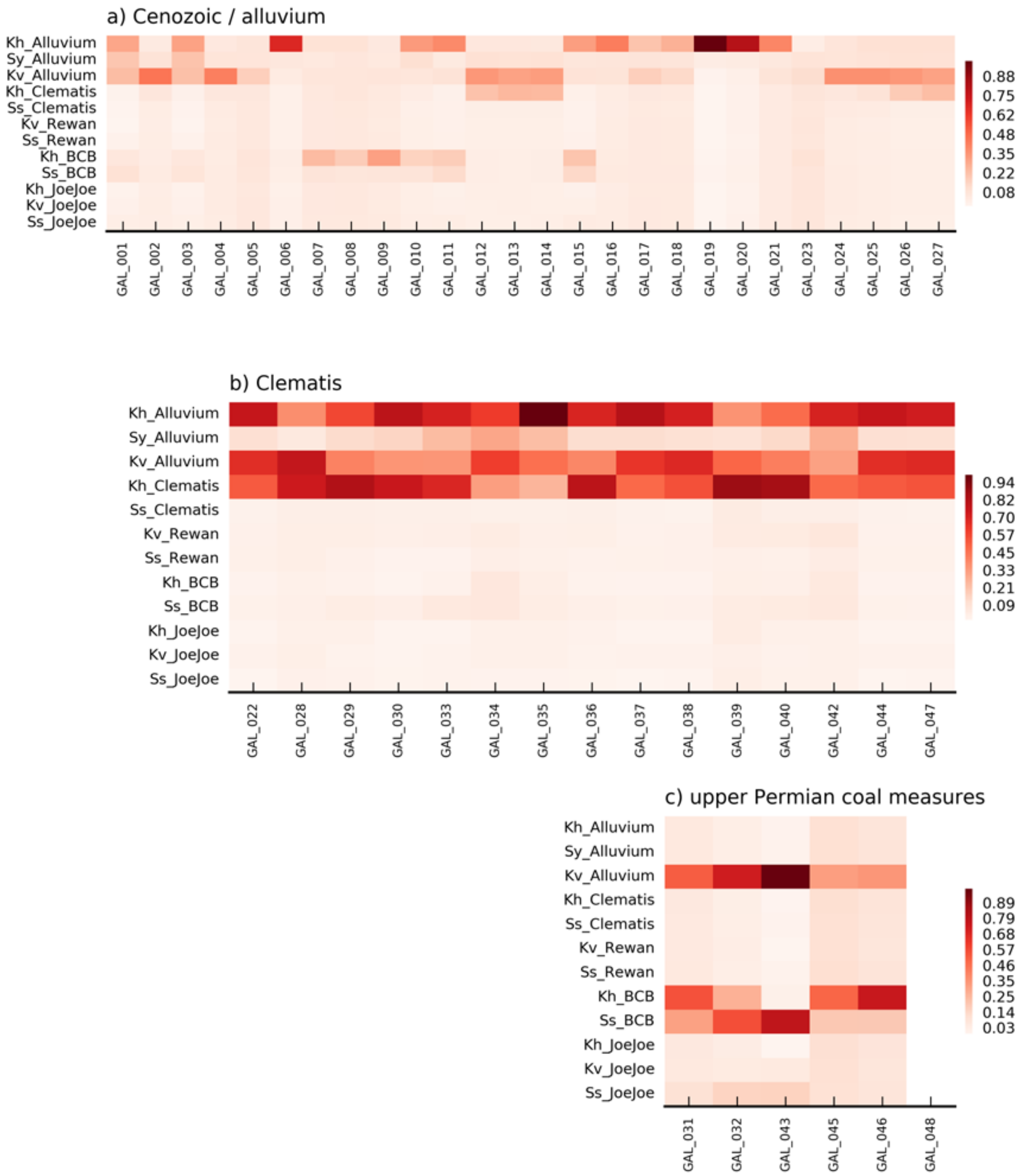

Figure 14 Sensitivity indices for all parameter–model node combinations for dmax, grouped per model layer

The colour scale represents the sensitivity index score where larger values represent higher sensitivity.
dmax = maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development
CRDP = baseline + additional coal resource development
Data: Bioregional Assessment Programme (Dataset 1)

The sensitivity indices shown in Figure 14(c) for the upper Permian coal measures confirm the relationships identified in Figure 13; the dominant parameters are the hydraulic properties of the upper Permian coal measures and the vertical hydraulic conductivity of the Cenozoic aquitard. The hydraulic properties of the upper Permian coal measures control the propagation of the cone of depression into this formation, where low values of both parameters will lead to large drawdowns. In model nodes close to the mine footprints, drawdowns are most sensitive to storage, while further away from the mines, the horizontal hydraulic conductivity is more important.

The vertical hydraulic conductivity of the Cenozoic aquitard controls the interaction with the constant drawdown boundary representing the Belyando River. High values of this parameter allow for more water to compensate the drawdown in the upper Permian coal measures aquifer and therefore result in lower drawdowns. The Joe Joe Group aquifer has a similar effect on drawdowns in the upper Permian coal measures as high vertical hydraulic conductivity of the Joe Joe Group aquitard and specific storage of the Joe Joe Group aquifer result in more water compensating drawdowns and thus smaller drawdowns in the upper Permian coal measures.

The drawdown in the Cenozoic and alluvial aquifer (Figure 14(a)) is dominated by the horizontal hydraulic conductivity of the Cenozoic and alluvial aquifer, followed by the vertical hydraulic conductivity and specific yield. The hydraulic properties of the upper Permian coal measures aquifer appear to only noticeably affect drawdown predictions at model nodes GAL_007 to GAL_011 and GAL_015. These are all situated in the area where the upper Permian coal measures subcrop directly underneath the Cenozoic cover. These sensitivity indices are related to the two stresses imposed to the system at the mine footprints: the pumping rates in the upper Permian coal measures, and the constant drawdown in the Cenozoic aquifer. In the vicinity of the mine footprints, the effect of the constant drawdown dominates which makes the horizontal hydraulic conductivity and specific yield of the Cenozoic aquifer the most important parameters. Further away from the mines, the influence of the constant drawdown boundary diminishes. At these model nodes, the propagation of drawdown through the Cenozoic aquitard becomes more important. For those model nodes, the vertical hydraulic conductivity of the Cenozoic aquitard and the hydraulic properties of the upper Permian coal measures become more important.

Figure 14(b) shows the sensitivity of *dmax* at the model nodes associated with the Clematis Group aquifer. The dominant parameters are the hydraulic conductivity of the Clematis Group aquifer and the hydraulic properties of the Cenozoic aquifer and aquitard. It is noteworthy that the hydraulic properties of the upper Permian coal measures aquifer and Rewan Group aquitard do not appear to affect the predictions. This is an indication that, despite the range of vertical hydraulic conductivities sampled for the Rewan Group aquitard, there is limited direct influence from the depressurisation of the upper Permian coal measures on drawdowns in the Clematis Group aquifer. The drawdowns realised in the Clematis Group aquifer are therefore mostly controlled by propagation of drawdown from the overlying Cenozoic cover. It is again emphasised that the propagation of drawdown from the Cenozoic and alluvium to the Clematis Group hinges on the assumption that the Cenozoic and alluvium are a continuous aquifer.

The change in surface water – groundwater flux with the Belyando River is not a hydrological response variable of the groundwater model, but will be an important input to the surface water model (see companion product 2.6.1 for the Galilee subregion (Karim et al., 2018)).

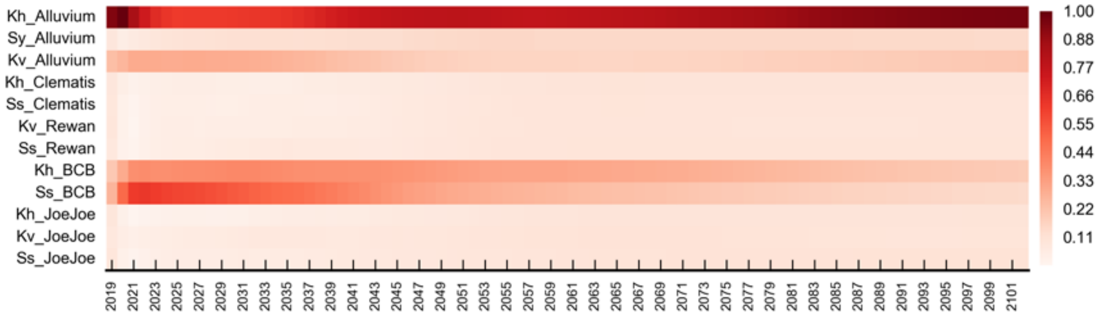

Figure 15 Sensitivity indices for surface water – groundwater flux of the Belyando River for each year of simulation

The colour scale represents the sensitivity index score where larger values represent higher sensitivity.
Data: Bioregional Assessment Programme (Dataset 1)

Figure 15 shows the sensitivity of the simulated surface water – groundwater flux for each year of simulation for all the segments of the Belyando River included in the GW AEM.

In the first two decades of coal resource development, the surface water – groundwater flux is controlled by the horizontal hydraulic conductivity of the Cenozoic aquifer and the specific storage of the upper Permian coal measures and to a lesser extent by the vertical hydraulic conductivity of the Cenozoic aquitard and the horizontal hydraulic conductivity of the upper Permian coal measures. As development continues, the sensitivity to both the storage of the upper Permian coal measures and the vertical hydraulic conductivity of the Cenozoic cover decreases, while sensitivity to the horizontal hydraulic conductivity of the upper Permian coal measures remains the same and sensitivity to the horizontal hydraulic conductivity of the Cenozoic cover increases.

These sensitivities reflect the transient nature of the coal resource development. In the first decades, most of the drawdown in the upper Permian coal measures is realised by depletion of the available storage. The drawdown is compensated by water coming from the Cenozoic aquifer, which is controlled by the Cenozoic aquitard conductivity. As the development continues, the drawdown is increasingly controlled by the ease with which water can be transferred through the upper Permian coal measures (i.e. the horizontal hydraulic conductivities). In the final stages of the simulation period, drawdowns in the upper Permian coal measures are recovering and the surface water – groundwater flux is controlled by the new equilibrium between the fixed drawdowns at the mine footprint and the Belyando River and thus the horizontal hydraulic conductivity of the Cenozoic aquifer.

Section 2.6.2.8 provides a more elaborate discussion on the spatial variation of predicted drawdown and year of maximum change.

References

Doherty J and Welter D (2010) A short exploration of structural noise, Water Resources Research 46, W05525.

Karim F, Viney NR, Wang B, Peeters LJM, Zhang YQ, Marvanek SP, Shi X, Yang A and Buettikofer H (2018) Surface water numerical modelling for the Galilee subregion. Product 2.6.1 for the Galilee subregion from the Lake Eyre Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/LEB/GAL/2.6.1.

Plischke E, Borgonovo E and Smith CL (2013) Global sensitivity measures from given data. European Journal of Operational Research 226, 536–550.

Datasets

Dataset 1 Bioregional Assessment Programme (2016) GAL groundwater numerical modelling AEM models. Bioregional Assessment Derived Dataset. Viewed 16 November 2016, http://data.bioregionalassessments.gov.au/dataset/2698f3c2-b8d4-4b4e-899c-d50e0e1aac1f.

Dataset 2 Bioregional Assessment Programme (2016) Galilee model HRV Receptors gdb. Bioregional Assessment Derived Dataset. Viewed 13 October 2016, http://data.bioregionalassessments.gov.au/dataset/ee766aad-3849-4a5a-92b7-ff4098bd874e.

2.6.2.8 Uncertainty analysis

Summary

The formal uncertainty analysis generates predictive distributions of drawdown (*dmax*) – the maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development – and year of maximum change (*tmax*) at the model nodes of the regional groundwater analytic element model (GW AEM). For the model nodes in the alluvium, the predicted *dmax* generally is less than 5 m and occurs in the second half of the simulation period. Beyond 20 km from the mine footprints, the probability of exceeding a drawdown of 0.2 m is small.

None of the model nodes associated with the Clematis Group have median drawdown in excess of 1 m. These drawdowns are linked to propagation of drawdown through the Cenozoic cover rather than propagation of drawdown through the Rewan Group.

Although drawdowns predicted in the upper Permian coal measures decrease rapidly with increasing distance to the mine footprints, *dmax* is generally in excess of 5 m throughout the model domain.

The discussion of model assumptions and their effect on predictions highlighted that the assumptions with the highest potential to affect predictions are the implementation of the CRDP, the representation of the Cenozoic and alluvial sediments and the conceptualisation of the surface water – groundwater interaction. The predictions of drawdown are considered conservative; more local hydrogeological information is required to make more precise predictions.

2.6.2.8.1 Quantitative uncertainty analysis

As outlined in Section 2.6.2.1.2.3, the quantitative uncertainty analysis for the GW AEM is limited to a Monte Carlo sampling of the prior parameter distributions.

Section 2.6.2.8.1.1 summarises the sampled parameter distributions, followed by a discussion of the resulting predictive distributions for the model nodes.

2.6.2.8.1.1 Parameter distributions

Figure 16 shows histograms of the 10,000 parameter combinations that are randomly sampled from the parameter distributions summarised in Table 12 and discussed in Section 2.6.2.6.

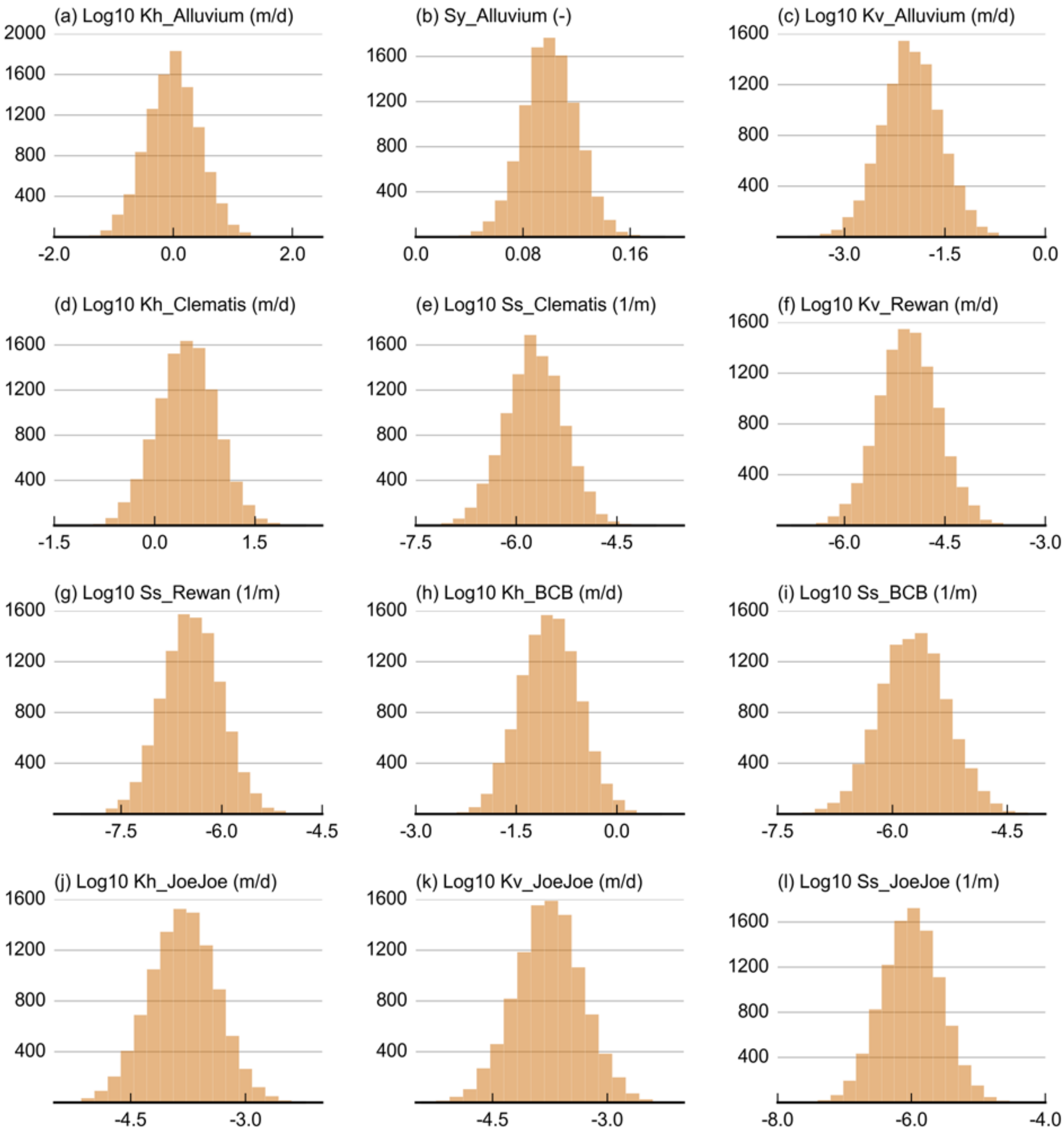

Figure 16 Histograms of posterior parameter distributions

Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.8.1.2 Predictive distributions

The parameter combinations shown in Figure 16 are evaluated with the GW AEM, and *dmax* and *tmax* are computed for the model nodes and for each hydrostratigraphic unit at the model nodes, shown in Figure 10 in Section 2.6.2.4. Before discussing in more detail the predicted hydrological change at the model nodes, it is verified if the number of samples – 10,000 – is sufficient. Figure 17 shows the convergence of the 5th, 50th and 95th percentile of drawdown due to additional coal resource development (additional drawdown) for three selected model nodes. For each of those model nodes, it is clear that at least 1000 samples are needed before the quantiles of the ensembles of prediction start to stabilise. From 5000 samples onwards, the quantiles appear not to change anymore. The selected sample size of 10,000 can therefore be considered as sufficient to characterise the median predicted drawdown and the associated 90% confidence interval. Although not shown in this product, during the analysis of the results, it is verified that *dmax* and *tmax* converge for all model nodes.

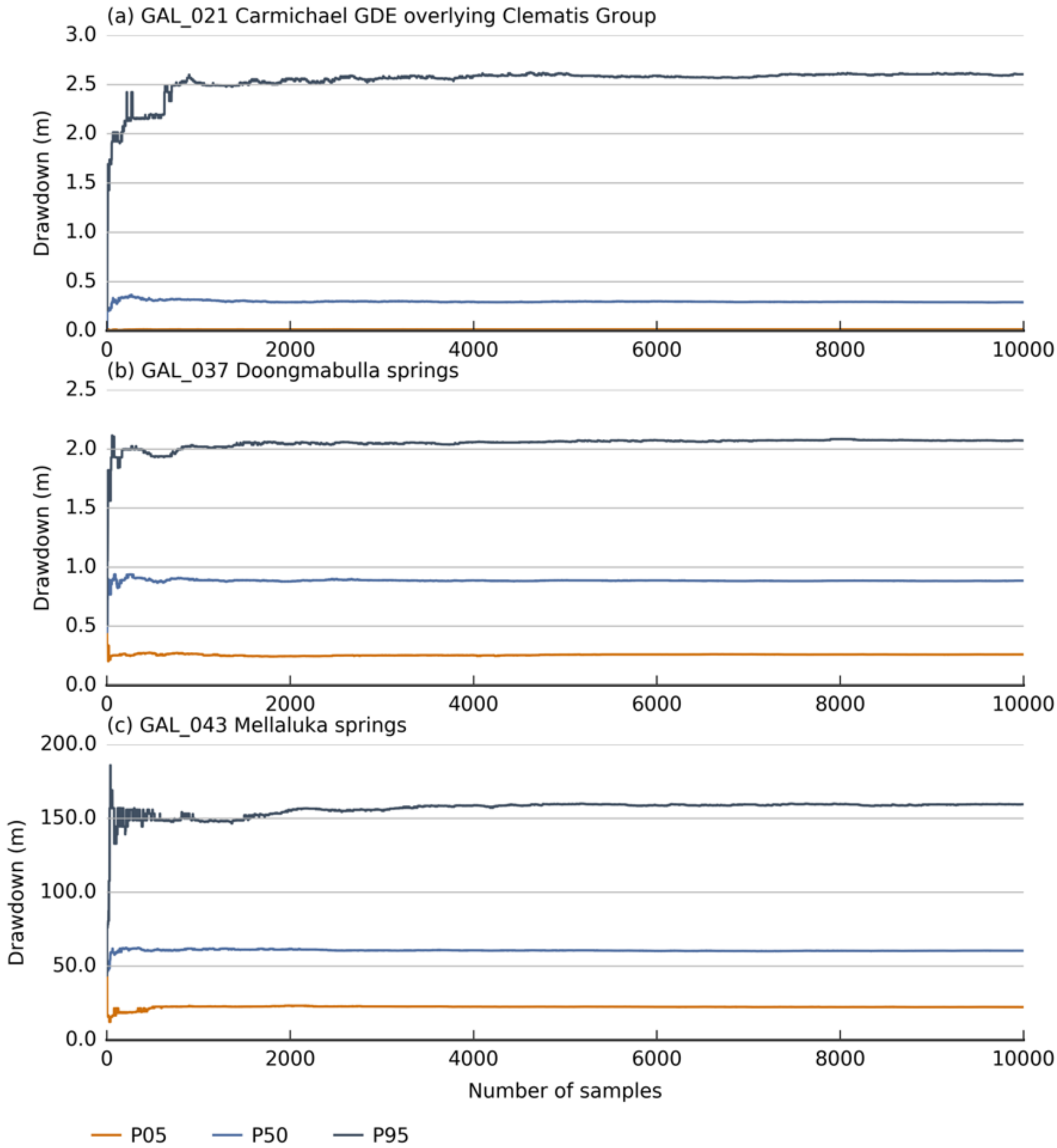

Figure 17 Convergence of 5th, 50th and 95th percentile of additional drawdown at selected model nodes of the Galilee subregion

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 1)

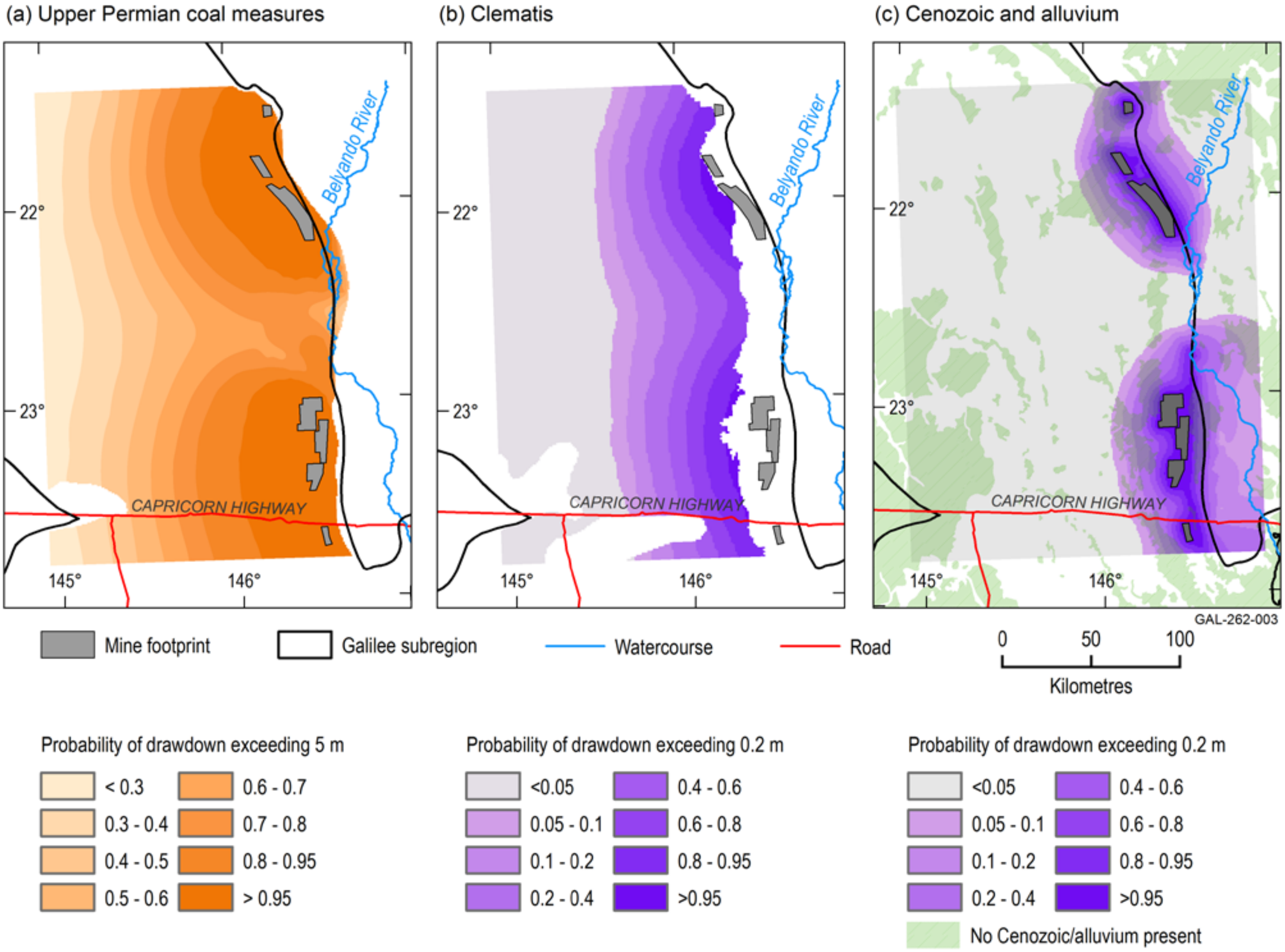

Figure 18 Probability of additional drawdown exceeding (a) 5 m in the upper Permian coal measures, (b) 0.2 m in the Clematis Group aquifer and (c) 0.2 m in the Cenozoic and alluvial aquifer

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 2)

Cenozoic and alluvium

Figure 19 shows the median and 90% prediction interval for *dmax* and *tmax* at the model nodes associated with the Cenozoic and alluvium hydrostratigraphic unit. Figure 18c shows the probability of *dmax* exceeding 0.2 m at the model nodes of the GW AEM in the alluvial hydrostratigraphic unit. The 0.2 m threshold is consistent with the threshold defined by QWC (2012) for impacts on springs.

For the majority of the model nodes the median drawdown in alluvium is less than 5 m and maximum change will occur near the end of the simulation period, after the peak coal production period (see Figure 28 in companion product 2.3 for the Galilee subregion (Evans et al., 2018b)). As the mine footprints in the Cenozoic and alluvial aquifer are implemented as a constant drawdown for the entire simulation period, any year of maximum change before the end of the simulation period indicates propagation of the depressurisation in the upper Permian coal measures.

Figure 18 shows that the change is greatest nearer to the mine footprints and decreases with increasing distance from the mining operations. Beyond 25 km from a mine footprint the probability of *dmax* exceeding 0.2 m is generally less than 5%.

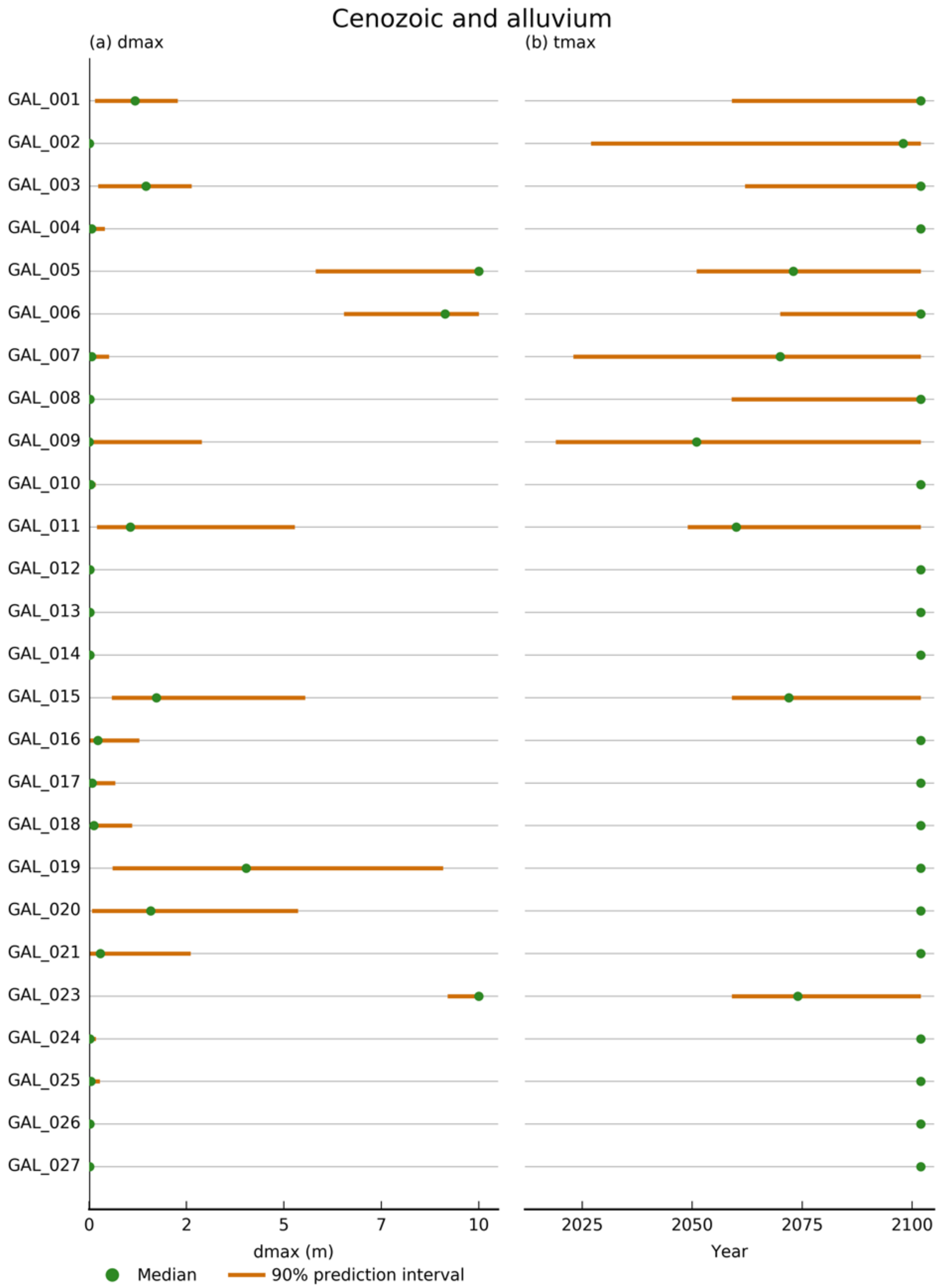

Figure 19 (a) additional drawdown (*dmax*) and (b) year of maximum change (*tmax*) at the model nodes associated with the Cenozoic and alluvium hydrostratigraphic unit in the Galilee subregion

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

Clematis Group

Figure 20 shows the median and 90% prediction interval of *dmax* and *tmax* at the model nodes associated with the Clematis Group hydrostratigraphic unit. Figure 18b shows the probability of *dmax* exceeding the 0.2 m threshold.

At the model nodes the drawdown is generally less than 2 m and will occur on or after the end of the simulation period. This also means that the additional drawdown is not achieved during the simulation period. From the sensitivity analysis it is clear that simulated drawdown in the Clematis Group aquifer is a propagation of the drawdown in the Cenozoic cover sediments. As the Clematis Group aquifer is simulated as a confined unit, with a specific storage rather than specific yield, the same change in flux will result in a larger drawdown in the Clematis Group aquifer than in the Cenozoic aquifer. This explains the larger spatial extent of the probability contour of more than 5% probability of exceeding 0.2 m drawdown.

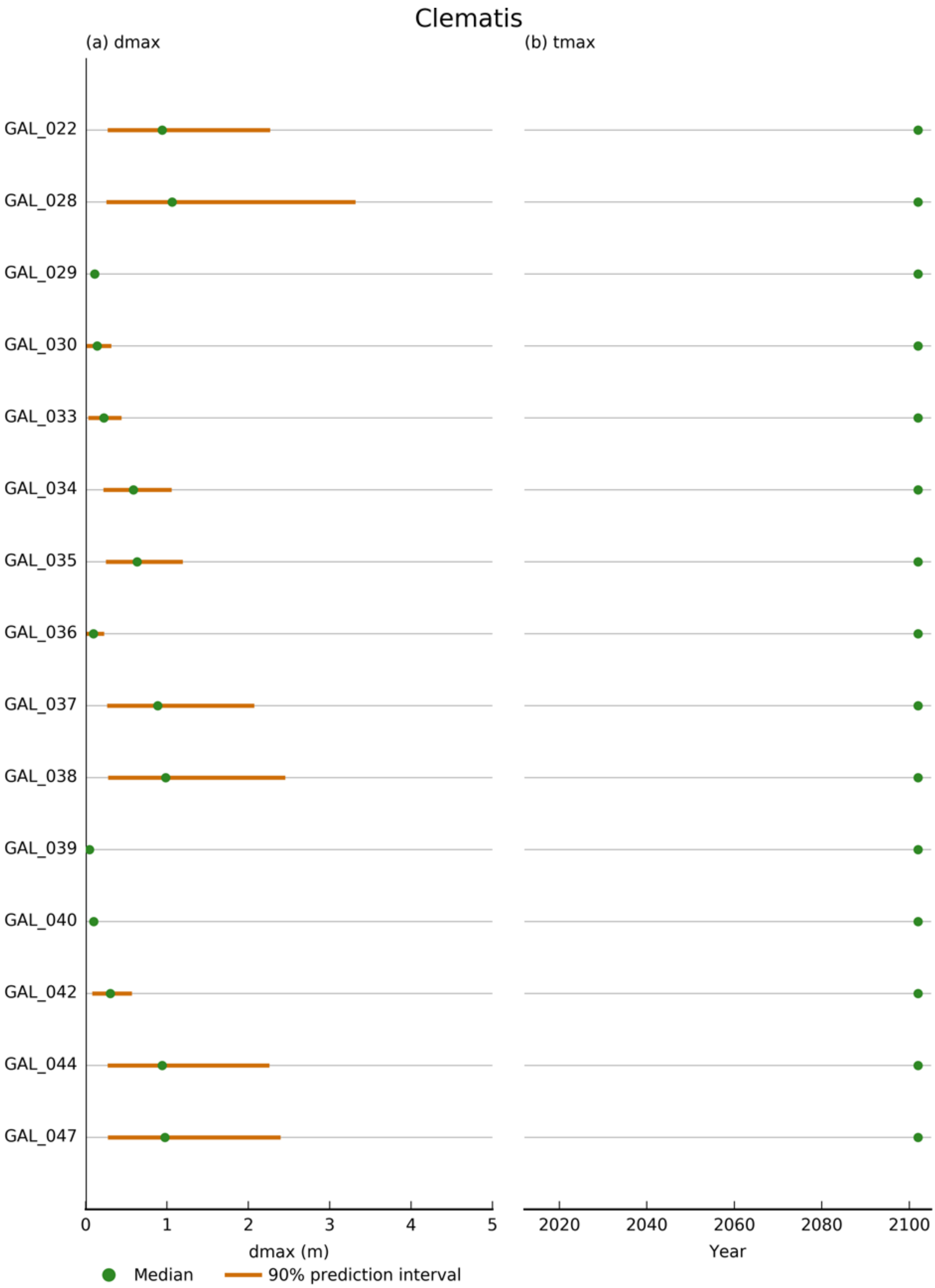

Figure 20 (a) additional drawdown (*dmax*) and (b) year of maximum change (*tmax*) at the model nodes associated with the Clematis Group hydrostratigraphic unit in the Galilee subregion

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

Upper Permian coal measures

Figure 21 shows the median and 90% prediction interval of the additional drawdown and year of maximum change at the model nodes associated with the upper Permian coal measures hydrostratigraphic unit. Figure 18a shows the probability of *dmax* exceeding the threshold for consolidated aquifers in Queensland, which is 5 m, at the model nodes in the upper Permian coal measures hydrostratigraphic unit.

Additional drawdowns at the model nodes in the upper Permian coal measures are sizeable with the upper boundary of 90% prediction interval in excess of 100 m for most model nodes. The year of maximum change is mostly realised within the simulation period and close to the peak coal production time.

Figure 18a shows that within the model domain, the probability of exceeding 5 m drawdown is relatively high everywhere. Even at a distance of more than 100 km west of the mine footprints, the probability of exceeding 5 m drawdown is still in excess of 20%.

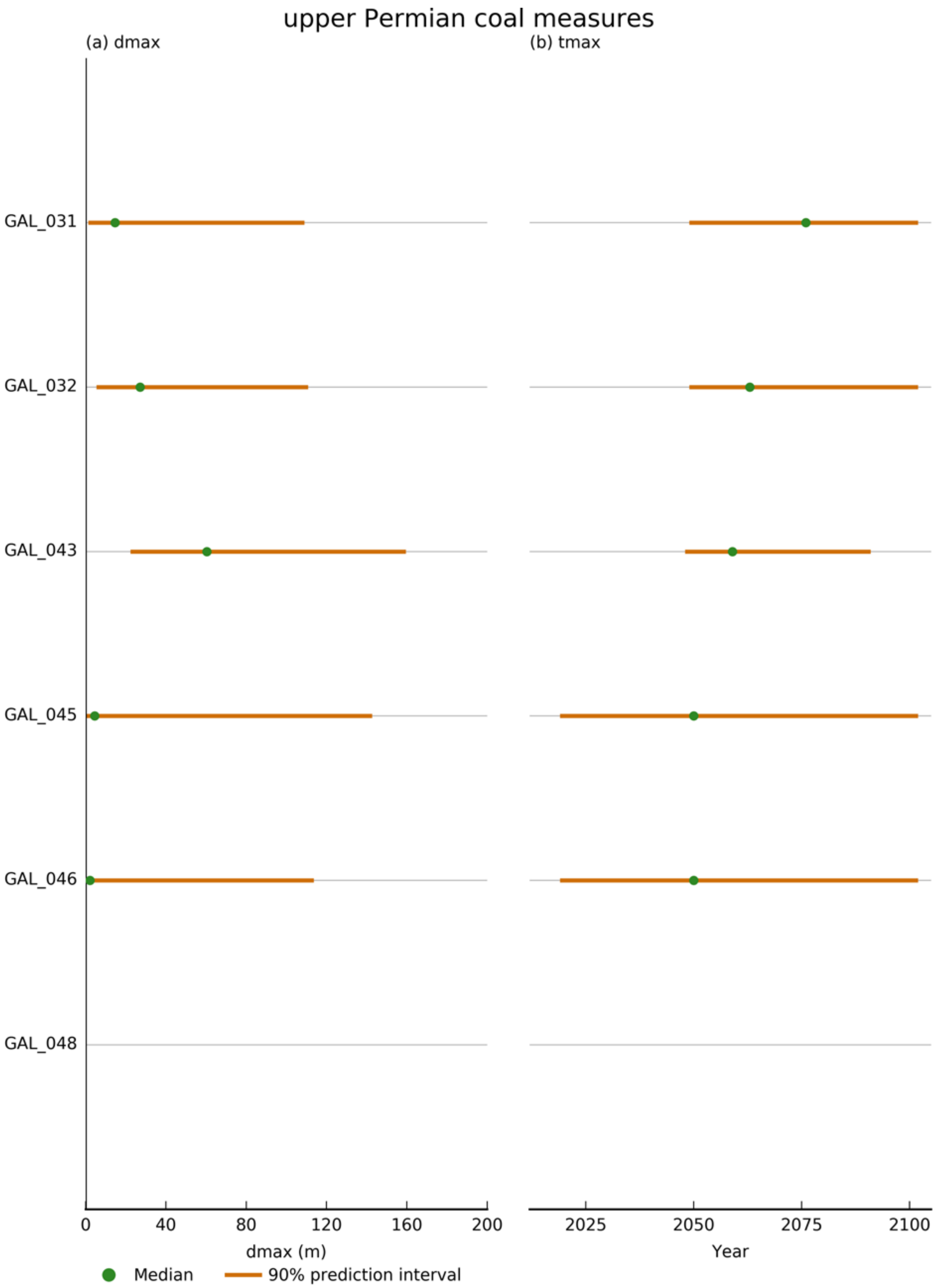

Figure 21 (a) additional drawdown (*dmax*) and (b) year of maximum change (*tmax*) at the model nodes associated with the upper Permian coal measures hydrostratigraphic unit in the Galilee subregion

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

Surface water – groundwater flux

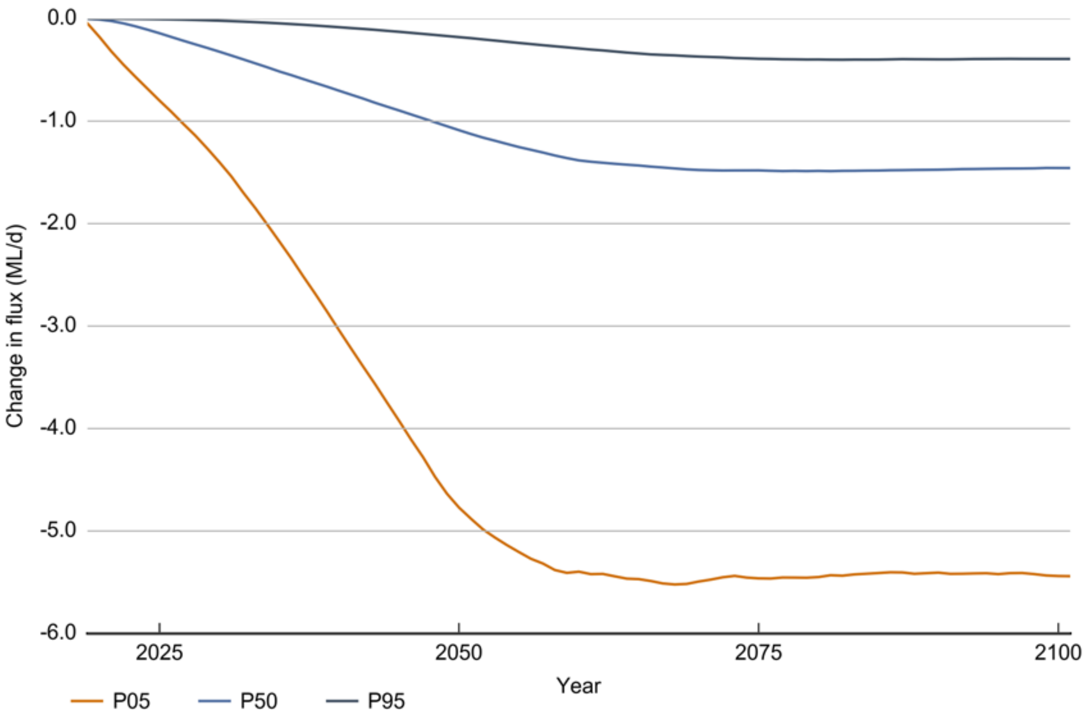

Figure 22 5th, 50th and 95th percentile of change in surface water – groundwater flux for the Belyando River

Data: Bioregional Assessment Programme (Dataset 1)

The 5th, 50th and 95th percentile of the change in total surface water – groundwater flux for the Belyando River is shown in Figure 22. The median change in flux at the end of the simulation period is close to 1.5 ML/day, with the 5th percentile around 0.3 ML/day and the 95th percentile close to 5.5 ML/day.

In Section 2.1.5 (surface water – groundwater interaction) in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a), the mean annual baseflow at Belyando Crossing is estimated to be 83 GL/year or 228 ML/day. The 5th, 50th and 95th percentile of change in baseflow due to coal mining therefore corresponds to 0.1%, 0.6% and 2.4% of baseflow at Belyando Crossing, respectively. Companion product 2.6.1 for the Galilee subregion (Karim et al., 2018) provides a more detailed and nuanced discussion on the hydrological change in different river reaches.

The simulated change in surface water – groundwater flux corresponds to about 1% of the pumping rates assigned to the mine footprints (see Table 11 in Section 2.6.2.5). This implies that, as there is no other source of water simulated in the GW AEM, the vast majority of the pumping rate is the depletion of the aquifer storage.

The maximum change is attained close to the time of maximum coal production. The change decreases very slowly after reaching this maximum. In the absence of any other sources of water, the Belyando River is the only source that compensates the cone of depression formed in the upper Permian coal measures, while maintaining the gradient to the constant drawdown at the mine footprints in the Cenozoic hydrostratigraphic unit. The rate of recovery is therefore very likely under estimated.

Comparison to other groundwater models

The only other regional groundwater model that encompasses all of the modelled developments, is the MODFLOW-USG model developed by HydroSimulations (Turvey et al., 2015). This is a deterministic model in which the pumping rates of the mines are calculated based on the modelled elevation of the coal seam floor (see Section 2.6.2.2). The total cumulative predicted mine pumping rates total 2822 GL, which is about twice the total cumulative mine pumping rate assigned to the analytic element model, which is 1361 GL.

Due to differences in conceptualisation, such as the definition of hydrostratigraphic units and the number of model layers, it is not straightforward to directly compare the predicted drawdowns. An in-depth comparison between the numerical model and analytic element model is therefore not warranted; a fair comparison is only possible when a common benchmark is available. As this is a greenfield site, there is no such common benchmark (e.g. historical drawdown caused by a known pumping rate).

The MODFLOW-USG model does not predict any drawdowns in the regolith layer, which corresponds to the Cenozoic / Alluvial model layer in the analytic element model. The MODFLOW-USG model does not simulate direct mine drainage in the regolith layer, which explains the discrepancy in model results.

The simulated drawdown in the Clematis Group, layer 8 in the MODFLOW-USG model, is less than 5 m. At the model nodes in the Clematis Group, the analytic element model predicted drawdowns do not exceed 4 m, although at several model nodes the median drawdown is close to 1 m. The contour of 50% probability of exceeding 0.2 m in Figure 18b corresponds broadly to the 1 m drawdown contour in layer 8 at 2090 (Turvey et al., 2015, p. 220).

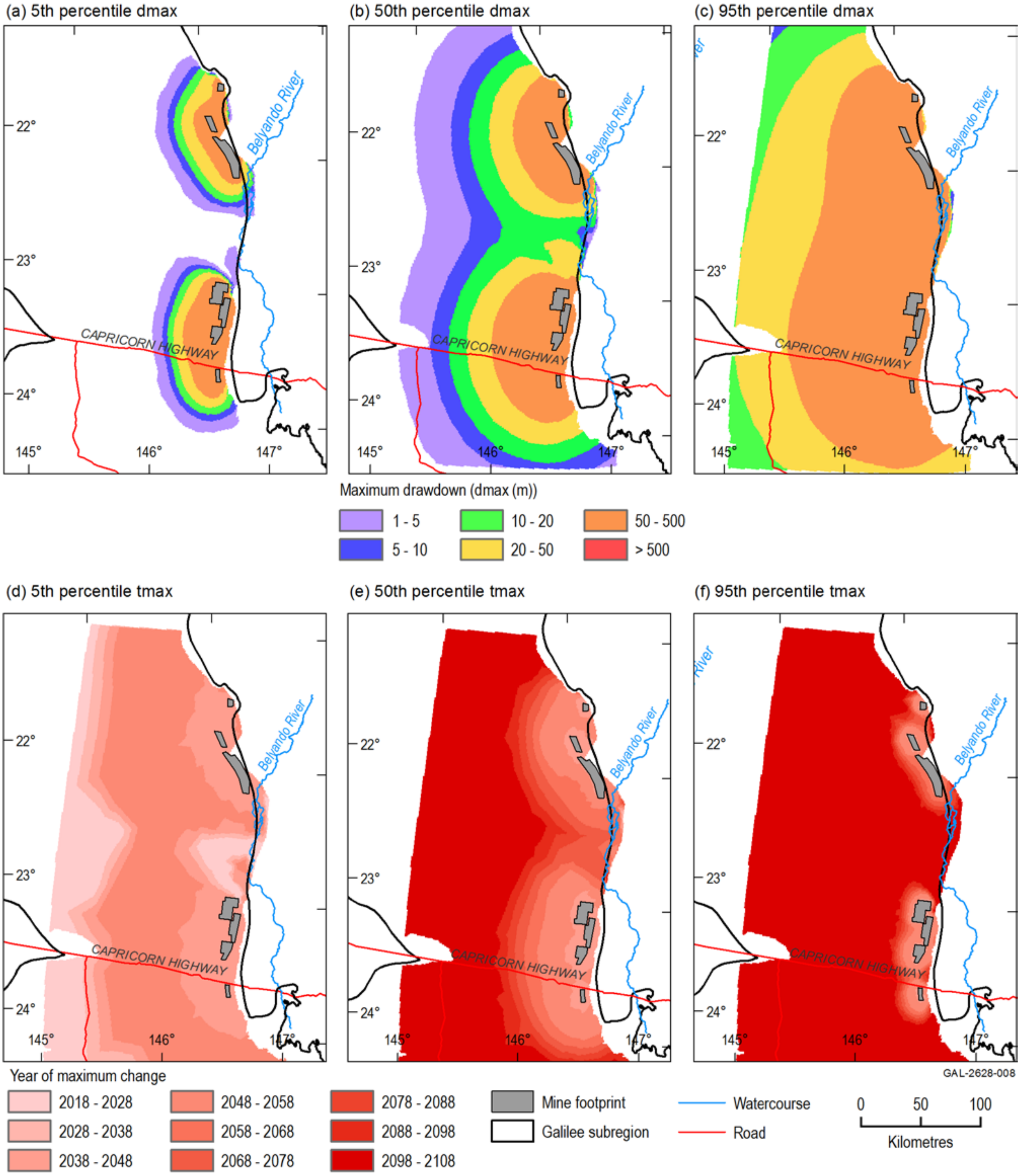

Figure 23 Contour maps of the 5th, 50th and 95th percentile of additional drawdown (top row) and year of maximum change (bottom row) in the upper Permian coal measures

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
tmax = year of maximum change
Data: Bioregional Assessment Programme (Dataset 2)

Figure 23 shows the 5th, 50th and 95th percentile of additional drawdown and year of maximum change in the upper Permian coal measures simulated with the analytic element model. As such, these results are not directly comparable to the results presented in Turvey et al. (2015) since in the numerical model, the upper Permian coal measures are divided into several layers and the results are presented as maps of drawdown at specific points in time, rather than the additional drawdown and year of maximum change. The drawdown map for layer 12 in 2058 (Turvey et al., 2015, p. 264) is reproduced in Figure 24. This shows the drawdown in the Betts Creek beds formation seam E. The map for 2058 is chosen as this time slice appears to have the maximum extent of drawdown.

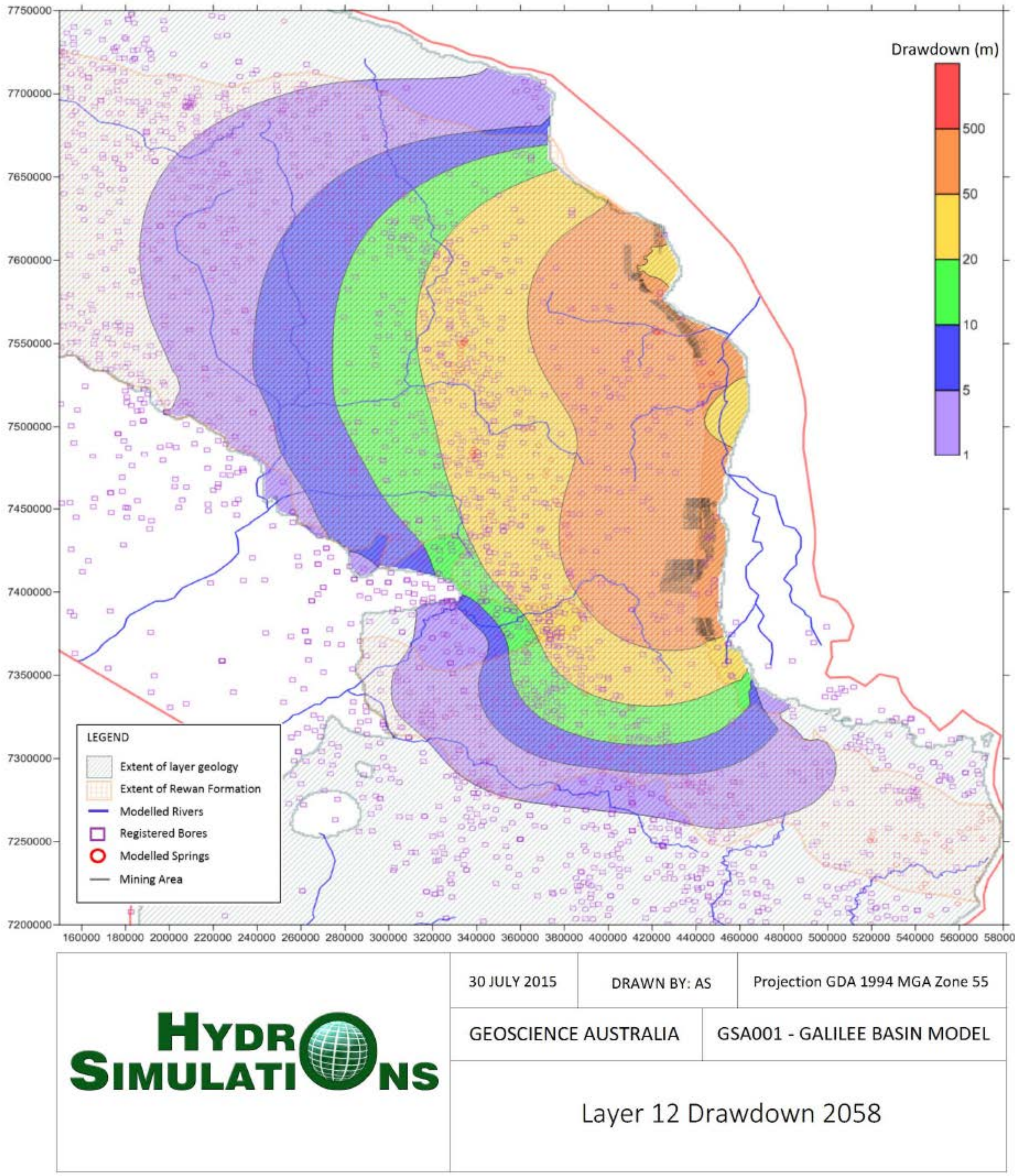

Figure 24 Drawdown in layer 12 (Betts Creek beds formation seam E) in 2058

Source: Turvey et al. (2015)

The drawdown contours depicted in Figure 24 are very similar to the contours shown in Figure 23c, the 95th percentile of additional drawdown. This is not unexpected as the pumping rates in the MODFLOW model are almost twice those applied to the analytic element model, and the calibrated horizontal hydraulic conductivities for the upper Permian coal measures in the MODFLOW model, which range from 0.13 to 2.5 m/day, are close to the 95th percentile of the parameter distribution for the horizontal hydraulic conductivity of the upper Permian coal measures (Figure 23).

A direct comparison between the predicted changes in baseflow between both models is not straightforward due to the differences in the conceptualisation and implementation of surface water – groundwater interaction. Table 5-2 in Turvey et al. (2015) lists a 0.2% reduction in baseflow in the Belyando River at the model edge. This is the same order of magnitude of baseflow reduction percentage as simulated with the GW AEM. Note that the hydrological change of the streamflow-related hydrological response variables is reported in companion product 2.6.1 for the Galilee subregion (Karim et al., 2018). In the surface water modelling the change in surface water – groundwater interaction flux from the GW AEM is combined with the reduction in runoff associated with coal mining.

2.6.2.8.2 Qualitative uncertainty analysis

The major assumptions and model choices underpinning the Galilee subregion GW AEM are listed in Table 15. 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 is discussed in detail, including the rationale for the scoring. The 'data' attribute is the degree to which the question 'if more or different data were available, would this assumption/choice still have been made?' would be answered positively. A 'low' score means that the assumption is not influenced by data availability while a 'high' score would indicate that this choice would be revisited if more data were available. Closely related is the 'resources' attribute. This column captures the extent to which resources available for the analysis and processing of the available data and the modelling, such as computing resources, personnel and time, influenced this assumption or model choice. This attribute explicitly does not consider spending additional resources on data acquisition, as this is covered in the data attribute. 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 'technical' attribute deals with the technical and computational issues. A score of '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, 'effect on predictions', addresses the 'so what?' question, 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 estimated rather than under estimated.

While this table is primarily intended to elaborate on the effects of model assumptions and choices, it can provide guidance for further research. A large number of assumptions in the Galilee subregion are mainly driven by the limited data and knowledge base. The effect on predictions column indicates which ones are considered to have the largest effect on predictions. The conclusions and opportunities section (Section 2.6.2.9) uses this table to identify the main data and knowledge gaps.

Table 15 Qualitative uncertainty analysis as used for the Galilee subregion

Description	Data	Resources	Technical	Effect on predictions
Layer cake geology – mean layer thickness	low	low	high	medium
Principle of superposition – direct simulation of change	medium	low	low	low
Spatially uniform hydraulic properties	high	low	high	low
Upper Permian coal measures as single layer	medium	low	low	medium
Belyando River alluvium as zero groundwater level change boundary condition	high	low	low	high
Representation of the Cenozoic and alluvial aquifer system	high	medium	medium	high
Implementation of the coal resource development pathway	high	low	low	high
Unconstrained posterior parameter distributions	high	medium	low	medium
Maximum drawdown not realised during simulation period	low	high	low	low
Model nodes assigned to hydrostratigraphic units	medium	medium	medium	medium

2.6.2.8.2.1 Layer cake geology – mean layer thickness

The analytic element modelling framework implemented in TTim (Bakker, 2015) only allows representing a groundwater system as a layer cake (i.e. all hydrostratigraphic units are horizontal and have a uniform thickness).

This assumption is therefore driven by technical constraints, not the availability of data or resources, as a three-dimensional geological model of the Galilee subregion has been developed by the Assessment team (see Section 2.1.2 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)). The data and resources columns are scored 'low' accordingly, while the technical attribute is scored 'high'.

The effect on the predictions of drawdown of not fully accounting for the geometry of the hydrostratigraphic units is considered small, at least in the confined part of the groundwater system. In a confined system, aquifer geometry only affects groundwater flow through its effect on the transmissivity. Evaluating a wide range of hydraulic conductivity values in the uncertainty analysis *de facto* means that a wide range of transmissivity values are evaluated. Conceptually, the uncertainty in aquifer geometry is absorbed in the variability of hydraulic conductivity. This is illustrated in the comparison of the analytic element model results and the MODFLOW model results, which shows that the drawdown predictions are comparable, despite the differences in simulated geometry in both models.

The local absence of model layers, such as the eastern limit of the extent of the Clematis Group and upper Permian coal measures, is accounted for by allowing direct contact between upper Permian coal measures and the alluvium where Clematis Group is absent and by a no-flow boundary at the eastern limit of the upper Permian coal measures.

In unconfined groundwater flow systems, especially in systems like the alluvium and Cenozoic aquifer with a highly variable geometry and a thin saturated zone, groundwater flow is more likely to be controlled by variations in geometry. The representation of the Cenozoic hydrostratigraphic unit is discussed in greater detail in Section 2.6.2.8.2.6.

The overall effect on predictions is scored 'medium', which reflects that the layer cake assumption will mostly have an effect on the predictions in the Cenozoic and alluvial sediments and will have much less effect on the confined aquifers.

2.6.2.8.2.2 Principle of superposition – direct simulation of change

A crucial assumption in the analytic element model is the validity of the principle of superposition; that is, that solutions to the groundwater flow equations are additive as long as the system behaves linearly, as outlined in Section 2.6.2.1. This assumption allows for simulating the change in the system due to coal resource development directly, rather than to simulate all fluxes and stores for two different futures and obtain the change as the difference between those two futures. This assumption allows the exclusion of processes that are not affected by coal resource development, such as regional diffuse recharge, from the modelling.

The data analysis in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a) highlighted the limited data availability on the current groundwater flow conditions in the Galilee sedimentary basin. The data attribute is nevertheless scored 'medium'. The reasoning behind this scoring is that additional data would only warrant to revisit the assumption if the principle of superposition would be shown not to be applicable; that is, if the additional data show that the aquifers in the Galilee Basin do not behave as a confined groundwater system.

The resources and technical attributes are both scored 'low' to reflect that this model choice is not driven by operational constraints or technical limitations.

The effect on predictions is scored 'low' as Reilly et al. (1987) and Rassam et al. (2004) showed that for mild violations of the linearity assumptions, the deviations in predictions caused by the non-linearity are generally very small and only become apparent in extreme cases. As processes such as regional diffuse recharge are not simulated and therefore cannot compensate for the coal mining related drawdown, the simulated drawdown can be considered as conservative.

2.6.2.8.2.3 Spatially uniform hydraulic properties

The transmissivity (the product of hydraulic conductivity and layer thickness) and storage are considered spatially uniform, at least in the horizontal direction.

The limited data available on these hydraulic properties does show that these properties are heterogeneous (companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)). Furthermore, changes to hydraulic properties due to longwall mining activities are not accounted for in this model. The data density is, however, too limited to empirically establish a spatial correlation structure to characterise the spatial variability in these properties. The sparse head observation dataset does not allow for estimating spatial variability through inverse modelling. The data attribute is therefore scored 'high'.

Incorporating spatial variability in the modelling would require additional resources as it takes time to develop spatial fields from the available data. In addition to that, incorporating spatial variability will increase the dimensionality of the parameter space. This increases the computational load as more model runs need to be added to the design of experiment to fully explore the larger parameter space. As the analytic element model has very short runtimes, the resources attribute is scored 'low'.

The analytic element code is not designed to handle spatial variability in hydraulic properties. The technical column is therefore scored 'high'.

The effect on prediction is scored 'low'. Groundwater level and flux estimates, especially at the regional scale, are dominated by the bulk hydraulic properties (Barnett et al., 2012). Companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016) illustrates that the probabilistic approach adopted in the bioregional assessments ensures that by varying the uniform hydraulic conductivity stochastically, the effects of spatial heterogeneity are captured in the predictive distributions of change in groundwater level. At a local scale, however, within a kilometre of a stress such as an open-cut mine, spatial heterogeneity is important (Crosbie et al., 2016).

2.6.2.8.2.4 Upper Permian coal measures as single layer

The upper Permian coal measures is not a single aquifer, but a heterogeneous alternation of coal seams and interburden layers. While at least locally the stratigraphic information is sufficiently detailed to split this hydrostratigraphic unit into separate units, the Assessment team decided against doing so, mainly because of difficulties with implementing the CRDP. The CRDP is implemented by assigning the individual proponent's mine dewatering rates from the relevant environmental impact statements (EISs) to the mine footprint. Insufficient information is available at present to distribute this pumping rate to separate units within the upper Permian coal measures for all proposed mines in the region. The data attribute is therefore scored 'medium', while the resources and technical attributes are scored 'low'.

Moore et al. (2015) illustrated that the way coal seams are amalgamated in groundwater models in the context of dual-phase flow when simulating effects of coal seam gas extraction can have an impact on predictions. Figure 25 therefore explores the effect of lumping all pumping together into a single layer on drawdowns. A seven-layer confined aquifer system is simulated with an analytic element model, in which three coal seams (CS) with a thickness of 4 m each are interspersed in between interburden layers (IB) with a thickness of 22 m each. Each coal seam is dewatered to its base elevation for a period of 30 years. The total resulting pumping rate is assigned to a single layer with hydraulic conductivity and storage equivalent to the seven-layer aquifer. The horizontal hydraulic conductivity of the coal seams is set to 0.1 m/d and the interburden to 0.001 m/d. The vertical hydraulic conductivity is ten times lower than horizontal hydraulic conductivity. The storage coefficient for coal seams and interburden are the same and equal to $1x10^{-6}$ 1/m. Initial conditions are set to zero metres for all layers.

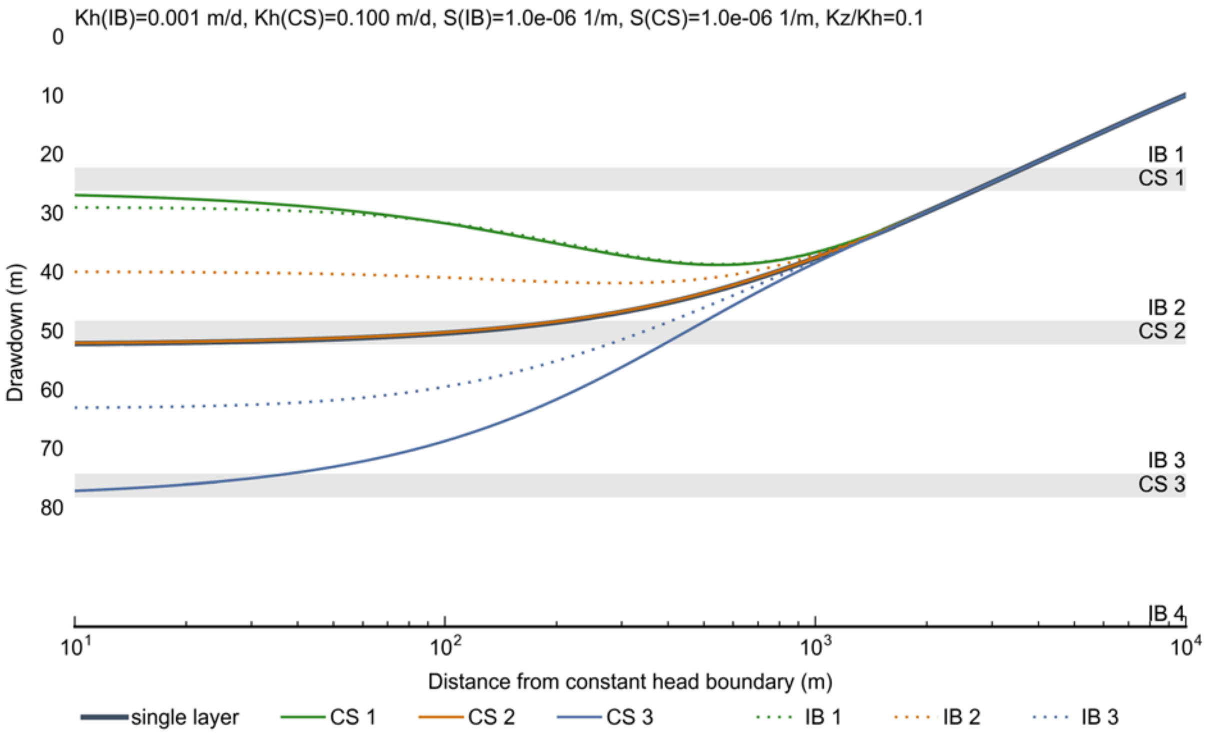

Figure 25 Drawdown in individual coal seams (CS) and interburden (IB) compared to drawdown in a single equivalent layer after 30 years of pumping

A seven-layer confined aquifer system is simulated with an analytic element model, in which three coal seams (CS) with a thickness of 4 m each are interspersed in between interburden layers (IB) with a thickness of 22 m each. Each CS is dewatered to its base elevation. The total resulting pumping rate is assigned to a single layer with hydraulic conductivity and storage equivalent to the seven-layer aquifer.

Figure 25 shows that the drawdown in the individual coal seams increases with depth. The equivalent drawdown in the single layer corresponds to the drawdown in coal seam 2. At the base of the overlying aquitard, the Rewan Group, the single-layer approach chosen for the regional-scale analytic element model over estimates drawdown, compared to the drawdown simulated at the base of the aquitard in the multi-layer model (IB 1). The overall effect on predictions is therefore scored ‘medium’.

2.6.2.8.2.5 Belyando River alluvium as zero groundwater level change boundary condition

The only surface water – groundwater interaction represented in the GW AEM is the main channel of the Belyando River. The Belyando River is considered a regional groundwater discharge feature that controls the groundwater levels either through baseflow contribution to the Belyando River or through evapotranspiration of the riparian vegetation. As this is not affected by coal mining, the change in groundwater level underneath the Belyando River is set at a constant level equal to zero metres. In effect, this is the same as the implementation of the river boundary condition in MODFLOW, where the river stage is specified independently from any mine development.

From the potentiometric surface of the Cenozoic aquifer in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a) it can be inferred that the Belyando River is the only surface water feature that is not considered to be maximally losing; that is, where groundwater levels are sufficiently far below the river bed elevation for the magnitude of the surface water – groundwater flux to become independent from the hydraulic gradient (Brunner et al., 2009). This potentiometric map is, however, based on very few groundwater-level and river-stage observations. It is very likely that this assumption will need to be revisited when more data are available to inform the river connection status. The data attribute is therefore scored 'high'.

The resources and technical attributes are both scored 'low' to reflect that the choice for this boundary condition is not influenced by operational or technical constraints.

This boundary condition obviously affects the drawdown predictions in the immediate vicinity of the Belyando River and therefore it can potentially lead to an underestimate of the drawdown if it should transpire that the Belyando River is maximally losing. Other streams, however, such as Native Companion Creek and Carmichael River, are not represented in the model. This implies that in the vicinity of those streams drawdown will be over estimated if these streams are not maximally losing.

Implementing the zero groundwater level change boundary results in an estimate of the change in surface water – groundwater flux. In this implementation it accounts for both changes in baseflow to the Belyando River and changes in the local evapotranspiration by riparian vegetation. The change in flux is integrated in the surface water modelling as a change in groundwater flow contribution to streamflow. As the change in evapotranspiration flux is included in this estimate, the change in baseflow flux will always be over estimated and the assumption can be considered to be conservative in the Belyando River channel.

For the other streams in the modelled region, baseflow contribution will not change if the maximally losing assumption is valid. The GW AEM will therefore potentially under estimate the change in baseflow, should this be proven not the case.

For Carmichael River it is noteworthy that part of the baseflow is provided by Doongmabulla Springs, which are sourced from the Clematis Group. The median of the additional drawdown at this location in the Clematis Group aquifer is about 2 m. The resulting change in spring flow is not simulated as no information is available on the hydraulic conductivity of these springs and the fraction of spring flow that contributes to Carmichael River.

The effect on predictions is scored 'high'.

2.6.2.8.2.6 Representation of the Cenozoic and alluvial aquifer systems

The Cenozoic and alluvial aquifer systems are represented as a layer of infinite extent, with a constant bottom elevation and a saturated thickness of at least 10 m.

From Section 2.1.2.2.5 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a) it is clear that the presence, extent, nature and thickness of Cenozoic and alluvial sediments is very variable. Drillhole data commonly lack detail in the description of these sediments. While a potentiometric surface for the Cenozoic is presented in Section 2.1.3.3.2 (Figure 53), the combined uncertainty in this surface and bottom elevation surface make it difficult to create a reliable map of the saturated thickness. The data availability is therefore scored ‘high’ for this assumption.

The technical attribute is scored ‘medium’ as it is possible with analytic element code to represent areas where the cover sediments are not present. Varying the thickness or bottom elevation, however, is not possible. Note that representing such thin, discontinuous aquifers will generally give rise to strong hydraulic gradients which are challenging to solve with the current generation of finite difference, element and volume solvers for groundwater flow equations.

The resources attribute is scored ‘medium’, mostly to reflect that the local information on the cover sediments held by mining companies is not yet incorporated in the geological model.

Representing the Cenozoic cover sediments as infinite in extent leads to an overprediction of the extent of drawdown, but can locally lead to an underprediction of the drawdown. The overall effect is therefore scored ‘high’.

2.6.2.8.2.7 Implementation of the coal resource development pathway

The mines are implemented as time series of specified pumping rates assigned to the mine footprints. In the Cenozoic and alluvial aquifers, a constant change in groundwater level of 10 m is assigned to reflect the complete removal and dewatering of the overburden.

To estimate the water production rates of the mines in the groundwater model, detailed information is needed on the geometry of the coal seams, the local hydrogeological properties and the mine progression plans. The pumping rates estimated in the EIS reports by the individual mines are currently considered the best integration of local information.

While the open-cut mines will remove overburden and therefore dewater the Cenozoic and alluvial aquifers, it is not clear from the available data (see previous discussion in Section 2.6.2.8.2.6) that these sediments are present at the mine location and have a saturated thickness of 10 m.

The data attribute is therefore scored ‘high’. The resources attribute is scored ‘low’ to reflect that this model choice is not dominated by operational constraints. The technical attribute is scored ‘low’ as it is possible to implement mines differently, such as through time-varying drainage levels in TTim.

The effect on predictions is scored ‘high’. In the confined parts of the system, the predicted drawdown is linearly related to the pumping rate; that is, a doubling of the pumping rate will result in a doubling of the drawdown (Reilly et al., 1987).

This relationship does not hold in the unconfined part as the specified boundary conditions represent a complete dewatering of the aquifer. The saturated thickness decreases close to the mine which means that the transmissivity of the aquifer, the product of hydraulic conductivity and saturated thickness, is no longer constant. Figure 26 explores the effect of this assumption by comparing drawdown in an unconfined aquifer cross-sectional model estimated with the analytic element code, assuming constant hydraulic properties, and a MODFLOW-2005 model (Harbaugh, 2005), in which transmissivity and storage vary spatially depending on the saturated thickness. An unconfined aquifer is considered with a horizontal hydraulic conductivity of 5 m/d and specific yield of 0.1. The base and top of the aquifer are both uniform and respectively set at –10 m and zero metres. Initial groundwater levels are set equal to the aquifer top at zero metres. A cross-sectional model is created, where the x-dimension is 10,000 m and the y-dimension 100 m. The y-direction is discretised in only one grid cell (one row of cells). The x-direction has a 100 m grid resolution (100 columns of cells). This grid resolution is representative of the discretisation that in practice can be achieved in regional-scale groundwater models. A constant head boundary of –10 m is introduced at x=zero metres representing constant drawdown due to mine dewatering. To mimic the infinite aquifer extent of the analytic element model in MODFLOW, a constant head boundary equal to zero metres is set at x=10,000 m. The intercell transmissivity is computed by the arithmetic mean of saturated thickness and logarithmic mean of hydraulic conductivity, as advised in Harbaugh (2005) for unconfined aquifers with gradually varying transmissivity.

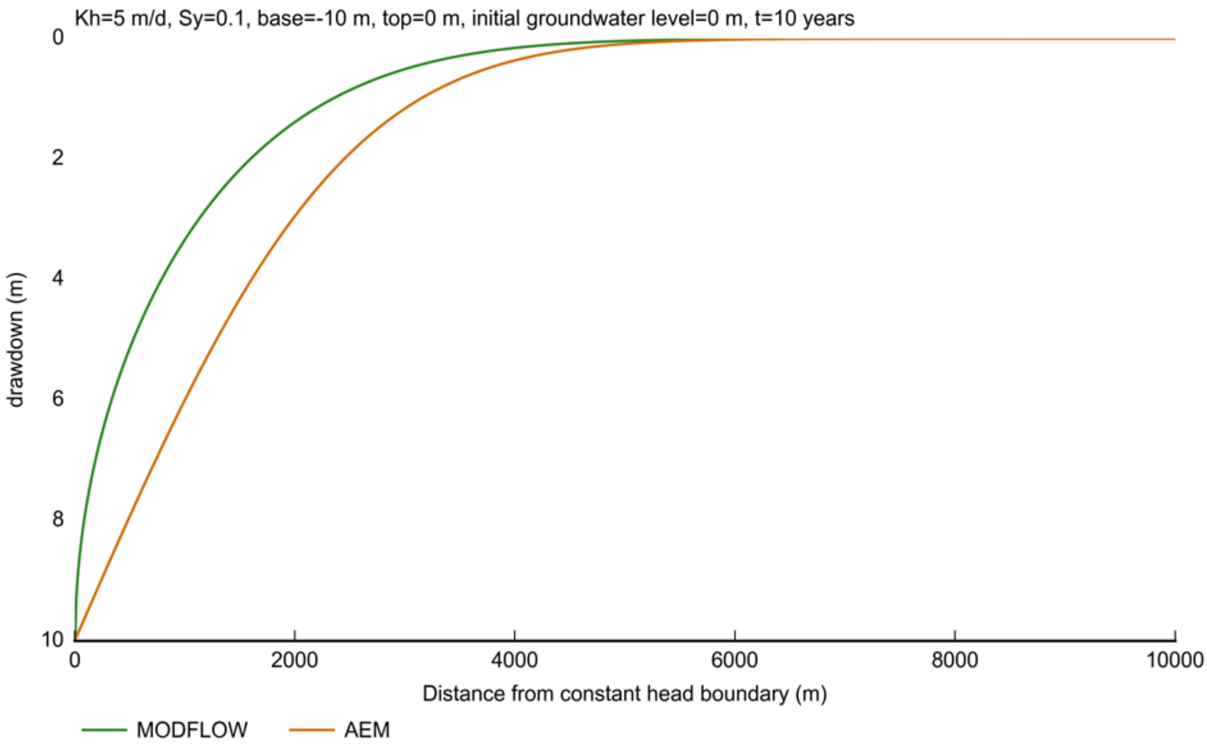

Figure 26 Comparison of drawdown in an unconfined aquifer due to a constant change in groundwater level of 9.9 m at x=zero metres after 10 years, simulated with an analytic element model (AEM) and a MODFLOW model (MODFLOW)

Aquifer is unconfined, with a constant thickness of 10 m. The cross-sectional model is 100 m wide and 10,000 m long. At x=10,000 m a drawdown of zero metres is specified in the MODFLOW models. No lateral boundaries are specified for the analytic element model.

Figure 26 shows that the drawdown by the analytic element model is larger than the drawdown simulated with the MODFLOW model. Dewatering the aquifer reduces the transmissivity to almost zero in the close vicinity of the constant head boundary. Low transmissivities allow for steeper gradients, hence the smaller drawdowns in the MODFLOW model. Transmissivity is constant in the analytic element model which means the gradient will be less steep and therefore estimated drawdown will be larger. This analysis shows the use of the analytic element model is conservative for drawdown predictions in the unconfined aquifer.

Applying a specified drawdown of 10 m in the unconfined aquifer, however, does require the unconfined aquifer to be present and to have a saturated thickness of at least 10 m. As pointed out in Section 2.6.2.8.2.6, this assumption is not justified everywhere, especially further away from the mine areas (further discussion of the spatial extent and thickness of the Quaternary alluvium and Cenozoic sediment aquifer in the area of the modelled coal mines is provided in companion product 3-4 (Lewis et al., 2018) for the Galilee subregion). This means that there is a propensity for the predictions to be overly conservative. To explore this, an alternative conceptualisation is evaluated in which the constant drawdown boundary condition is removed (Figure 27).

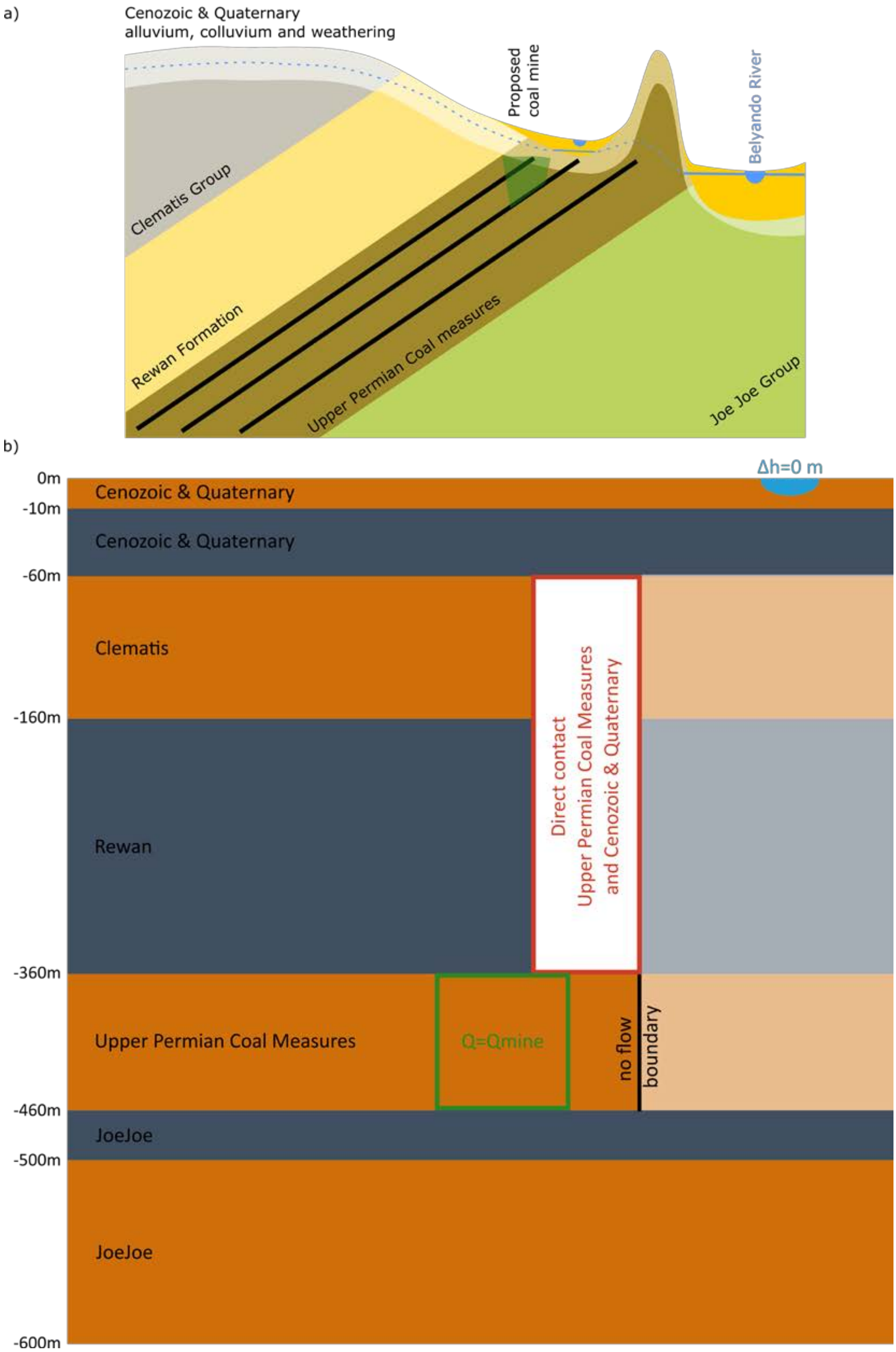

Figure 27 Illustration of alternative conceptualisation in which the constant drawdown boundary in the Cenozoic and Quaternary sediments is removed

The same set of 10,000 posterior parameter combinations as presented in Section 2.6.2.8.1 are evaluated with this alternative conceptualisation.

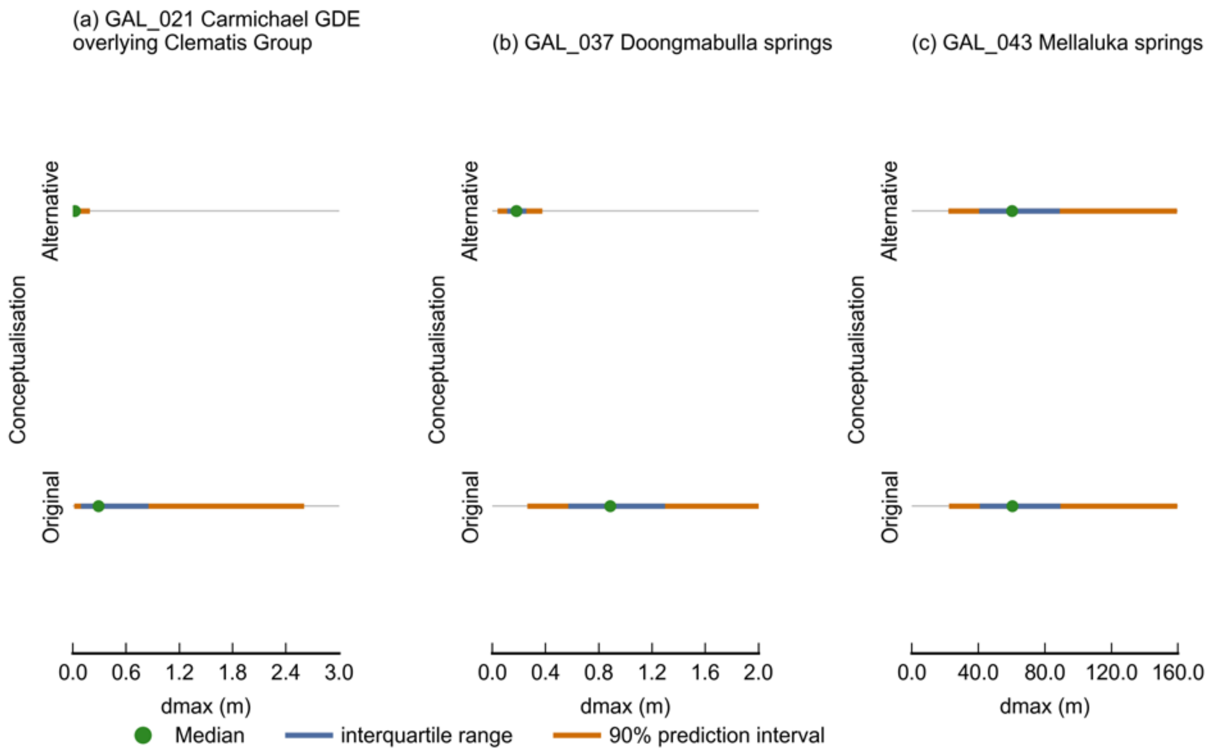

Figure 28 Boxplots of *dmax* for the original and alternative conceptualisation at (a) GAL_021 Carmichael GDE overlying Clematis Group, (b) GAL_037 Doongmabulla Springs and (c) GAL_043 Mellaluka Springs

Additional drawdown is *dmax*, the maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
GDE = groundwater-dependent ecosystem

Figure 28 shows the boxplots of maximum drawdown for both conceptualisations for the model nodes associated with the Carmichael groundwater-dependent ecosystem (GDE) overlying Clematis Group (GAL_021, unconfined Cenozoic and Quaternary), Doongmabulla Springs (GAL_037, confined Clematis) and Mellaluka Springs (GAL_043, confined upper Permian). The plot shows that the removal of this constant drawdown boundary condition has a very large effect on model nodes GAL_021 and GAL_037. The median *dmax* values at Carmichael GDE decrease from 0.29 m to 0.02 m, while at Doongmabulla Springs, the median *dmax* values drop from 0.88 m to 0.18 m. The *dmax* values at Mellaluka Springs are not noticeably affected by the conceptual change.

These results highlight that locally, in the vicinity of the mines, in the unconfined Cenozoic sediment and Quaternary alluvial aquifer and the underlying confined Clematis aquifer, most of the simulated drawdown is caused by the constant drawdown boundary in the unconfined aquifer, which assumes a continuous unconfined aquifer with a saturated thickness of 10 m. When this assumption is not valid, the predictions can be over estimated by up to an order of magnitude.

Despite its closer proximity to the mine, the *dmax* values at the Carmichael GDE are smaller than these at Doongmabulla Springs. This is because the model node associated with Doongmabulla Springs is situated in the confined Clematis aquifer (see Section 3.5 of companion product 3-4 (Lewis et al., 2018) for the Galilee subregion for further discussion of the likely source aquifer for the Doongmabulla Springs complex), where the storage is orders of magnitude smaller than in the overlying unconfined aquifer in which the Carmichael GDE model nodes are situated. For the same change in flux, the smaller storage will lead to larger drawdown.

The two conceptualisations evaluated using the analytic element model for the Galilee subregion (as described above) are the focus of more detailed discussion presented in Section 3.3.2 of companion product 3-4 (Lewis et al., 2018). In particular, the analysis in Lewis et al. (2018) explores how the different conceptual frameworks affect the application of the regional-scale groundwater modelling results, especially for the local (i.e. point-scale) assessment of potential drawdown impacts at some locations in the vicinity of the seven proposed coal mines modelled for this BA (such as Doongmabulla Springs).

2.6.2.8.2.8 Unconstrained posterior parameter distributions

The posterior parameter distributions are estimated by the Assessment team, informed by the locally available measurements. The relatively large ranges specified for these parameters reflect the confidence the Assessment team has in the estimates. The GW AEM is designed to simulate change directly, not to reproduce historical conditions. It is therefore not possible to infer or constrain model parameters by fitting the model to historical observations of groundwater level or flux.

The data attribute is scored ‘high’ as there are very limited measured data available on the hydraulic properties of the system. Resources are scored ‘medium’ as operational constraints did not allow for the establishment of a formal expert elicitation of model parameter prior distributions. The technical attribute is scored ‘low’ as it is straightforward to change the parameter distributions.

The effect on predictions is scored ‘medium’. A change in posterior parameter distributions will result in different predictions. The wide range of these parameters, however, makes the predictions conservative.

Although constraining the parameters with historical state observations is not possible with the current implementation of the GW AEM, it is unlikely that the current historical observations have sufficient information to greatly constrain the parameters relevant to the predictions. Figure 3-14 in Turvey et al. (2015), for instance, shows that the calibration metric is not very sensitive to some of the most important parameters for drawdown prediction, such as the hydraulic properties of the upper Permian coal measures. A similar conclusion was reached in companion product 2.6.2 (groundwater modelling) for the Clarence-Moreton bioregion (Cui et al., 2016), where the historical observations were shown to be unable to constrain the parameters relevant to the predictions.

2.6.2.8.2.9 Maximum drawdown not realised during 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'. Ensuring that the 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 'low' as it is trivial to extend the simulation period.

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

In the Cenozoic and Clematis Group aquifers, the drawdown is dominated by the specified drawdown in the Cenozoic aquifer, which is 10 m. This drawdown is specified for the entire simulation period to represent that a non-rehabilitated open pit will continue to drain a shallow unconfined aquifer, even after mining operations cease. As this stress operates for the entire simulation period, it is unlikely that the maximum drawdown is realised within the simulation period in the Cenozoic and Clematis Group aquifers. This drawdown will, however, by design, not exceed 10 m. In order to simulate the year of maximum change, mine rehabilitation plans need to be incorporated to represent when the aquifer is restored to pre-mining conditions. These site-specific details are beyond scope and highly speculative.

2.6.2.8.2.10 Model nodes assigned to hydrostratigraphic units

This is scored 'medium' in the data attribute as, with the exception of some springs, it is generally well known which hydrostratigraphic unit a model node sources water from. Resources are also scored 'medium'. The technical attribute is scored 'medium' as the vertical resolution of the model is not sufficient to assign some model nodes to the correct hydrostratigraphic unit. An example is model node GAL_039, Spring 107A, which has the Ronlow beds as water source but is assigned to the underlying Clematis Group layer.

Any misclassification has the potential to greatly affect the predictions as the difference in drawdown can be an order of magnitude for different hydrostratigraphic units at the same location. The effect on predictions is therefore scored 'medium'.

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2.6.2.9 Limitations and conclusions

Summary

The hydrological change due to additional coal resource development in the Galilee subregion is probabilistically estimated with a groundwater analytic element model (GW AEM). It provides the change in drawdown in the upper Permian coal measures, the Clematis Group and the Cenozoic and alluvial sediments as well as the change in the surface water – groundwater flux that is integrated in the Australian Water Resources Assessment landscape (AWRA-L) surface water model, which is reported in companion product 2.6.1 for the Galilee subregion (Karim et al., 2018).

Drawdown in the upper Permian coal measures extends far into the Galilee Basin, with probabilities of exceeding 5 m drawdown in excess of 30% at places 50 km west of the coal mines. The Rewan Group aquitard provides a regional seal that prevents this drawdown to propagate upwards into the overlying Clematis Group and Eromanga Basin.

Simulated drawdowns in the Clematis Group and Cenozoic cover and alluvial sediments are controlled by the direct extraction of water from the Cenozoic and to a much lesser extent by the extraction of water from the upper Permian coal measures. From a distance of about 25 km from the edge of the mine footprints, the probability of exceeding 0.2 m drawdown decreases to less than 5%.

The simulated change in surface water – groundwater flux includes the change in baseflow to the Belyando River and the evapotranspiration by riparian vegetation. The maximum additional change is less than 1% of the baseflow for the Belyando River, estimated in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018).

The greatest potential in reducing the predictive uncertainty lies in improved characterisation of the surface water – groundwater interaction in the subregion and the Cenozoic and alluvial aquifer systems. Further development of the numerical MODFLOW model (as outlined in Turvey et al., 2015), including its integration into a probabilistic framework, has great potential to improve the current predictions.

2.6.2.9.1 Data gaps and opportunities to reduce predictive uncertainty

The qualitative uncertainty analysis in Section 2.6.2.8 highlighted several model choices and assumptions that have a high potential impact on the predictions, such as the connection status of the river stream network, the representation of the Cenozoic cover and Quaternary alluvial sediments, and the implementation of the coal resource development pathway. These assumptions are all driven by limited data availability.

A comprehensive assessment of the connection status of the stream network in the Galilee subregion will allow for the nuanced assumption that all but the Belyando River are maximally losing streams, and the implementation in numerical models. These assumptions imply that there is potential for a change in streamflow anywhere where a non-negative drawdown is simulated in the unconfined aquifer. Whether or not this drawdown will manifest itself as a change in streamflow will depend on local conditions, including the connection status of the stream.

The geological model developed and presented in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018) provides a solid basis for the representation of the regional geology. Adding local detail on the Cenozoic cover sediments and the position and extent of coal seams in the upper Permian coal measures will not only allow for the making of more robust and accurate predictions of the hydrological change in the Cenozoic cover, but it will allow independent estimates of mine pumping rates, as for example has been done in Turvey et al. (2015).

Further investment in the development of the Galilee Basin hydrogeological (GBH) numerical model presented in Turvey et al. (2015), such as improving numerical stability, and integration of such a model in a probabilistic framework, such as is outlined, for example, in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016), will allow for the making of more robust predictions, and formally test the effect of the technical limitations in the analytic element model, such as the layer geometry and spatially varying properties.

The sensitivity analysis indicated that the hydraulic properties of the upper Permian coal measures and the Cenozoic cover are the most influential parameters to estimate maximum drawdown and year of maximum change. Turvey et al. (2015) indicated that the current observation dataset is not well suited to constrain these parameters. The predictive uncertainty has the most potential to be reduced by gathering additional information on both the upper Permian coal measures and the Cenozoic cover. This includes both observations of the hydraulic parameters, the conductivity and storage, and observations of the state variables such as fluxes and groundwater levels.

Further discussion of some other gaps, limitations and opportunities identified from the wider body of work undertaken for this BA is provided in Section 3.7.4 of companion product 3-4 (Lewis et al., 2018) for the Galilee subregion.

2.6.2.9.2 Limitations

The qualitative uncertainty analysis in Section 2.6.2.8.2 lists the major assumptions and model choices that form the basis of the probabilistic assessment of the impacts of coal resource development on model nodes associated with groundwater in the Galilee subregion. Within the context of the goal of the Bioregional Assessment Programme, the Galilee subregion modelling 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; therefore, the modelling team recommends not using these models for any other purpose without a formal assessment of the suitability of the conceptualisation, parameterisation and implementation for the changed objective.

Should these models be considered for any other purpose, there should be 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). All model files and executables are available at www.bioregionalassessments.gov.au. It is recommended to contact the model development team for detailed information on the groundwater models.

The chain of models described in this product is designed to estimate impacts on a regional scale. This unfortunately means trade-offs are made in terms of local resolution of the model. Especially in the immediate vicinity of coal mines, the effect of coal mining activity will be largely dominated by local variations in geology and hydrogeology. The reliability of any predictions made by this model will be inferior to the reliability of predictions made by a local groundwater model that fully accounts for this level of detail.

The models are 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. 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 2.6.2.8. Input data, model files, (including the pre- and post-processing scripts and executables) and results are available at www.bioregionalassessments.gov.au.

The utmost care has been devoted to ensuring the results presented are in accordance with the conceptual understanding of the system and the stresses imposed on it. This is mostly done by targeted spot checks of model outputs and visual examination of the response of model outputs to varying parameter values. While these checks minimise the risk that artefacts have gone undetected, as in any modelling exercise of this scale, there is no guarantee that there are no artefacts of modelling included in the results.

2.6.2.9.3 Conclusions

For the Bioregional Assessment Programme, a GW AEM is developed to probabilistically estimate the hydrological change due to coal resource development in the Galilee subregion. The groundwater model provides the change in surface water – groundwater flux that is integrated in the surface water model, AWRA-L, which is reported in companion product 2.6.1 for the Galilee subregion (Karim et al., 2018).

The simulations indicate that the maximum drawdown in the upper Permian coal measures extends far into the Galilee Basin, with probabilities of exceeding 5 m drawdown in excess of 30% 50 km west of the coal mines. The Rewan Group aquitard acts as a regional seal that impedes upwards propagation of drawdown from upper Permian coal measures into the overlying Clematis Group aquifer and Eromanga Basin.

The Cenozoic cover and alluvial sediments are modelled as laterally infinite and continuous. As illustrated by the sensitivity analysis, drawdowns in this hydrostratigraphic unit are controlled by the direct extraction of water from this unit and to a much lesser extent by the extraction of water from the upper Permian coal measures. Drawdowns are specified as smaller or equal to 10 m. The probability of exceeding 0.2 m drawdown generally drops below 5% from about 25 km from the edge of the mine footprints.

Simulated drawdowns in the Clematis Group are the result of propagation of drawdown from the Cenozoic aquifer layer, which requires the unconfined aquifer system to be laterally continuous between the mines and the Clematis Group outcrop area.

The change in surface water – groundwater flux includes the change in baseflow to the Belyando River and the evapotranspiration by riparian vegetation. The maximum change is less than 1% of the baseflow estimated for the Belyando River, estimated in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018). In companion product 2.6.1 for the Galilee subregion (Karim et al., 2018) this change in surface water – groundwater flux is integrated with the total streamflow to estimate the change in selected aspects of the hydrograph, summarised in hydrological response variables.

Companion product 3-4 (Lewis et al., 2018) for the Galilee subregion reports impacts on, and risk to, landscape classes and water-dependent assets arising from the simulated changes in groundwater and surface water reported in this product and in companion product 2.6.1 for the Galilee subregion (Karim et al., 2018).

The greatest potential in reducing the predictive uncertainty lies in improved characterisation of the surface water – groundwater interaction and the Cenozoic and alluvial aquifer systems. Further development of the numerical MODFLOW model (as outlined in Turvey et al., 2015), including its integration into a probabilistic framework, has great potential to improve the current predictions.

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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

additional drawdown: the maximum difference in drawdown (dmax) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development

analytic element model: a groundwater model in which the groundwater flow equations are solved based on the representation of internal boundary conditions, points, lines or polygons where constant groundwater level, constant flux or flux dependence on groundwater level is imposed (Bakker, 2013). The resulting groundwater flow equations can be evaluated at arbitrary points in space and time. The solution is therefore independent of a spatial discretisation of the model domain into grids, and a temporal discretisation into time steps, as is necessary for finite element or finite difference groundwater models.

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.

artesian aquifer: an aquifer that has enough natural pressure to allow water in a bore to rise to the ground surface

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.

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system 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

baseline drawdown: the maximum difference in drawdown (dmax) under the baseline relative to no coal resource development

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.

Clarence-Moreton bioregion: The Clarence-Moreton bioregion is located in north-east NSW and south-east Queensland and adjoins the Northern Inland Catchments bioregion. Along with the towns of Casino, Lismore and Grafton, it contains the outskirts of the Queensland cities of Brisbane, Ipswich, Logan and Toowoomba. The bioregion contains large river systems (including the Clarence, Richmond and Logan-Albert rivers) and extensive wetlands, some of which are nationally important. Many of these wetlands are home to water-dependent plants and animals that are listed as rare or threatened under Queensland and Commonwealth legislation. The bioregion contains numerous national parks and forest reserves and includes sites of international importance for bird conservation. A large area of the bioregion is used for dryland farming and plantations and as grazing land for livestock. Irrigated agriculture takes up a comparatively small area. Groundwater is extracted for various uses but most commonly for livestock and agricultural purposes. The largest water reservoir in this bioregion is Lake Wivenhoe on the Brisbane River, which supplies Brisbane and its surrounds. The NSW part of the bioregion has smaller dams located in the upper Richmond river basin.

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).

depressurisation: in the context of coal seam gas operations, depressurisation is the process whereby the hydrostatic (water) pressure within a coal seam is reduced (through pumping) such that natural gas desorbs from within the coal matrix, enabling the gas (and associated water) to flow to surface

dewatering: the process of controlling groundwater flow within and around mining operations that occur below the watertable. In such operations, mine dewatering plans are important to provide more efficient work conditions, improve stability and safety, and enhance economic viability of operations. There are various dewatering methods, such as direct pumping of water from within a mine, installation of dewatering wells around the mine perimeter, and pit slope drains.

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 and/or quality of surface water or groundwater. An effect is a specific type of an impact (any change resulting from prior events).

ephemeral stream: a stream that flows only briefly during and following a period of rainfall, and has no baseflow component

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

Galilee subregion: The Galilee subregion is part of the Lake Eyre Basin bioregion and is entirely within Queensland. It extends westwards across the Great Dividing Range and into the Lake Eyre drainage basin. The subregion is sparsely populated, with most people living in towns and localities including Charleville, Barcaldine, Blackall and Hughenden. The subregion encompasses the headwaters of several major waterways including the Cooper Creek and the Diamantina, Belyando, Cape, Thomson, Barcoo, Flinders, Bulloo, and Warrego rivers. In addition to the river systems, the subregion has numerous wetlands, springs, waterholes and lakes, including the nationally important lakes Buchanan and Galilee. Some of these are home to diverse and unique plants and animals, many of which are listed as rare or threatened under Queensland and Commonwealth legislation. Native vegetation consists largely of grasslands in the west and open eucalyptus woodlands in the east. Cattle and sheep grazing on native pasture is the main land use and groundwater is of great importance.

goaf: That part of a mine from which the coal has been partially or wholly removed; the waste left in old workings.

groundwater: water occurring naturally below ground level (whether stored in or flowing through aquifers or within low-permeability aquitards), 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 flow 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 and/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 and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis

inflow: surface water runoff and deep drainage to groundwater (groundwater recharge) and transfers into the water system (both surface water and groundwater) for a defined area

Lake Eyre Basin bioregion: The Lake Eyre Basin bioregion covers an area of about 1.31 million square kilometres of central and north-eastern Australia, which is almost one-sixth of the country. It extends across parts of Queensland, SA, NSW and the NT and incorporates the whole of the Lake Eyre drainage basin. The bioregion was selected for assessment because of the likelihood of coal seam gas and coal mining development and the potential for water-dependent impacts on the environment and other industries that use water such as agriculture.

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. Note that there is expected to be less heterogeneity in the response within a landscape class than between landscape classes. 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.

life-cycle stage: one of five stages of operations in coal resource development considered as part of the Impact Modes and Effects Analysis (IMEA). For coal seam gas (CSG) operations these are exploration and appraisal, construction, production, work-over and decommissioning. For coal mines these are exploration and appraisal, development, production, closure and rehabilitation. Each life-cycle stage is further divided into components, which are further divided into activities.

likelihood: probability that something might happen

model chain: a series of linked models where the output of one model becomes an input to another

model node: a point in the landscape where hydrological changes (and their uncertainty) are assessed. Hydrological changes at points other than model nodes are obtained by interpolation.

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

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.

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'.

quantile: a set of values of a variate that divide the range of a probability distribution into contiguous intervals with equal probabilities (e.g. 20 intervals with probability 0.05, or 100 intervals with probability 0.01). Within bioregional assessments, probability distributions are approximated using a number of runs or realisations.

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

receptor impact model: a function that translates hydrological changes into the distribution or range of potential ecosystem outcomes that may arise from those changes. Within bioregional assessments, hydrological changes are described by hydrological response variables, ecosystem outcomes are described by receptor impact variables, and a receptor impact model determines the relationship between a particular receptor impact variable and one or more hydrological response variables. Receptor impact models are relevant to specific landscape classes, and play a crucial role in quantifying potential impacts for ecological water-dependent assets that are within the landscape class. In the broader scientific literature receptor impact models are often known as 'ecological response functions'.

recharge: see groundwater recharge

riparian: An area or zone within or along the banks of a stream or adjacent to a watercourse or wetland; relating to a riverbank and its environment, particularly to the vegetation.

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.

saturated zone: the part of the ground in which all the voids in the rocks or soil are filled with water. The watertable is the top of the saturated zone in an unconfined aquifer.

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 (including from Programme partner organisations) or a dataset created by the Programme based on analyses conducted by the Programme for use in the bioregional assessments (BAs)

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.

stratigraphy: stratified (layered) rocks

subcrop: 1 - A subsurface outcrop, e.g. where a formation intersects a subsurface plane such as an unconformity. 2 - In mining, any near-surface development of a rock or orebody, usually beneath superficial material.

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

tenement: a defined area of land granted by a relevant government authority under prescribed legislative conditions to permit various activities associated with the exploration, development and mining of a specific mineral or energy resource, such as coal. Administration and granting of tenements is usually undertaken by state and territory governments, with various types related to the expected level and style of exploration and mining. Tenements are important mechanisms to maintain standards and safeguards relating to environmental factors and other land uses, including native title.

transmissivity: A parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow).

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)

water use: the volume of water diverted from a stream, extracted from groundwater, or transferred to another area for use. It is not representative of 'on-farm' or 'town' use; rather it represents the volume taken from the environment.

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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