Australian Government

BIOREGIONAL ASSESSMENTS

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

Groundwater numerical modelling for the Hunter subregion

Product 2.6.2 for the Hunter subregion from the Northern Sydney 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.

Department of the Environment and Energy

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Authorship is listed in relative order of contribution.

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Cover photograph

Oblique view west of Muswellbrook showing Bengalla coal storage (left foreground) with irrigated agriculture and riparian vegetation either side of the Hunter River and Mount Arthur coal mine in the distance (right background), NSW, 2014

© Google earth (2015), Sinclair Knight Merz Imagery date 16 December 2008. Position 32°17′58′′ S, 150°48′51′′ E, elevation 136 m, eye altitude 1.59 km

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CSIRO

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Executive summary

Coal resource development can potentially affect water-dependent assets through impacts on groundwater hydrology. The bioregional assessment (BA) groundwater numerical modelling provides probabilities of groundwater drawdown and changes in the surface water – groundwater exchange flux from coal resource development in the Hunter subregion.

This product describes the model development and presents the modelled hydrological changes in response to coal resource development in the Hunter subregion. Results are reported for the difference between the two potential futures considered in a BA:

- *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 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**.**

The Hunter subregion has a long history of coal mining. In the CRDP for the Hunter subregion there are 42 baseline mines, 1 of which was not included in the modelling and 22 additional coal resource developments, 5 of which were not included in the modelling. Reasons for not modelling these 6 mines were insufficient data or that the additional coal resource development produced negligible changes to the flow rates of groundwater into the mine. Therefore, the groundwater numerical modelling in the Hunter subregion includes 58 mines comprising 41 baseline mines and 17 additional coal resource developments. In the Hunter subregion there are no CSG fields in the CRDP.

The modelling approach in the Hunter subregion is consistent with that detailed in submethodology M07 for groundwater modelling, and in submethodology M09 for propagating uncertainty through models. The modelling approach is implemented in the Hunter subregion as follows:

- The model chain comprises a subregion-wide groundwater model, built specifically for the Hunter subregion in the Multiphysics Object Oriented Simulation Environment (MOOSE).
- Model emulators, trained on a large number of groundwater model simulations, characterise the prediction uncertainty for two hydrological response variables: *dmax*, the maximum difference in drawdown between CRDP and baseline due to the additional coal resource development, and *tmax*, the year of maximum change.

- The model is built upon the nine geological horizons in the Hunter subregion geological model outlined in companion product 2.1-2.2 (observations analysis, statistical analysis and interpolation) for the Hunter subregion. Additional layers are added to represent near-surface groundwater processes and the presence of coal seams.
- The modelling domain spans an area of about 34,000 km^2, with a best spatial resolution in plan view of 500 m, and with depths below surface ranging from about 300 m to 3000 m.
- Representation of the modelling domain in plan view is by a variable triangulated mesh with greater resolution around mines and streams.
- All major rivers, along with some minor reaches, are represented in the model and define the locations where the groundwater model interacts with the Hunter river model. Changes in these surface water – groundwater fluxes are incorporated into the streamflow changes in the river model and are reported in companion product 2.6.1 (surface water numerical modelling) for the Hunter subregion.
- The model has 22 parameters, which need to be specified. Ten of these are varied in the uncertainty analysis.
- Regional-wide observational data to constrain model parameters are poor or lacking. Groundwater level observations from 64 groundwater monitoring sites and observed streamflow data are used to impose upper and lower bounds on the modelled drawdowns.
- The surface water – groundwater flux simulations are constrained as part of the surface water modelling.

The predictions from the groundwater numerical modelling for the Hunter subregion show that the extraction of water by coal mines generally causes baseflow (i.e. the groundwater contribution to stream) to decrease.

More than three-quarters of the model nodes have drawdowns due to additional coal resource development of less than 2 m; two-thirds have drawdowns less than 0.2 m. The drawdowns resulting from the mining operations of the additional coal resource development are localised around the mines. At a distance of about 20 km from these mine sites, there is approximately a 5% probability of the drawdown exceeding 0.2 m. In general, the year of maximum change occurs relatively quickly in the immediate vicinity of the mines, but progressively later with increasing distance from the mines.

As in any modelling exercise, a number of assumptions have been made, some of which are not included in the formal uncertainty analysis. Many are necessitated through insufficient data, but lack of resources to undertake more rigorous analyses and technical issues have also necessitated some assumptions. In general, these assumptions lead to overestimation of the groundwater changes from mining. Results of the sensitivity analysis indicate that the depth of the river bed and parameterisation of hydraulic conductivities have the biggest effect on historical model predictions; whereas drawdown due to the additional coal resource development (additional drawdown) is sensitive to some of the same parameters but also sensitive to the baseline porosity parameter and the parameters that define the changes arising from coal resource development.

The use of regional parameters can result in overestimations of the range of potential drawdown at any particular point in the landscape. Constraining the regional model results in the Wyong

River based on local geological and hydrogeological data indicated that the area affected by drawdowns exceeding 0.2 m due to the additional coal resource development is likely to be far less extensive than that predicted using the full set of regional parameterisations.

The results of groundwater numerical modelling for the Hunter subregion inform product 3-4 (impact and risk analysis). Estimates of the probability of hydrological changes due to coal resource development will be used to assess direct impacts on water-dependent assets, such as groundwater-dependent ecosystems and economic bores.

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This technical product was reviewed by several groups:

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This work was supported by resources provided by the Pawsey Supercomputing Centre with funding from the Australian Government and the Government of Western Australia.

Currency of scientific results

The modelling results contained in this product were completed in July 2016 using the best available data, models and approaches available at that time. The product content was completed in August 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 will be different, due in part to regional differences, but also in response to the availability of data, information and fit-for-purpose models. Where differences occur, these are recorded, judgments exercised on what can be achieved, and an explicit record is made of the confidence in the scientific advice produced from the BA.

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

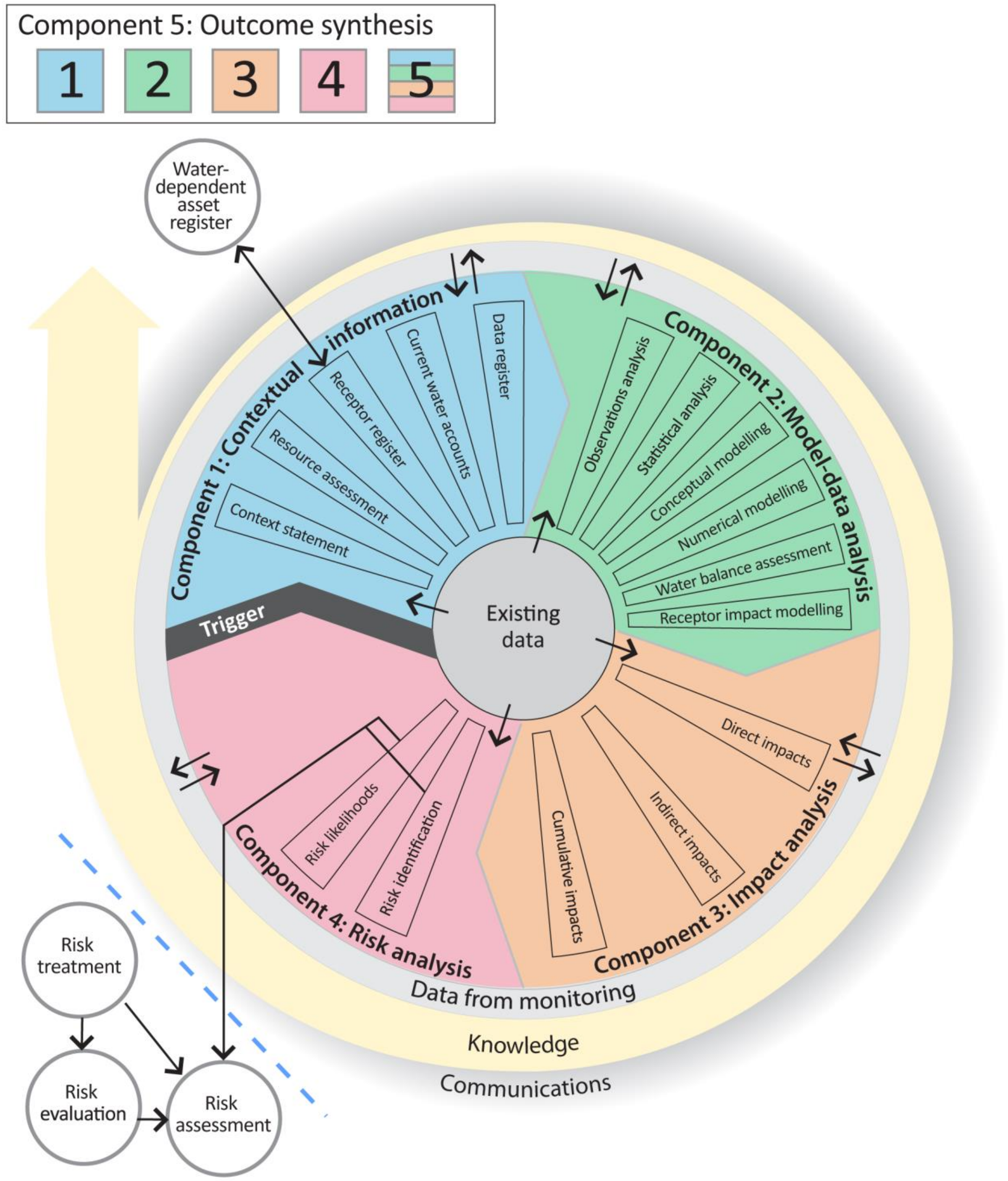

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

The overall scientific and intellectual basis of the BAs is provided in the BA methodology (Barrett et al., 2013). Additional guidance is required, however, about how to apply the BA methodology to a range of subregions and bioregions. To this end, the teams undertaking the BAs have developed and documented detailed scientific submethodologies (Table 1), 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.

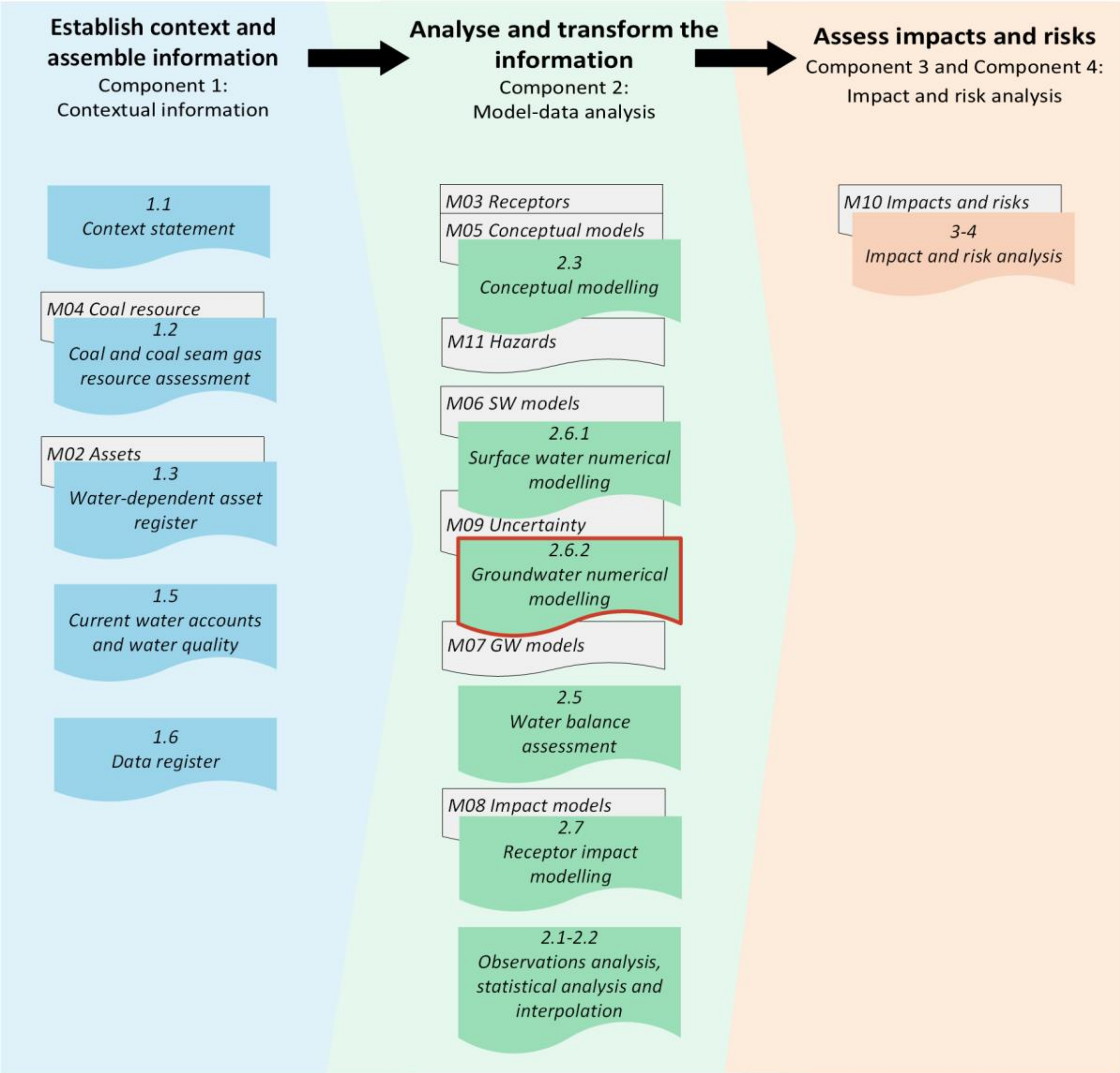

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Hunter subregion

For each subregion in the Northern Sydney 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 Hunter 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 Hunter 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 Hunter subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Hunter subregion	5	Outcome synthesis	2.5.5	PDF, HTML

[a]The types of products are as follows:

- 'PDF' indicates a PDF document that is developed by the Northern Sydney 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 151.0° East for the Northern Sydney Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://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.

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Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 4 March 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 4 March 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 Hunter 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 Hunter 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 coal resource development pathway (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

The groundwater numerical modelling is designed to provide probabilistic estimates of groundwater drawdown and changes in the surface water – groundwater exchange flux due to additional coal resource development in the Hunter subregion. Results can be expressed in terms of contour maps of the probability of exceeding a specified depth of drawdown and/or percentiles of drawdown depths. The approach in the Hunter subregion is consistent with the Bioregional Assessment Programme's companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016), and companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016).

The model chain comprises a subregion-wide groundwater model, built specifically for the Hunter subregion and model emulators, trained on a large number of groundwater model simulations, to characterise the prediction uncertainty for two hydrological response variables: *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, and *tmax*, the year of maximum change.

The modelled changes in surface water – groundwater exchange flux inform the potential hydrological changes on total streamflow, modelled using the Hunter subregion surface water model (see companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)).

This section summarises the groundwater modelling approach with reference to the Hunter subregion conceptual model and the objectives of the bioregional assessment.

2.6.2.1.1 Background and context

The groundwater modelling in bioregional assessments has a very specific objective: to probabilistically evaluate potential drawdown and changes in surface water – groundwater flux relevant to the surface water modelling in the coal resource development pathway (CRDP) relative to the baseline at specified locations in the landscape to inform the impact and risk analysis reported in companion product 3-4 for the Hunter subregion (as listed in Table 2).

The modelling is focused on the change in hydrogeological stress and the hydraulic properties, rather than on reproducing historical conditions or predicting future-state variables of the system, such as groundwater levels of fluxes. The main rationale for this approach is that in confined groundwater systems, and to an extent in unconfined systems, the response in groundwater level or flux is linear with respect to the change in stress – that is, a doubling of the pumping rate will result in a doubling of drawdown (Reilly et al., 1987; Rassam et al., 2004). If a system behaves linearly, it means 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 September 2015, following the Hunter subregion conceptual modelling and CRDP workshops at which stakeholder feedback was sought. During the uncertainty analysis, these parameter combinations are filtered in such a way that only those that are consistent with the available observations and the understanding of the system are used to generate the ensemble of predictions. When no relevant observations are available, the prior parameter combinations are not constrained. The details are documented in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016).

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

A precautionary approach is adopted in making modelling choices and assumptions to reduce the likelihood of underestimating the hydrological changes arising from 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 will be revisited as part of the model development process. This precautionary approach allows us to be very confident in areas that are ruled out of having any potential impacts due to drawdown.

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.

This product reports only the drawdown due to coal resource development. The drawdown due to additional coal resource development is particularly emphasised, and drawdown under baseline and under the CRDP are also reported for context. 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 Hunter 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 documents for this subregion and the BA 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, 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

In the Hunter subregion, the groundwater model has been developed in the Multiphysics Object-Oriented Simulation Environment (MOOSE) (Section 2.6.2.3). To be fit for the purposes of a bioregional assessment (BA), the groundwater model needs to satisfy the criteria listed in Table 3. The remainder of this section discusses each of these criteria having regard to the numerical modelling approach undertaken in the Hunter subregion.

Table 3 Assessment of groundwater numerical modelling approach in the Hunter 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 in BAs is to assess hydrological changes arising from coal resource development using a probabilistic approach. In the Hunter subregion, the CRDP includes existing open-cut and underground mining operations, proposals to expand existing open-cut and underground mines and proposals for new open-cut and underground mines (see Section 2.3.4 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018)). There are no CSG developments.

The groundwater and surface water models predict changes for a set of hydrological response variables, chosen to represent important hydrological characteristics of the system or landscape class (e.g. flow volumes, flow frequencies). Some of the hydrological outputs become inputs to receptor impact models through which the potential impacts of coal resource development on some water-dependent assets can be evaluated. Receptor impact models will not necessarily be generated for all water-dependent assets, so the modelled hydrological outputs will also be used to inform more qualitative assessments of other potentially impacted water-dependent assets.

The hydrological response variables for groundwater are (i) 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 (*dmax*) and (ii) time of maximum change (*tmax*). Drawdown is the difference in groundwater level between the baseline and CRDP within a regional-scale, unconfined aquifer that spans the entire model domain. These variables are generated in the model at the groundwater model nodes shown in Figure 3. Although change in baseflow is an output of the groundwater model, it is an input into the surface water modelling and therefore encapsulated within the set of surface water hydrological response variables (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)). The surface water – groundwater nodes in Figure 3 show where change in baseflows are generated in the groundwater model. Changes in the nine hydrological response variables for streamflow due to the additional coal resource development are reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018). Figure 3 shows the location of the surface water model nodes relative to the groundwater model nodes where surface water – groundwater fluxes are calculated.

The groundwater model is run many times using a wide range of parameter values to generate an ensemble of predictions. From this set of runs, a probability distribution is defined for each groundwater hydrological response variable at each groundwater model node in the subregion. This distribution summarises the uncertainty in the prediction (Section 2.6.2.8).

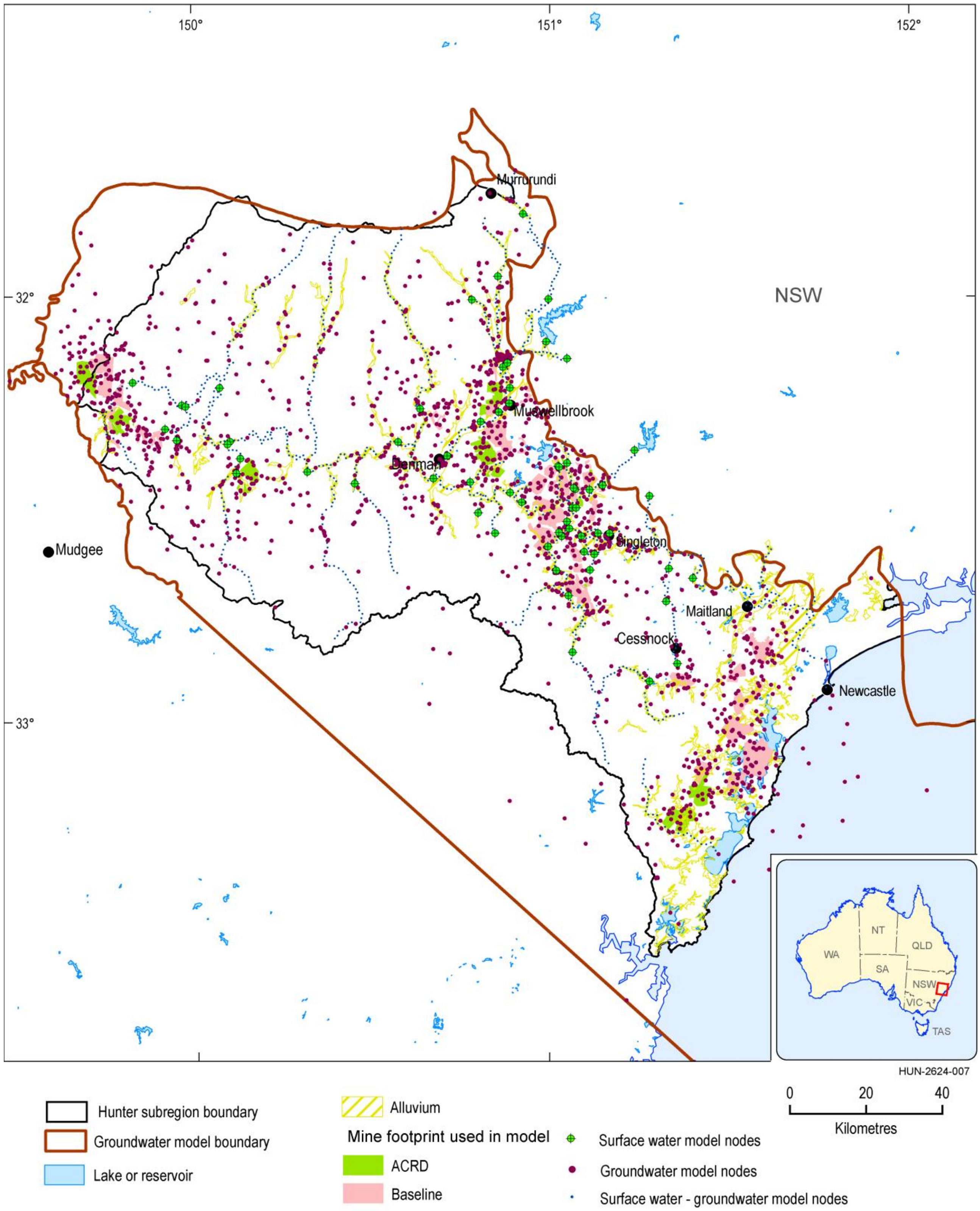

Figure 3 Groundwater and surface water model nodes in the Hunter subregion

ACRD = additional coal resource development, CRDP = coal resource development pathway
The maximum extent of the coal resource developments in CRDP is equal to the union of extents for baseline and ACRD.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3, Dataset 4); CSIRO (Dataset 5)

Pumping water that flows from the coal seam, interburden and weathered rock into the working area during mining produces a cone of drawdown and a drop in the watertable around the worked area. Where drawdowns expand into alluvial aquifers that intersect the river channel, the flux of water from the alluvial aquifer to the river will tend to decrease. To represent this surface water – groundwater interaction, the groundwater model must either represent alluvial aquifers and the river network in its model structure or interface with an alluvial groundwater model that does. A surface water model constructed to represent the same river network can receive these changes in baseflow at specified points along its network to represent the combined effect of changes to surface runoff and groundwater input on streamflow. Since groundwater and surface water systems operate at different temporal scales, the models used to represent these processes run on different time steps. Streamflow is very responsive to individual rainfall events and is usually modelled at a daily time step or finer. Groundwater levels in shallow, unconsolidated alluvium are also responsive to changes in rainfall and river stage, but also to exchanges with deeper, intermediate and regional-scale groundwater aquifers in more consolidated material (i.e. lower transmissivities), which respond relatively slowly to changes in rainfall recharge. To predict these intermediate and regional-scale groundwater systems, a monthly or more infrequent time step can suffice.

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

For the Hunter subregion, the modelling suite includes the Australian Water Resource Assessment landscape (AWRA-L) water balance model (Viney et al., 2015) to calculate the surface runoff to streams; the MOOSE groundwater model to predict watertables and change in baseflows (detailed in this product); and the AWRA-R (river) model (Dutta et al., 2015) via which surface runoff and change in baseflow are propagated downstream. The individual models have different spatial and temporal resolution which requires a set of customised processing steps to upscale or downscale model data to allow the models to be linked.

Figure 4 illustrates the model sequencing, parameters exchanged between models and the outputs generated at model nodes to inform the receptor impact modelling. The MOOSE, AWRA-L and AWRA-R baseline runs predict the hydrological changes of coal mines that were commercially producing coal as at December 2012. The corresponding CRDP runs predict the combined hydrological changes of the baseline coal resource development (baseline) and those expected to begin commercial production after 2012 (see Section 2.3.4 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018)).

The difference in predicted drawdown between baseline and CRDP runs, expressed in terms of *dmax* and *tmax*, yields the predicted hydrological changes due to the additional coal resource development in the Hunter subregion. In the receptor impact analysis, the ecological consequences of the predicted changes in HRVs in the fractured rock aquifers and alluvial aquifers are assessed.

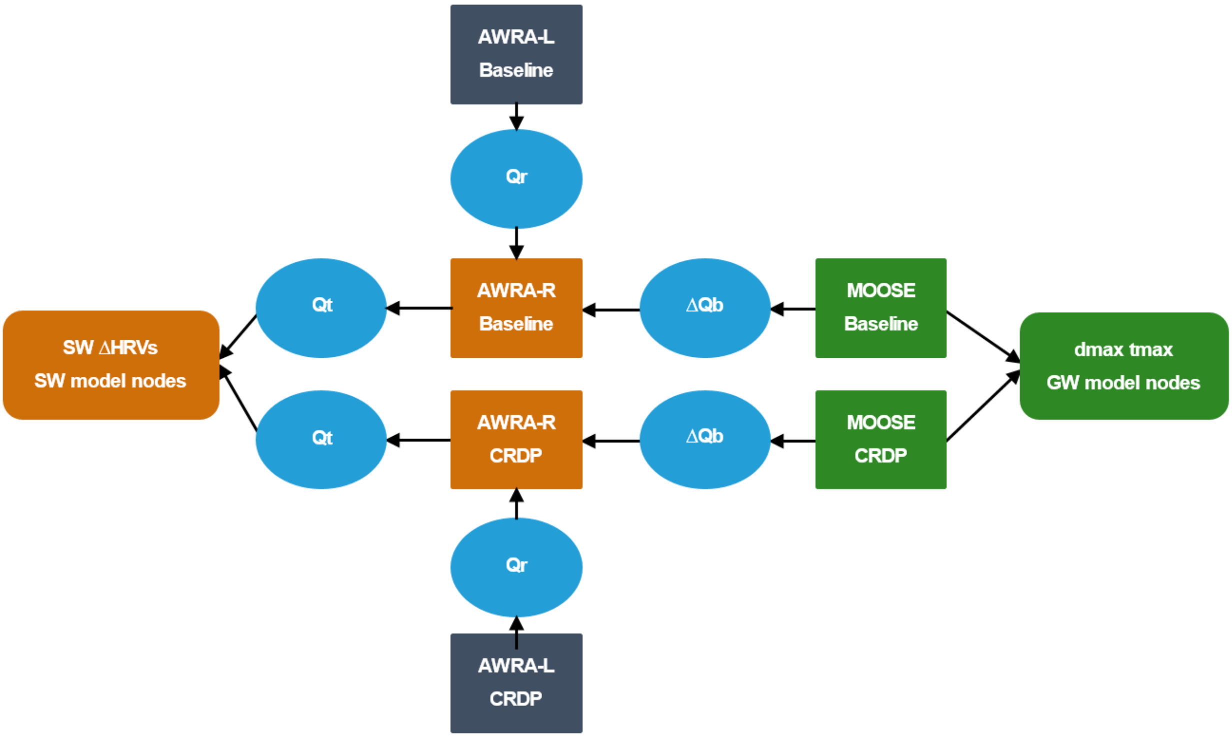

Figure 4 Model sequence for the Hunter subregion

AWRA-L = rainfall-runoff model; AWRA-R = river model; CRDP = coal resource development pathway; 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; ΔHRV = change in hydrological response variable; MOOSE = groundwater model; ΔQb = change in baseflow relative to no development baseflow; Qr = surface runoff; Qt = total streamflow; SW = surface water; tmax = year of maximum change

2.6.2.1.2.2 Design and construction

According to the Australian groundwater modelling guidelines (Barnett et al., 2012), the design and construction of a groundwater model should meet a clear set of objectives (see preceding section) and provide some measure of model confidence. The model confidence level is an *a priori* categorisation of a groundwater model to reflect its predictive capability and is a function of model complexity, prediction time frame and data availability. As explained in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016), the groundwater models in the BAs are all Class 1 (lowest level) models because they are required to make predictions of unprecedented stresses over time frames longer than the periods with data available to constrain the model.

Further technical detail of the conceptualisation, parameterisation and implementation are provided in Section 2.6.2.3 for the MOOSE groundwater model and in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018) for the AWRA-L and AWRA-R models.

2.6.2.1.2.3 *Integration with sensitivity and uncertainty analysis workflow*

Companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016) discusses in detail the propagation of uncertainty through numerical models in the BAs. Figure 5 summarises the uncertainty propagation workflow which consists of four major steps:

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

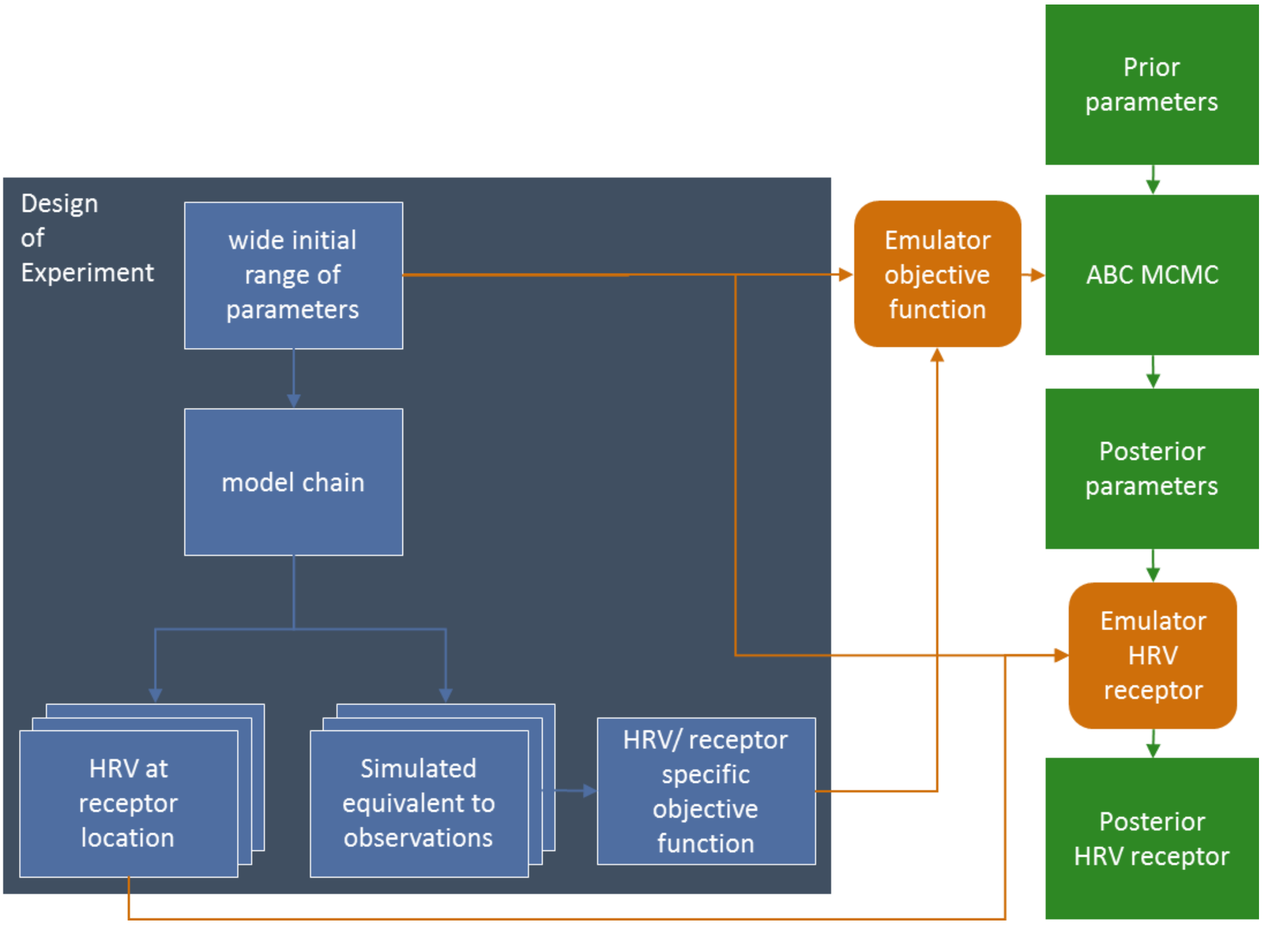

Figure 5 Uncertainty analysis workflow

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

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

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

This type of uncertainty analysis requires a very large number of model evaluations. To reduce the computational load associated with running the numerical model, the original model chain in the uncertainty analysis is replaced by emulators, statistical functions that closely mimic the effect of parameter values on predictions. These emulators take little time to evaluate and are straightforward to integrate in the uncertainty analysis workflow.

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

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

Section 2.6.2.7 and Section 2.6.2.8 provide details of the implementation of this uncertainty propagation workflow for the Hunter groundwater model. The uncertainty analysis for the AWRA-L model is in Section 2.6.1.5 and Section 2.6.1.6 of companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018). These sections also have a qualitative uncertainty analysis that provides a structured discussion of the assumptions and model choices not included in the numerical uncertainty analysis and the perceived effect on the predictions.

2.6.2.1.2.4 Constraining regional results with local information

The main aim of a BA is to provide a regional-scale assessment of the potential hydrological changes and impacts that accumulate over time and space from multiple coal resource developments. Results from this assessment identify areas within the Hunter subregion that are potentially at risk from additional coal resource development. While some model parameters are locally constrained by observation data, the range of most parameters are informed by regional data.

The stochastic, prediction focussed approach permits the use of local scale information, such as contained in environmental assessments for the individual mines or from other local studies, to constrain the regional parameterisation, without the need to run the computationally intensive regional scale groundwater model again. In section 2.6.2.8.1.4, this concept is illustrated for the Wyong area.

2.6.2.1.2.5 Water balance components

A secondary objective of the numerical models is to inform the water balance reporting in companion product 2.5 for the Hunter subregion (Herron et al., 2018). The groundwater model and AWRA models produce estimates of the water balances under baseline and CRDP.

2.6.2.1.2.6 Transparent and reproducible model outputs

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

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

As the evaluation of the model chain is a highly automated and scripted process, it is possible to reproduce the results reported in this product using the scripts and executables, provided the computational resources are available.

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2.6.2.2 Review of existing models

Summary

A review of groundwater models that have been developed for use in the Hunter subregion was undertaken. Existing models were found to be local-scale models intended to assess groundwater hydrological changes of mining at the individual mine scale. Their spatial extents and resolutions mean they are not suitable for modelling cumulative hydrological changes of multiple mining operations at the scale of the Hunter subregion. Furthermore, they are deterministic models, not suited to quantification of modelling uncertainties using a probabilistic approach.

Groundwater modelling undertaken as part of a mine's environmental assessment provides local-scale information on hydraulic properties for informing the regional-scale modelling undertaken in this product.

Results from a limited number of local-scale mine groundwater models have been used to suggest a groundwater impact zone can be approximated around existing open-cut mines in the Hunter Coalfield using a generalised buffer of 4 km (EMM, 2015). The groundwater modelling reported here goes further: it includes current and proposed, open-cut and underground mines within the Hunter, Western and Newcastle coalfields; considers the timing of the developments; performs a cumulative impact assessment; and includes an estimation of the changes in surface water – groundwater flux that inform the Hunter surface water model. These are all framed within a comprehensive uncertainty analysis.

Many local-scale groundwater flow models have been developed in the Hunter subregion to support mine environmental assessments. These are generally local-scale models developed to assess the hydrological changes due to a single development. Table 4 summarises the spatial extent and resolution of 43 models reviewed for the Hunter subregion. Model domains vary from as little as 26 km^2 (Awaba; GHD, 2010) to 2750 km^2 (Moolarben; Aquaterra, 2008b). Not one comes close to providing the level of coverage needed for regional-scale groundwater assessments. Pixel sizes range from a very fine 5 m in the COSFLOW model for Bulga Coal (Guo et al., 2014) to 340 m in the MODFLOW-SURFACT model for Spur Hill (HydroSimulations, 2013a), with average pixel size of around 65 m. This granularity is intended to capture a level of detail about the hydrogeological domain appropriate to a site-scale assessment, but is too fine for practical regional-scale modelling. The groundwater model developed for the Hunter subregion covers an area of approximately 34,000 km^2, with a best spatial resolution of 500 m.

Quantification of the uncertainties arising from model conceptualisation, parameterisation and available data is a major objective of the bioregional assessments. These mine-scale models were not intended to evaluate the direct, indirect and cumulative hydrological changes of mining operations in a probabilistic manner. Rather, the intent of these models is to use the best local-scale information available (often collected by the mining company and the consultant preparing the assessment) to determine as accurately as the information allows, the specifics of mine water pumping, drawdowns and local disruptions to surface drainage for the purposes of obtaining licences to dewater mines and to discharge to streams, and to develop environmental management plans that minimise impacts to the environment. The environmental assessments contain a wealth of information concerning local hydraulic properties (conductivities and porosities), which have been used to inform the development of the Hunter groundwater model (see Section 2.1.3 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)).

For reasons of scale, extent and purpose of modelling, none of the models listed in Table 4 is appropriate for use in a bioregional assessment.

Table 4 Summary of existing groundwater models in the Hunter subregion

Mine	Software	Approximate spatial extent (km^2)	Approximate best spatial resolution (m)	Source
Abel	MODFLOW-SURFACT	550	50	RPS Aquaterra (2013)
Anvil Hill	MODFLOW-SURFACT	132	50	Mackie (2006)
Ashton	MODFLOW-SURFACT	132	100	Aquaterra (2009a)
Awaba	MODFLOW	26	43	GHD (2010)
Bengalla	FEFLOW	200	30	AGE (2013a)
Bickham	MODFLOW-SURFACT	270	20	Aquaterra (2009b)
Bloomfield	MODFLOW-SURFACT	200	25	Aquaterra (2008a)
Bulga	MODFLOW-SURFACT	360	50	Mackie (2012a)
Bulga	MODFLOW-SURFACT	360	50	Mackie (2012b)
Bulga	COSFLOW	240	5	Guo et al. (2014)
Bylong	MODFLOW-SURFACT	1300	50	AGE (2013b)
Chain Valley	MODFLOW-SURFACT	263	50	GeoTerra (2013)
Drayton	FEFLOW	170	80	AGE (2006b)
Drayton South	MODFLOW-SURFACT	377	50	AGE (2012)
Drayton South	MODFLOW-SURFACT	374	50	AGE (2015)
Hunter Valley Operations	FEFLOW	156	25	ERM (2008)
Integra	MODFLOW	495	75	AGE (2007)
Integra	FEFLOW	280	?	GeoTerra and Golder (2009a)
Integra	FEFLOW	280	?	GeoTerra and Golder (2009b)
Liddell	MODFLOW	560	100	SKM (2013)
Moolarben	MODFLOW-SURFACT	2750	100	Aquaterra (2008b)
Moolarben	MODFLOW-SURFACT	2725	100	RPS Aquaterra (2011) and HydroSimulations (2015)
Mount Arthur	FEFLOW	400	?	AGE (2006a)
Mount Arthur	FEFLOW	400	100	Mackie (2007)
Mount Arthur	FEFLOW	250	?	AGE (2009)
Mount Arthur	FEFLOW	250	?	AGE (2013c)

Mine	Software	Approximate spatial extent (km^2)	Approximate best spatial resolution (m)	Source
Mount Owen	MODFLOW-SURFACT	450	100	Jacobs (2014)
Mount Thorley	MODFLOW-SURFACT	344	?	AGE (2014a)
Ravensworth	Inhouse	100?	?	ERM (1997)
Ravensworth	MODFLOW-SURFACT	240	100	Mackie (2009a)
Ravensworth	MODFLOW-SURFACT	240	100	Mackie (2012c)
Rix's Creek	MODFLOW-SURFACT	174	50	RPS Aquaterra (2014)
Spur Hill	MODFLOW-SURFACT	1048	340	HydroSimulations (2013a)
Tasman	MODFLOW-SURFACT	550	50	RPS Aquaterra (2012)
Ulan	MODFLOW-SURFACT	1681	50	Mackie (2009b)
Ulan	MODFLOW-SURFACT	1681	50	Mackie (2015)
Wallarah 2	MODFLOW-SURFACT	575	50	Mackie (2009c)
Wallarah 2	MODFLOW-SURFACT	575	50	Mackie (2013)
Wambo	MODFLOW-SURFACT	300	50	Heritage (2012) and NOW (2015)
Warkworth	MODFLOW-SURFACT	572	30	AGE (2010)
Warkworth	MODFLOW-SURFACT	344	30	AGE (2014b)
West Muswellbrook	MODFLOW-SURFACT	500	100	AGE (2014c)
Wilpinjong	MODFLOW96	450	70	HydroSimulations (2013b)

In a study of Mid Hunter groundwater (EMM, 2015), commissioned by DPI Water to inform the development of the now commenced (from 1 July 2016) Water Sharing Plan for the North Coast Fractured and Porous Rock Groundwater Sources, results from some local-scale mine groundwater models were used to determine the extent of significant drawdown from coal resource developments in the Hunter Coalfield. Results suggested that the union of a generalised buffer of 4 km around each existing mine could be used to define the potential impact area from all the mines in the Hunter Coalfield based on drawdowns less than or equal to 2 m. In contrast to this study, the groundwater model described here also: includes the Western and Newcastle coalfields, underground mines, and proposed and approved developments that had not commenced at the time of study; considers the timing of the developments; performs a cumulative impact assessment; and includes an estimation of the changes in surface water – groundwater flux that inform the Hunter surface water model. These are all framed within a comprehensive uncertainty analysis.

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2.6.2.3 Model development

Summary

A regional-scale numerical groundwater model was built using the Multiphysics Object-Oriented Simulation Environment (MOOSE) modelling platform to evaluate the hydrological changes due to additional coal resource development on groundwater resources in the Hunter subregion.

The groundwater model is built upon the nine geological horizons in the Hunter subregion geological model. Additional layers are added to better represent groundwater processes in the alluvium and near-surface unsaturated zones and to define the coal seams around mines. The modelling domain spans an area of about 34,000 km^2 with depths ranging from about 300 m to 3000 m. It is represented by a variable triangulated finite-element mesh with greater resolution around mines and streams.

Saturated flow is governed by Darcy's equation, and single-phase unsaturated flow by Darcy-Richards equation. Changes in subsurface physical flow paths following mining subsidence are represented by enhancing hydraulic conductivities above the longwall mines.

2.6.2.3.1 Objectives

The primary objective of bioregional assessment (BA) groundwater modelling is to quantify the hydrological changes on regional groundwater due to additional coal resource development, which is based on the difference in results between the baseline and coal resource development pathway (CRDP) simulations. The significance of the hydrological changes due to the additional coal resource development can only be understood when considered against the results of the hydrological changes from the baseline simulation. In order to represent uncertainty, a probabilistic approach is used, which requires the groundwater model to be run thousands of times with different parameter combinations. This can have high computational overheads if the model domain is large and finely resolved. For the Hunter subregion, the modelling domain must be at least 17,000 km^2 and 2 to 3 km deep. Given this large domain and the requirement to do thousands of simulations, the groundwater model must be computationally efficient, represent just the key processes for a regional-scale assessment and have a spatial resolution appropriate for representing local to regional effects of coal resource development.

The model needs to represent the main causal pathway groups that link mine hazards to groundwater responses on and off the mine sites: 'Subsurface depressurisation and dewatering', which involves subsurface depressurisation and dewatering from excavation of coal seams and mine water pumping; 'Subsurface physical pathways', which involves changes in subsurface physical pathways due to hydraulic conductivity changes resulting from rock deformation due to mining; and 'Surface water drainage', which involves changes to surface water drainage through its interaction with groundwater (see companion product 2.3 for the Hunter subregion (Dawes et al., 2018).

Key outputs from the model are groundwater drawdowns and changes in baseflow, which are summarised as changes in key groundwater and surface water hydrological response variables at model nodes across the modelling domain (Section 2.6.2.1.2.1).

Drawdowns due to the additional coal resource development are reported as probability distributions of the differences in drawdown between the coal resource development pathway (CRDP) and the baseline simulations. The drawdowns are reported by the groundwater model at each model node in the model domain, but since most water-dependent assets are near the ground surface in the alluvium, these are the model nodes of greatest interest.

The changes in baseflow from the CRDP and baseline simulations are used in the Hunter river model, where they are incorporated into the hydrological response variables generated as part of the surface water modelling (see companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)).

Since the main objective of the BA numerical modelling is to quantify the difference between two modelled futures, the emphasis on producing a well-calibrated model is lower than if the objective were to predict the state of groundwater in the future under baseline and coal resource development pathway (Section 2.6.2.1.2).

2.6.2.3.2 Hydrogeological conceptual model

A summary of the key system components, processes and interactions in the Hunter subregion is provided in companion product 2.3 for the Hunter subregion (Dawes et al., 2018).

The geology is characterised by near horizontal sandstone, shale and coal beds, which have undergone mild deformation. It is represented as nine horizons in the regional-scale geological model built as part of the BA for the Hunter subregion (Figure 6), described in Section 2.1.2 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018). Figure 7 shows how the geological model layers map to the stratigraphic sections in the Hunter subregion coalfields (see also Table 4 in Herron et al. (2018)). The groundwater model is built directly upon this broad-scale layer-cake conceptualisation of the Hunter geology, but includes worked coal seams only in the vicinity of mines. Small local-scale geological and geophysical features are not represented in the geological model. It is acknowledged that faults may be important in the hydraulic connectivity of fractured rock and alluvial aquifers in some locations and would need to be considered in more local-scale analyses.

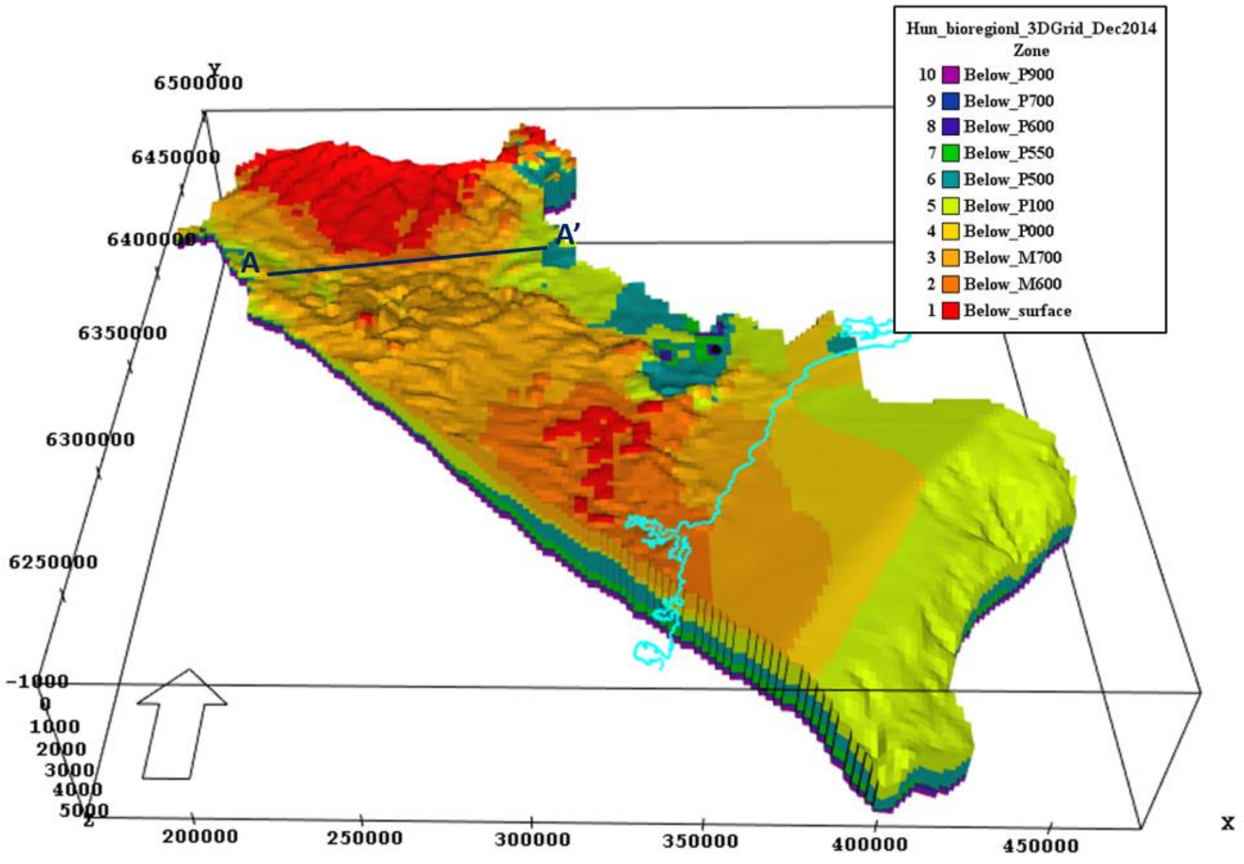

Figure 6 Three-dimensional geological model of the Hunter subregion

Colours/labels represent layers in the geological model and correspond to changes in stratigraphy shown in Figure 7. A-A' identifies the location of the cross-section shown in Figure 8.
Data: Bioregional Assessment Programme (Dataset 1)

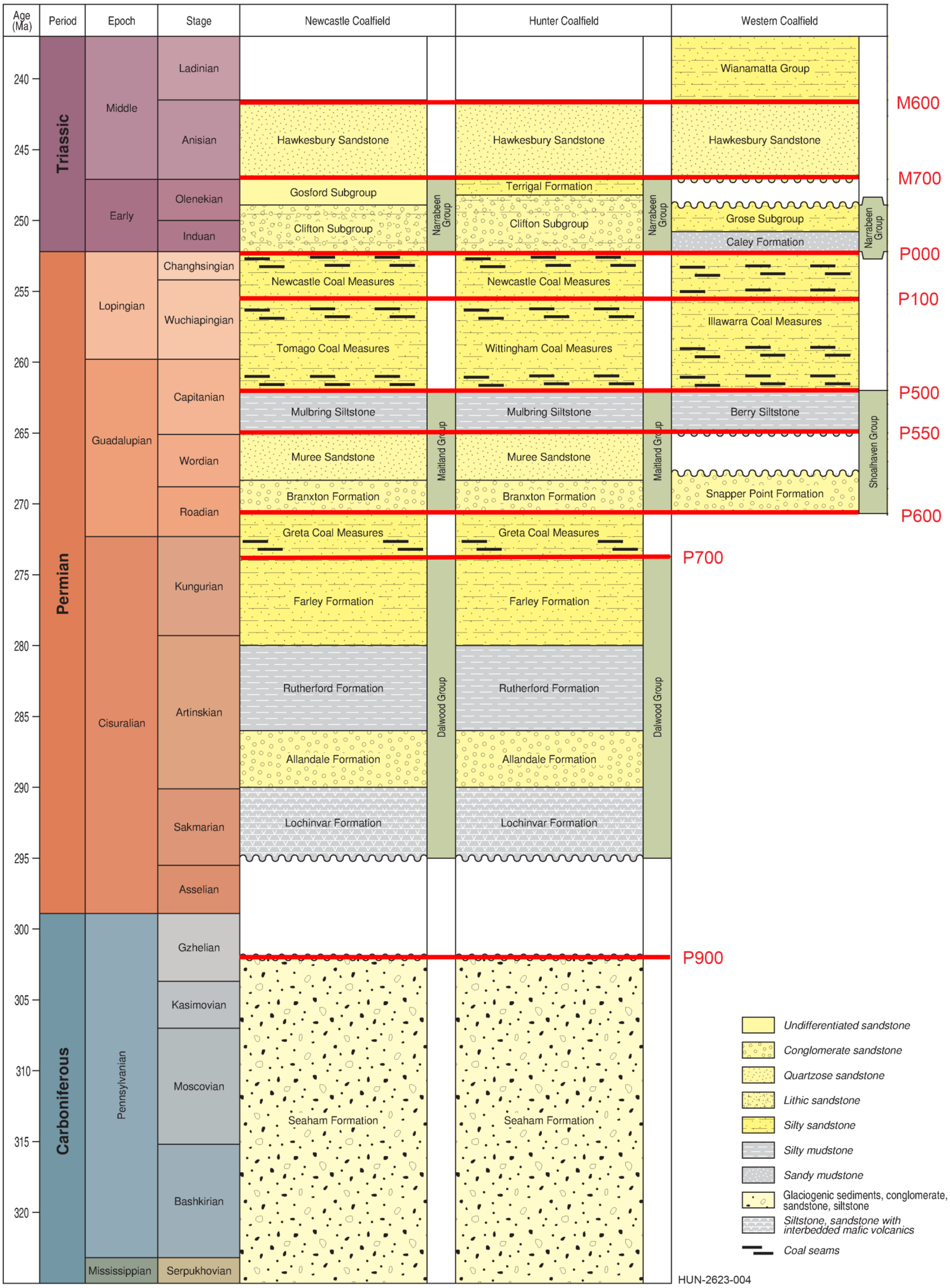

Figure 7 Generalised stratigraphic column of the Permian and Triassic units in the main coalfields of the Hunter subregion, showing the corresponding layers in the Hunter geological model

Source: produced for Bioregional Assessment Programme based on stratigraphic unit information from Geoscience Australia and Australian Stratigraphy Commission (2016).

This figure has been optimised for printing on A3 paper (297 mm x 420 mm)

Hydrogeologically, it is typical for the sandstone layers to act like aquifers, whereas shale and siltstone layers have hydraulic properties typical of aquitards. Non-alluvial near-surface rock units are typically more weathered and have higher hydraulic conductivities than deeper rock units and are commonly only partially saturated. However, an analysis of hydraulic conductivity measurements from 577 points throughout the Hunter subregion shows little correlation with lithology and stratigraphy (Figure 26 and Figure 27 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)). A weak correlation with depth is evident. Quaternary-age alluvial deposits occur along the main river valleys and coastal sand beds around the Hunter River estuary and along the coastal plain. They are important sources of fresh groundwater for the subregion and have higher hydraulic conductivities than the underlying rocks.

The subregion boundary to the north-eastern side is defined by the Hunter-Mooki Thrust Fault, which separates the geological Sydney and Werrie basins. Since this is the edge of the basin, it is assumed to be a zero-flow boundary, as discussed further in Section 2.6.2.4. Groundwater flow can occur across the other boundaries, which are defined by surface water catchment boundaries and in the ocean approximately 100 km offshore (see Section 2.6.2.4). Regional-scale groundwater flow generally follows the direction of the topography from north-west to south-east.

Rainfall recharge is the major input to the groundwater systems, but losses from streams can also recharge aquifers. In Section 2.1.5 (see companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)), estimates of baseflow were found to be highly variable but may be of the order of 10% of recharge to the groundwater system. Discharges of groundwater to draining streams (i.e. baseflow) are important for sustaining flow in many streams, but estimates of their contribution to total flow are highly variable. Because of this uncertainty, model parameters that control baseflow are varied in the uncertainty analysis (see Section 2.6.2.7).

Coal mining is undertaken using open-cut, longwall and bord-and-pillar mining methods in the three major coalfields of the Hunter subregion. These methods of coal extraction involve mine dewatering, resulting in aquifer depressurisation. The methods of extraction modify subsurface physical flow paths, particularly above longwall mines where hydraulic enhancement is an inevitable consequence of collapsing the longwall panels. The effects of these changes are drawdown of watertables and changes in the magnitude and timing of discharges to streams that intersect groundwater.

Details of the datasets and data analyses that have informed the conceptualisation and development of the groundwater model are provided in Section 2.1.3 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018). They include the mapped extent of the Hunter alluvium (Section 2.1.3.1.1), the generation of a spatially varying rainfall recharge surface for the subregion (Section 2.1.3.2.1), and results from the analysis of hydraulic conductivity measurements by lithology (Section 2.1.3.2.2). Details of the mine footprints and flow rates (i.e. the assumed pumping rates to dewater mines) used to represent the hydrological changes due to mining are provided in Section 2.1.6.3.

2.6.2.3.3 Design and implementation

2.6.2.3.3.1 Geometry and hydrostratigraphy

The model is built directly upon the three-dimensional geological model (Bioregional Assessment Programme, Dataset 1) described in Herron et al. (2018) and shown in Figure 6. It uses the nine geological horizons above the base of the Permian horizons (P900) and topographic data (Geoscience Australia, Dataset 2, Dataset 3) to define nine regional groundwater model layers of varying thickness. At this stage it is a coarse geometric model with no coal seams, alluvium or hydraulic properties, as illustrated with a representative cross-section in Figure 8.

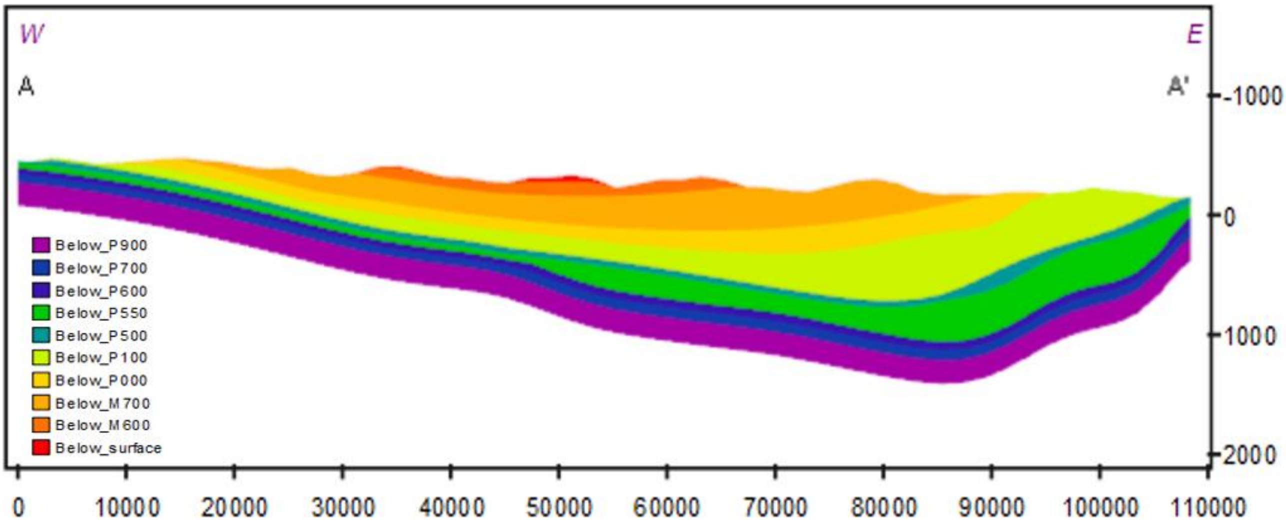

Figure 8 Gulgong (west) – Muswellbrook (east) cross-section from the Hunter subregion geological model showing layers of variable thickness, but without explicit representation of coal seams and alluvium

The location of the cross-section (A-A') is shown in Figure 6.
Data: Bioregional Assessment Programme (Dataset 1)

To better represent near-surface groundwater processes, two additional layers are added at the top of the model:

- A layer with a uniform thickness of 3 m to allow more accurate representation of the unsaturated zone. This does not mean that the watertable needs to lie 3 m below the topography (the watertable often lies tens of metres below the topography in hilly regions, meaning the unsaturated zone is often tens of metres thick beneath hills). Instead, because the groundwater dynamics are highly nonlinear in the unsaturated zone, this extra 3 m thick layer aids in accurately representing that nonlinear behaviour.
- A layer of non-constant thickness, based on regolith thickness (Figure 15 in Section 2.1.3 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)), which allows the depth of alluvium to be defined in areas with alluvium (Figure 16 in Section 2.1.3 of Herron et al. (2018)). The floor of this layer is defined so that the top two layers have a combined thickness equal to the regolith thickness. This layer is important for representing interactions with the surface water system.

Because the horizons in the geological model outcrop in places, some areas have fewer than 11 layers. These discontinuities are unwieldy to implement in the groundwater model because many small finite elements are necessary to precisely represent an outcrop in the model. To simplify the mesh and improve computational efficiency, the missing layers have been extended into these areas and given a minimum layer thickness of 10 m, which ensures there are 11 continuous layers throughout the entire model (ranging in thickness from 3 m to 1650 m, with mean 36 m). This minor modification is a common approach in groundwater modelling (Barnett et al., 2012). It will not have a noticeable effect on predictions because the hydraulic properties (conductivity and porosity) assigned to the extensions may be defined based on the lithology of the area in which they occur (see below), not just upon layer number.

Figure 9 depicts a vertical cross-section of the final finite-element mesh (construction details are given below) showing the layer immediately below P500 up to topmost layer (the 3 m thick layer at the model's top). In the cross-section shown in Figure 9 the layers above P000 have outcropped in the geological model, but the horizons P000, M700 and M600 have been shifted downwards to ensure these layers do exist in the groundwater model with a minimum layer thickness of 10 m (see Figure 7 for an explanation of these horizons). Other aspects of Figure 9 are discussed below. The model geometry does not represent any geological structures, including the major fault structures that are known in the geological Sydney Basin.

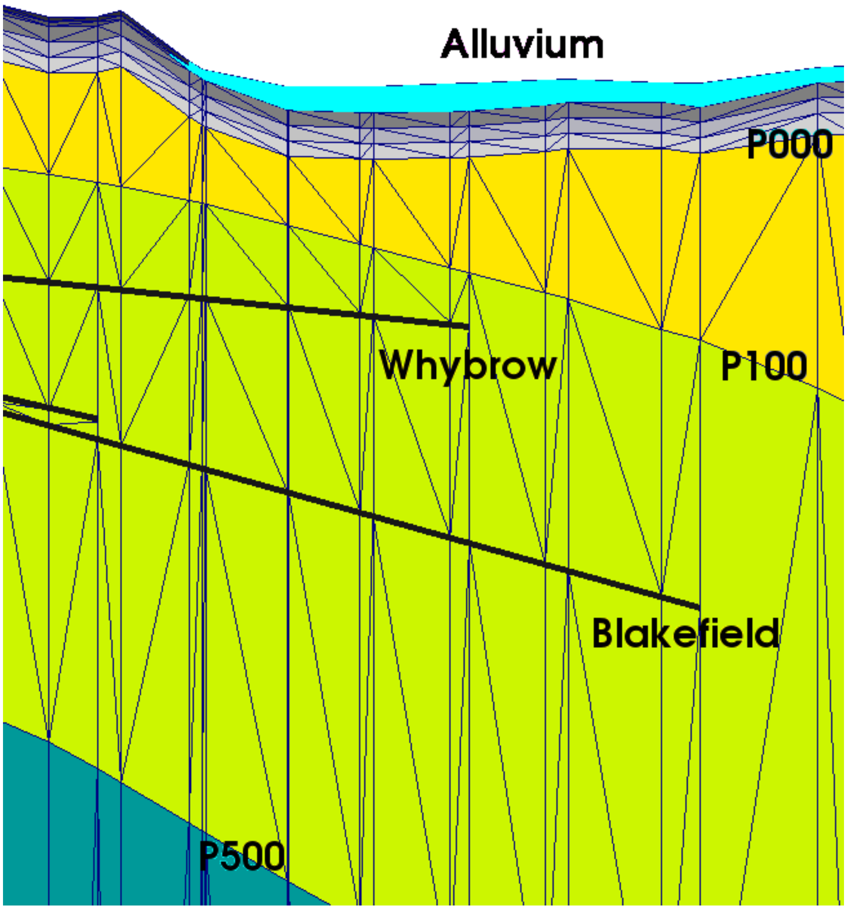

Figure 9 Cross-section through part of Bulga coal mining area, including the alluvium (light blue) and Whybrow and Blakefield coal seam discs (bold black lines)

The geological layers are differentiated by colour and labelled: P500, P100 and P000. The finite-element mesh is shown as thin blue lines. There is a vertical exaggeration of 10.
Data: Bioregional Assessment Programme (Dataset 4)

Seam discs – enhancement around mines

Coal seams are not represented explicitly in the geological model, so additional layers are created in the vicinity of mines within the groundwater model to ensure their accurate representation in the groundwater model. Every working seam for every mine working listed in Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018) is represented as a disc, as illustrated conceptually in Figure 10. Each disc is planar and has a radius that just exceeds the spatial extent of its associated mine workings. It is placed at the depth, dip angle and direction within the model corresponding to the working seam, as shown in Figure 10. If a disc's geometry causes it to outcrop, the outcropping areas are 'bent down' so that they remain within the three-dimensional model.

Because each disc is planar, they do not accurately represent the undulating nature of real coal seams, and because they only exist in the vicinity of each mine workings they do not represent the continuous nature of coal seams that may exist for tens of kilometres. The discs do not affect water flow any more than the horizons affect water flow: water flows along the plane of the disc just as it flows along the horizons. Nevertheless, including these discs in the geometry of the model has the advantages of (i) increasing the number of layers in the vicinity of mines, which means a more accurate representation of both the lithology and water head in the vertical direction, and (ii) allowing water to be withdrawn from the model at approximately the correct depth. Note that water is not withdrawn from the entire disc, just from the mine-workings polygon (Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)) superimposed upon the disc, as described in Section 2.6.2.5.2.

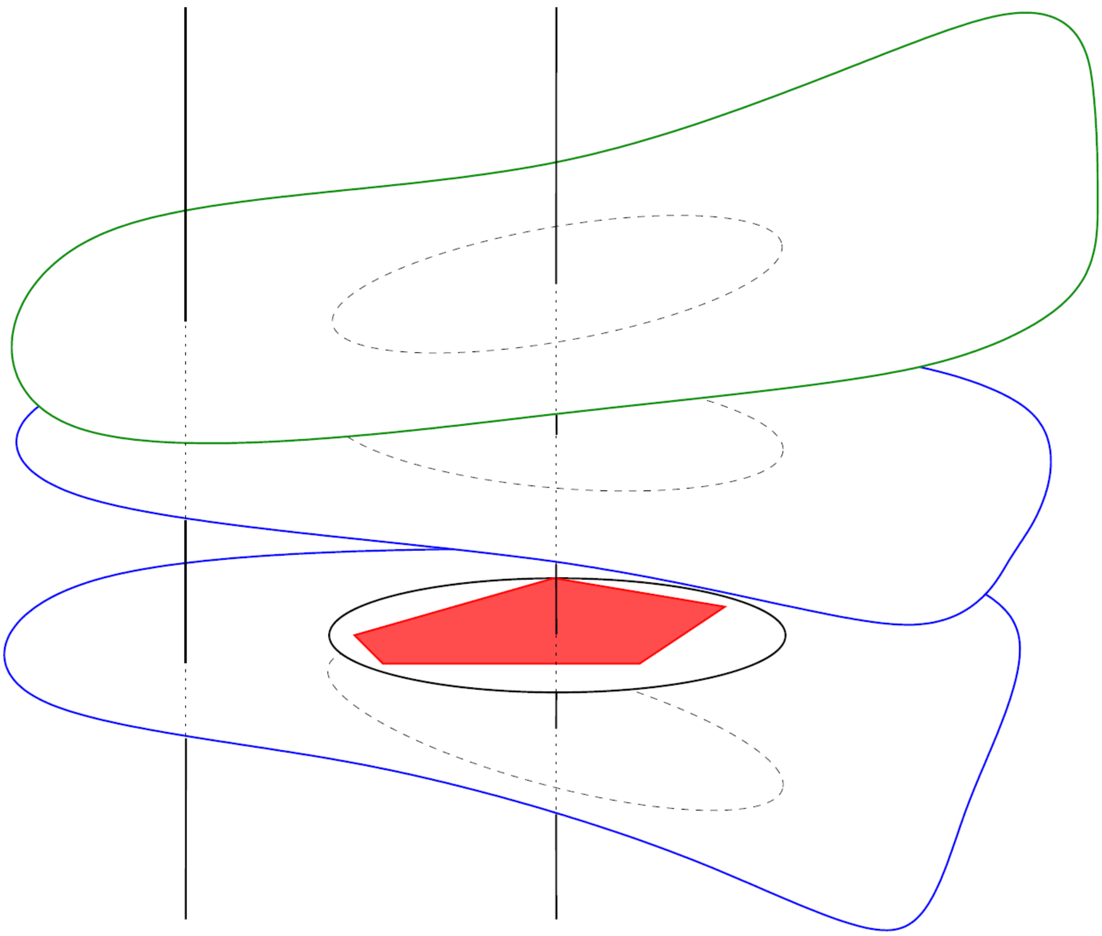

Figure 10 Conceptual representation of disc insertion into the groundwater model

The green area represents a portion of the topography and the blue represents two subsurface horizons from the regional geology model. A disc (in black) is inserted between the two horizons to represent a coal seam around a mine workings (in red). Dashed lines represent the superposition of the seam disc upon the horizons and the topography. Insertion of the disc means there is one model layer more on the right-hand vertical line compared to the left-hand vertical line.

Lithology

The lithological (facies) model in Figure 13 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018) informs the groundwater model. The lithological model is a three-dimensional model that covers the three-dimensional groundwater model's domain. Each point in the domain is categorised as either:

- predominantly sandstone
- predominantly siltstone
- predominantly shale

- sand beds
- predominantly coal
- fine sands and silts
- mixtures of shale, siltstone and mudstone.

The groundwater model is built such that the hydraulic properties at any location may be dependent upon the layer number and lithological classification at that location. This makes the modification of horizons to avoid explicit outcropping less important, as hydraulic conductivity needs not be uniform across an entire layer. The explicit parameterisation of hydraulic conductivities is presented in Section 2.6.2.6.

Alluvium

As previously stated, a layer is included at the top of the model to represent the alluvium. The spatial extent of the alluvium is defined by the mapped alluvium (Bioregional Assessment Programme, Dataset 5) and the regolith thickness (CSIRO, Dataset 6) (see Section 2.1.3.1.2 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)). The model treats the alluvium as another lithology, yielding seven different lithologies in total. Locations classified as 'alluvium' occur in the top two layers of the model only – that is, the topmost uniform 3 m thick layer and the layer defined by the regolith thickness. The alluvium thickness is non-uniform and equal to the regolith thickness. Alluvium is evident in Figure 9 in the top two layers.

2.6.2.3.3.2 Element mesh

The numerical solver, MOOSE, uses the finite-element technique. The finite-element size in plan view is chosen to be 500 m in the vicinity of the mines, and up to 15 km elsewhere. Triangular elements are used. The plan mesh is shown in Figure 11. The finer mesh clearly identifies the areas of mining within the Hunter subregion. Also visible is a higher density of elements along the river network. More finite-element nodes were included along the rivers to provide higher resolution output of the change in baseflow for input into the Australian Water Resource Assessment river (AWRA-R) model (see companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)). The resulting mesh has 29,248 triangular elements in plan view, covering an area of approximately 34,000 km^2.

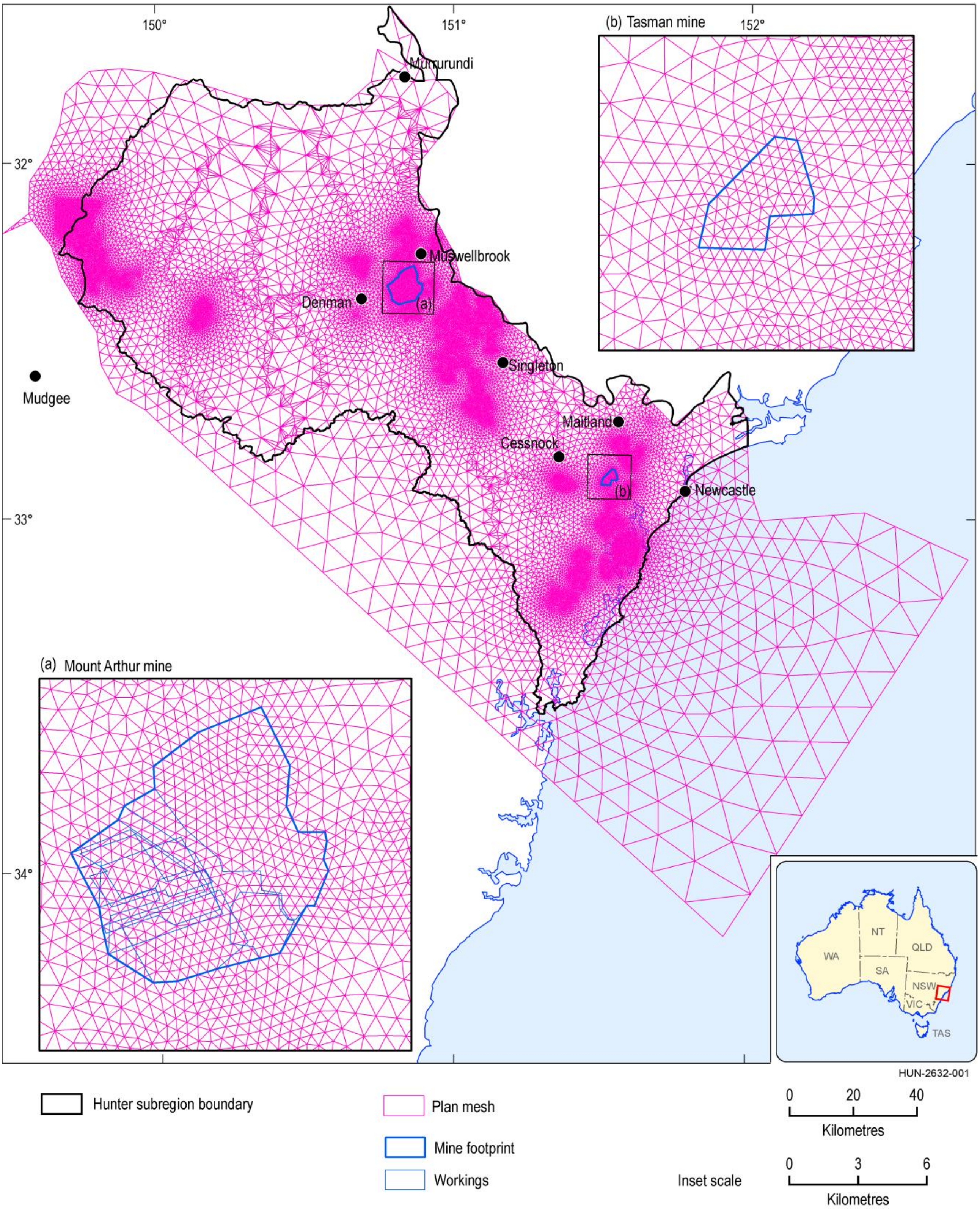

Figure 11 Plan mesh of the Hunter groundwater model, showing the finer mesh around areas of mining and along the river network. Insets are shown for (a) the Mount Arthur mine footprint, where the mesh does not conform exactly, and for (b) the Tasman mine footprint, where the mesh conforms exactly

Data: Bioregional Assessment Programme (Dataset 4, Dataset 7)

Where possible, the plan mesh conforms to the mine polygons (see Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)). However, this is not always possible due to overlapping polygons in multi-seam workings and complicated mines, and where polygons overlap with river polylines. Figure 11 illustrates conforming and non-conforming mine polygons: In inset (a) of Figure 11, which shows the mine polygons (in blue) for Mount Arthur mine, there are too many polygons for the mesh to faithfully conform to each one; In inset (b) of Figure 11 the mesh around the Tasman mine (in blue) conforms perfectly with the mine footprint. Figure 11 also shows the fairly coarse scale used in the model. Mesh elements must be labelled as either 'inside' or 'outside' each mine polygon, so that the non-conformance of some mine polygons means that the mined area may be misrepresented in the model by up to 250 m (or half the size of an element). This does not mean that a greater or lesser amount of groundwater is extracted by the mine (as those rates are fixed for each mine: see Section 2.6.2.5) but that the position of the mine relative to points of interest, such as rivers, may be inaccurate by up to 250 m. Given the wide range of parameter values modelled as part of the probabilistic approach to modelling, this small error in positional accuracy is unlikely to significantly affect the range of predicted drawdowns and changes in surface water – groundwater fluxes.

In the vertical direction each layer is defined by a single element. The plan mesh is swept vertically through the 11 model layers to create 321,728 wedge elements. These are further subdivided by the seam discs in the vicinity of the mines to yield a total of 340,811 wedge elements.

A sample cross-section of the finite-element mesh is shown in Figure 9. The alluvium can be seen within the top two layers with non-constant thickness; the other layers also vary in thickness, but with a minimum thickness of 10 m. Figure 9 also shows an explicit example of disc insertion. The layer between horizons P500 and P100 is split by three seam discs. The discs corresponding to the Whybrow and Blakefield coal seams have been labelled. The insertion of the discs means that in this cross-section the groundwater model has either 11 layers (where there are no discs), 12 layers (where there is just 1 disc), 13 layers (2 discs) or 14 layers (at places where 3 discs exist).

2.6.2.3.4 Representation of groundwater processes

Most of the rock strata within the model are fully saturated and Darcy's equation governs the flow of groundwater. However, many of the water-dependent assets identified in the asset register for the Hunter subregion (see companion product 1.3 for the Hunter subregion (Macfarlane et al., 2016)) lie close to the surface, and are either within the unsaturated zone or are directly affected by it. Therefore, single-phase unsaturated Darcy-Richards physics is used in the model.

The groundwater model assumes water has a constant bulk modulus of 2 GPa, and that the Biot coefficient is 1, which is standard practice in poroelasticity (the study of fluid flows in elastic media, see Detournay and Cheng, 1993). Therefore, the specific storage does not include any effects from rock elasticity. If the Biot coefficient is less than 1 and the rock bulk modulus is not too large then the specific storage is increased because the rock grains can be squashed to accommodate more water. For example, if porosity is 0.05 and rock bulk modulus is 10 GPa, then the maximum specific storage (at Biot coefficient 0.525) is almost twice that used by the groundwater model. This causes the response time of any drawdown effect to be increased (but not linearly with respect to storage increase since the main driver of the timescales involved is the mine pumping rates) and reduces the magnitude of the drawdown. Therefore, by assuming the Biot coefficient is unity or that the rock is incompressible, the Hunter groundwater model will slightly overestimate the magnitude of drawdown. Since porosity is varied by more than an order of magnitude in the uncertainty analysis, it more than compensates for any changes in specific storage from varying the Biot coefficient. To assess the effect of altering the Biot coefficient or the rock bulk modulus, the emulators can be biased towards slightly higher porosity.

To represent the hydrological changes due to longwall mining on groundwater fluxes, hydraulic conductivities are enhanced in mesh elements above the longwall mines. Section 2.6.2.6 details the relevant parameters for defining magnitude and depth of enhancement.

2.6.2.3.5 Model code and solver

The model is run using the finite-element package, MOOSE (2016a). Many other groundwater models of coal mining in the Hunter Valley use FEFLOW or versions of MODFLOW (see Section 2.6.2.2). MOOSE offers the following features:

- open source and well tested. MOOSE has been built by the nuclear industry and, as such, is subjected to continual and rigorous testing (MOOSE, 2016b).
- able to run in batch-mode on high-performance computing clusters in order to complete the uncertainty analysis. MOOSE is designed for efficient parallel computing on high-performance machines, so its size is limited only by the machine.
- able to represent both fine spatial details, both horizontally and vertically around mines, as well as a large regional area. This is important in the Hunter subregion which is both large in size, but heavily mined in certain areas. MOOSE is a finite-element code: the finite-element method is the preferred numerical method of capturing such differences in length scales. The finite-element mesh can be fine around rivers and mines in plan view, as well as containing more model layers in the vicinity of mines to accurately model multi-seam mining operations, and coarse in regions of lesser interest.
- ability to accurately model the dynamics of unsaturated flow, especially around the alluvium. MOOSE solves three-dimensional unsaturated flow.
- ability to enhance hydraulic conductivity around longwall mines. MOOSE naturally includes spatially and temporally varying hydraulic properties
- numerically stable so that certain parameter combinations encountered in the uncertainty analysis do not cause the program to crash. MOOSE uses a fully implicit time-stepping scheme. This means it is unconditionally stable (irrespective of the number of source/sink terms and nonlinearities), can take large time steps, and it automatically conserves mass (the mass-balance errors are of the order of machine precision which is approximately 10–13%).

In conclusion, MOOSE incorporates all the requirements of the Hunter groundwater model.

Simulations are run in parallel using 48 cores per simulation on supercomputers, chiefly the Pawsey computer 'Magnus' (Pawsey Supercomputing Centre, 2015) and the CSIRO computer 'Pearcey'.

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MOOSE (2016b) Multiphysics Object-Oriented Simulation Environment. Idaho National Laboratory, Idaho. Code coverage report can be found at (viewed 19 July 2016) http://mooseframework.org/docs/coverage/richards/richards_coverage/.
At the time of writing, code coverage for the Richards module is 99.4%. The test input files are at https://github.com/idaholab/moose/tree/devel/modules/richards/tests.
Documentation of most of the tests run by the test harness is at https://github.com/idaholab/moose/raw/devel/modules/richards/doc/tests/tests.pdf.

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2.6.2.4 Boundary and initial conditions

Summary

The north-eastern spatial boundaries of the Hunter groundwater model are defined by the northern extent of the geological Sydney Basin and a small part of the geological Werrie Basin and are assumed to be impermeable. Elsewhere the model domain extends beyond the subregion boundary in order to minimise boundary effects in the model results, and general-head boundary conditions are used. The model's base is assumed to be impermeable.

The model's land surface is subject to rainfall recharge and evapotranspiration, both of which are spatially and temporally varying.

All major rivers, along with some minor reaches, are represented in the model. These represent the points at which the groundwater model interacts with the Hunter surface water model. Perennial rivers may leak to the groundwater system if the watertable is below the river stage, and all rivers may be supplied by the groundwater system if the watertable is higher than the river.

A total of 868 groundwater extraction bores are included in the model. Each is assumed to extract water according to its full entitlement.

2.6.2.4.1 Boundaries

The groundwater model's boundary conditions are specified in this section.

The model is a three-dimensional model with vertical sides. Its base is defined by the P900 horizon in the geological model of the Hunter subregion (see Section 2.1.2 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)) (Bioregional Assessment Programme, Dataset 1). Its top is defined by the land topography (Geoscience Australia, Dataset 2) and the bathymetry of the ocean floor (Geoscience Australia, Dataset 3), which have been combined into the Hunter subregion topographic surface for groundwater modelling (Bioregional Assessment Programme, Dataset 4).

The model's outer boundary was chosen to coincide with the outer boundary of the subregion on its north-eastern side. Here the subregion boundary is defined by the northern extent of the geological Sydney Basin and a small part of the much smaller Werrie Basin around Murrurundi. Lying along the Hunter-Mooki Thrust Fault, and being the boundary of the Sydney Basin, this portion of the model's lateral boundary is assumed to be a no-flow boundary – that is, not hydrologically connected to the Hunter subregion (shown in Figure 12 by the pink line).

The groundwater modelling domain was extended approximately 100 km from the coastline into the ocean to approximately align with the edge of the Sydney Basin, and approximately 40 km west and south-west of the surface water catchment boundaries which separate the Hunter subregion from the Northern Inland Catchments and Sydney Basin bioregions (see Figure 4 in companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). These extensions were chosen to minimise boundary effects at the ocean–land interface and along the west and south-west boundaries where there are no geological constraints on the groundwater systems, which would restrict the movement of water across this boundary. The areas of extension are evident in Figure 12.

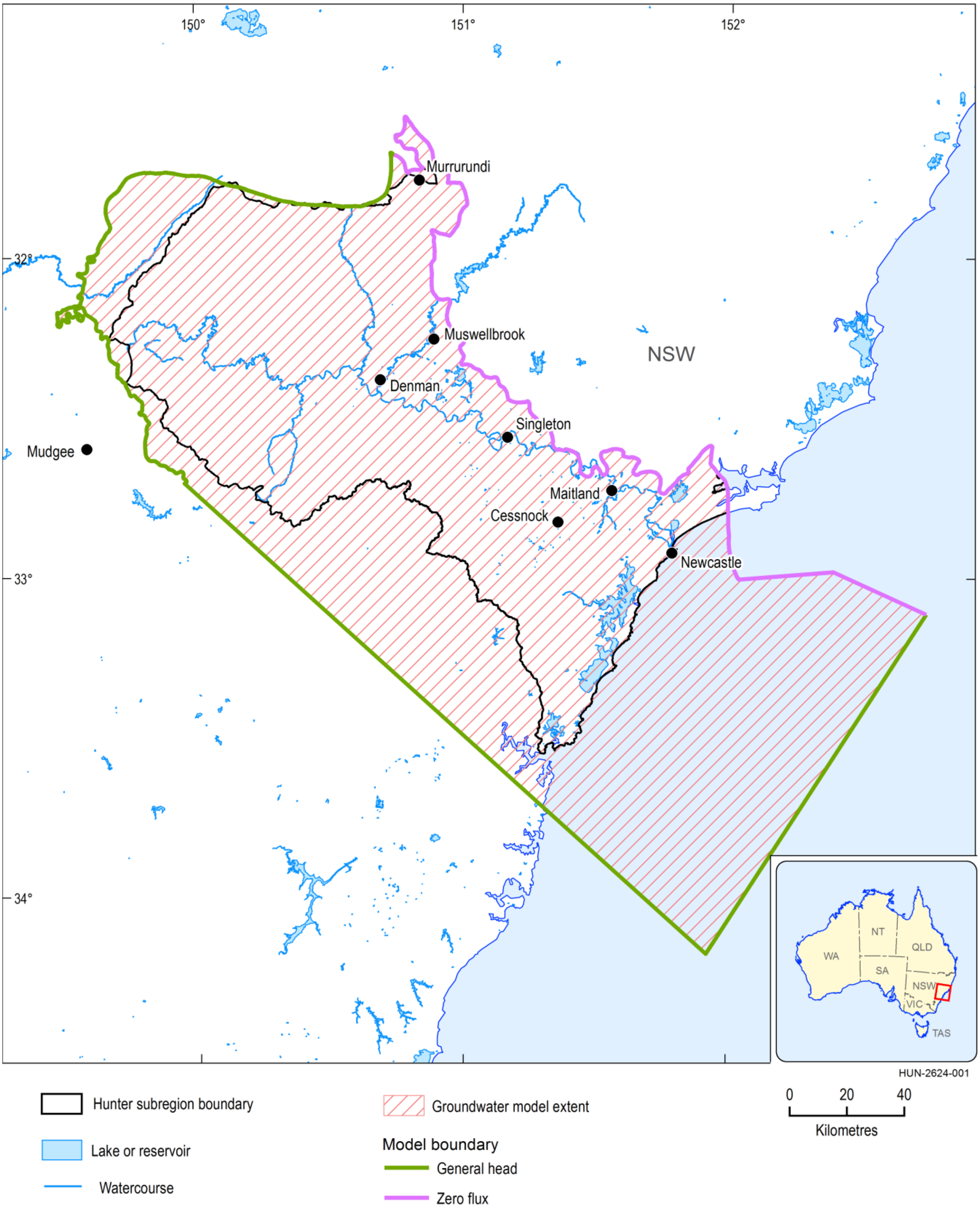

Figure 12 Hunter subregion groundwater modelling domain, showing the boundaries where general-head and zero-flux conditions are assumed

Data: Bioregional Assessment Programme (Dataset 5)

The boundary conditions placed on the model's outer boundaries are:

- Base. The base of the three-dimensional model is assumed to be impermeable and is defined as a no-flow boundary.
- Top boundary. Conditions at the land surface are driven by dynamic hydrological processes: rainfall recharge, evapotranspiration, and seepage to and from rivers. Details of these fluxes are provided in the following sections. The ocean floor has general-head boundary conditions.
- Vertical sides. The boundaries drawn with a green line in Figure 12 are represented by general-head boundary conditions; the Sydney Basin and Werrie Basin geological boundaries (pink line) are assumed to be impermeable to groundwater and represented by no-flow boundary conditions.

A general-head boundary condition means that fluxes across the boundary are dynamic. The flux (measured in ML/year/m^2) at a point (x,y,z) at time (t) is a function of conductance C and the hydraulic gradient, corresponding to the difference in groundwater level h(x,y,z,t) and a reference groundwater level h_0(x,y,z):

$$\text{flux} = C(h - h_0) \qquad (1)$$

A uniform conductance $C = 10^{-5}$ ML/year/m^3 is applied over the entire model. The reference groundwater level for the ocean floor is the ocean depth at that point. To obtain the reference groundwater levels on the vertical sides, the groundwater model is first run to steady state using zero-flux boundary conditions, and the reference groundwater levels are set equal to those steady-state heads for the dynamic model runs.

2.6.2.4.2 Land-surface fluxes

2.6.2.4.2.1 Recharge

Rainfall recharge is spatially and temporally varying, reflecting spatial differences in geology and temporal variation in rainfall. The derivation of a mean annual recharge surface for the Hunter subregion using a chloride mass balance approach is described in Section 2.1.3 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018). The long-term temporal variation of rainfall is described in Section 1.1.2 of the Hunter context statement (companion product 1.1 (McVicar et al., 2015)). This is normalised so its average throughout the period 1983 to 2012 is one, and the resultant time series is multiplied by the spatial variation to yield the final recharge applied to the model. Recharge is applied as a source of water of prescribed rate to the land surface of the model. To account for uncertainties in both the temporal and spatial variation of recharge, its magnitude is varied in the uncertainty analysis (see companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016)).

2.6.2.4.2.2 Evapotranspiration

Evapotranspiration is represented by a sink of groundwater applied across the entire land surface of the model, excluding the parts under the ocean. Generally in groundwater models, evapotranspiration from groundwater is assumed to be maximum when the phreatic surface is close to the ground surface, or above it (e.g. in the case of ponding). This gives rise to the so-called 'potential evapotranspiration', *PET*, which is the maximum possible rate of evapotranspiration. *PET* is temporally and spatially varying, *PET = PET(x,y,t),* which reflects seasonal changes, and different vegetation and surface expression of geology. Conversely, evapotranspiration from groundwater is generally assumed to be zero when the phreatic surface is deep below the ground surface since plant roots cannot draw water from the deep groundwater reserves. This gives rise to the so-called 'extinction depth', *d*, which parameterises the depth of plant roots. Clearly *d* depends on the type of vegetation, as discussed below. When the phreatic surface is somewhere between the extinction depth and the ground surface, evapotranspiration is a fraction of *PET.*

The Hunter groundwater model uses the daily *PET* time series produced by the Australian Water Resource Assessment landscape (AWRA-L) model (Bioregional Assessment Programme, Dataset 6), which was based on one particular future climate scenario (See Section 2.6.1.3 in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)). The groundwater model is run using monthly time steps. Appropriate averaging of the daily PET time series provides data that can be used in the groundwater model, and this is conveniently represented by:

- a spatial variation reflecting different vegetation, landscapes and geology (shown in Figure 13), multiplied by
- a monthly time series representing seasonal changes (shown in Figure 14).

To obtain the PET at a location and a specific month, the PET of the appropriate pixel shown in Figure 13 is multiplied by the temporal factor of Figure 14.

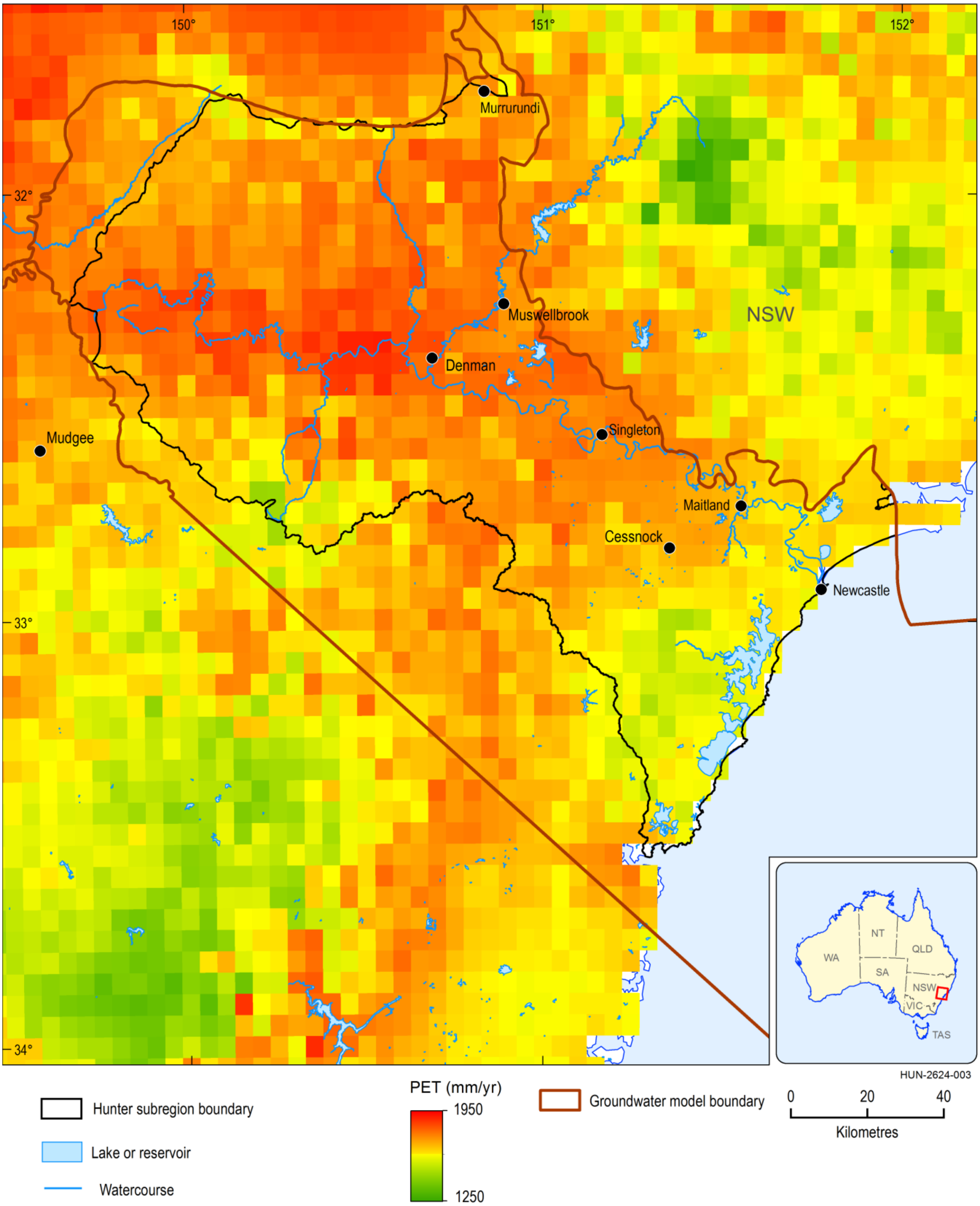

Figure 13 Spatial variation of potential evapotranspiration (*PET*) from AWRA-L

Data: Bioregional Assessment Programme (Dataset 6)

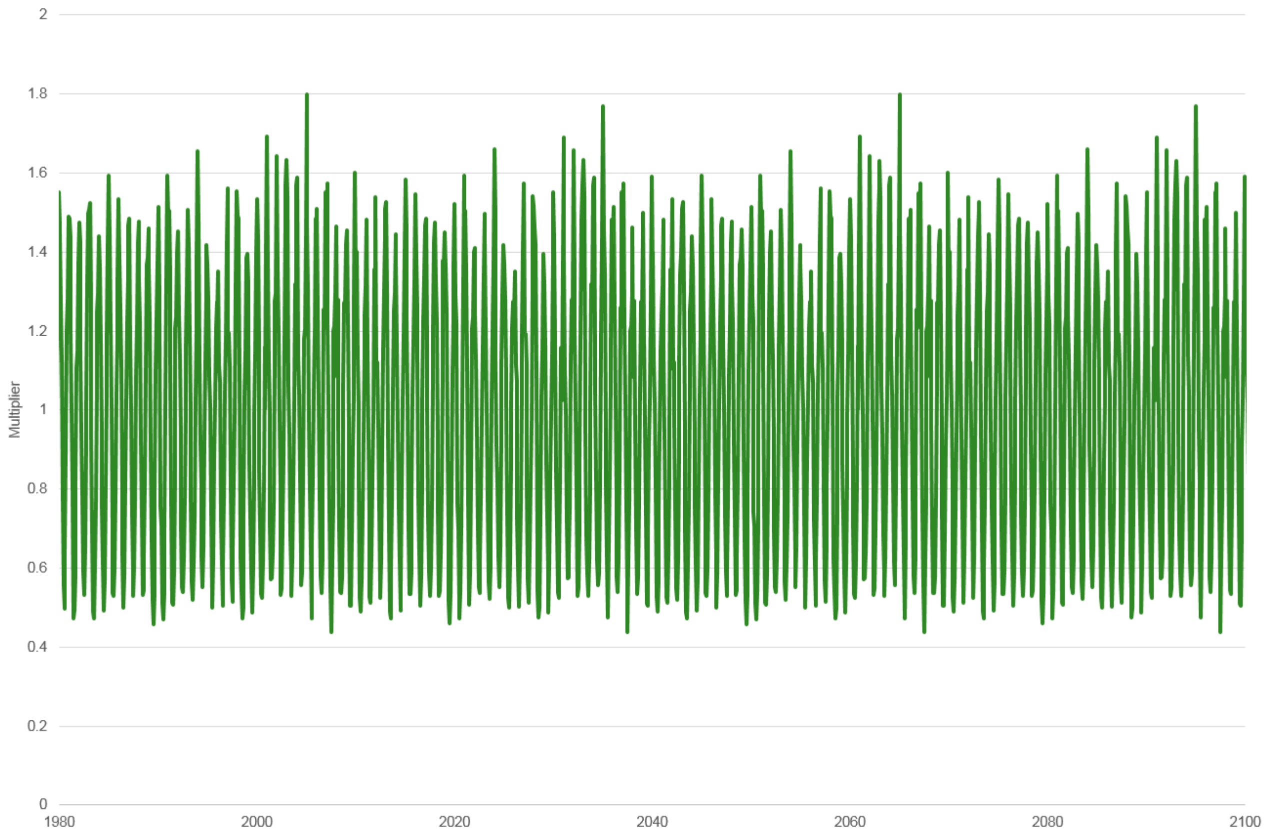

Figure 14 Temporal multiplier for potential evapotranspiration (*PET*) in the groundwater model

Data: Bioregional Assessment Programme (Dataset 6)

Generally in groundwater models the extinction depth, *d*, is set between 0 m (zero vegetation) and 20 m (deep rooted trees) with a value of 5 m being typical (Doble and Crosbie, 2016). In the Hunter groundwater model *d* varies between 0 m and 10 m. It is assumed that *d* is proportional to vegetation height, *V,* with the rationale being that taller trees typically have deeper roots than smaller shrubs or grasses (Canadell et al., 1996). Vegetation height is quantified in Figure 18 of companion product 1.1 for the Hunter subregion (McVicar et al., 2015) and details of the vegetation height dataset (Caltech/JPL, Dataset 7) can be found in Section 2.1.1 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018). Since it varies between 0 m and 39 m throughout the subregion, the groundwater model uses:

$$d = V/4 \quad (2)$$

At any point on the surface of the Hunter groundwater model, evapotranspiration varies as a cubic function of groundwater head, *h*, at that point, as shown in Figure 15. When *h* is high (the groundwater level is above the topography) *ET = PET,* but when *h* is low (the groundwater level is well below the topography) *ET* = 0. The transition from the cubic to *PET* is chosen to be at *h* = 2 m. If this transition was chosen to be at *h* = 0, as is common, and a point happened to have *d* = 0 (which is quite common when using the vegetation height to define *d*), the numerical solver may only slowly converge to the solution for groundwater levels due to the sudden transition from *PET* to zero.

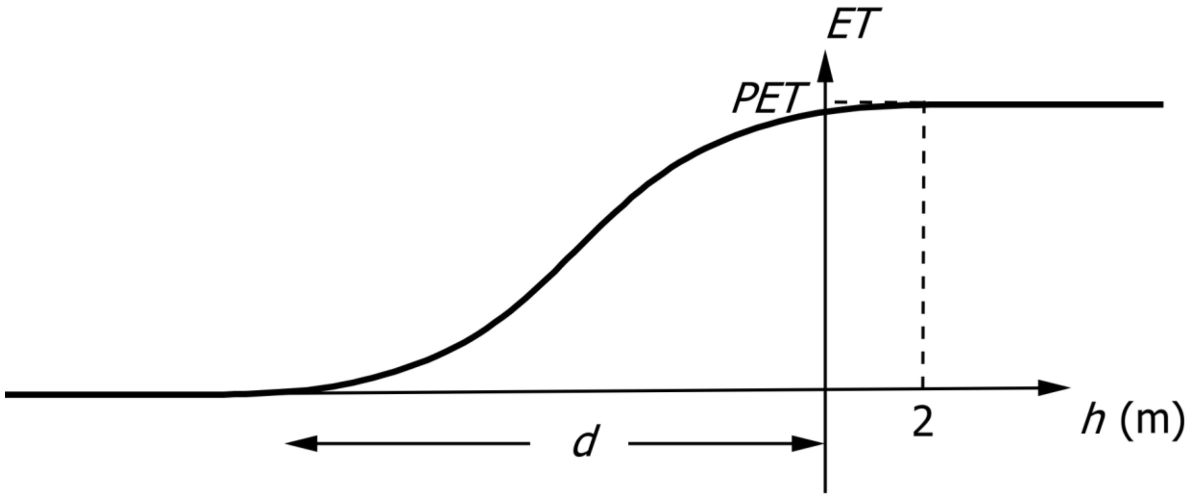

Figure 15 Relationship between evapotranspiration (*ET*) in the model, the potential evapotranspiration (*PET*), the groundwater level (*h*) and extinction depth (*d*)

ET = PET for *h>2* m as indicated by the dashed lines.

2.6.2.4.3 Surface water – groundwater interactions

2.6.2.4.3.1 Geometry

All major rivers (31 named reaches) within the Hunter subregion (Geoscience Australia, Dataset 8) are represented in the model. Some additional small reaches were added to ensure that change in baseflows could be generated along rivers represented in the AWRA-R (river) node-link network. The polylines used to define the locations of rivers in the groundwater model are shown in Figure 16.

Figure 16 River network for groundwater modelling

Data: Bioregional Assessment Programme (Dataset 9)

The Multiphysics Object-Oriented Simulation Environment (MOOSE) software used to implement and run the model cannot represent line sources and sinks, only point sources and sinks, so each river was decomposed into a sequence of points, spaced at 1 km intervals. This means baseflow is recorded only at 1 km intervals, rather than continuously along a river reach.

These points are placed at a depth of 5 m below the model's topography. This is for two reasons. Firstly, rivers tend to incise channels below the land surface at a scale that may be too fine to be represented in the 3-second digital elevation model (Geoscience Australia, Dataset 2) used to define the surface topography. At some points on the river network, surveyed information has been recorded that could be used instead, but this is not available for most of the river network. Secondly, the model further discretises this digital elevation model with resolution as coarse as 15 km, so many points at their true elevation according to the digital elevation model would lie outside the model domain (above the model topography). For these two reasons it is appropriate to shift the points' vertical position downwards. This shift is varied in the uncertainty analysis.

2.6.2.4.3.2 Baseflow and leakage

At each point, representing a 1 km section of river, along the river network, the model can lose water to represent fluxes to the river (i.e. baseflow) or gain water, representing leakage from the river, according to:

$$F = C(h - h_0), \text{ for } h-h_0>T \qquad (3)$$

$$F = CT, \text{ for } h-h_0 \leq T \qquad (4)$$

where:

- F is the flux out of the groundwater system (in kg/year) and is positive for baseflow and negative for leakage
- h is the groundwater level at the point
- h_0 is the river stage height
- C is the riverbed conductance, which has a base value of 320 ML/m/year, but which is a parameter varied in the uncertainty analysis
- T is a parameter that limits the leakage. For perennial rivers $T = -1$ m, while for ephemeral rivers $T = 0$. This means there is no leakage for ephemeral rivers, while the leakage from perennial rivers does not increase once the water head is 1 m below h_0.

The base value of C is motivated by assuming the riverbed has a width of order 10 m and thickness of order 1 m and conductivity of 0.1 m/day. The river stage height defaults to $h_0 = 3$ m, for all points. However, because the depth of the points is varied in the uncertainty analysis, this effectively also varies h_0.

2.6.2.4.3.3 AWRA-R baseflows

The surface water model contains 63 nodes at which the groundwater model can provide change in baseflow estimates. Nodes mostly correspond to streamflow gauging stations, but some nodes have been included specifically for assessing hydrological changes in response to coal resource development under the baseline and coal resource development pathway (CRDP). The baseflows (positive) and leakages (negative) are summed for all the points in the link upstream of a node in order to predict the total baseflow at the node. The numerical implementation of the groundwater model runs using nominal monthly time steps, so can only provide a monthly time series of gauge baseflows. The surface water model runs using daily time steps, and the groundwater results are interpolated linearly to provide this.

2.6.2.4.4 Bore extraction

The Hunter subregion contains many bores licensed to extract from groundwater (Bioregional Assessment Programme, Dataset 10). After removing points that lie outside the model domain and those associated with mine licence volumes which are already accounted for in the model via the water makes (Section 2.6.2.5), a total of 868 production bores were represented in the model (Bioregional Assessment Programme, Dataset 11). These are shown in Figure 17, and are placed at their correct depth relative to the discretised model topography.

The start date of each bore is known. The licensed extraction volumes (ML/year) are known, but not the actual volumes of groundwater removed in any given year. These extractions are potentially the greatest sink of groundwater in the region (apart from natural evapotranspiration), so represent a significant source of uncertainty in the modelling. For surface water extractions, WaterNSW water balance reports for the Hunter Regulated River between 2010 and 2015 indicate that, on average, slightly less than half (~46%) of the allocated volume is extracted for use (WaterNSW, 2016). Data for groundwater extractions are not available. Because groundwater extractions are assumed to be the same under the baseline and CRDP, the uncertainty associated with this unknown is unlikely to impact the quantification of hydrological changes of the additional coal resource development.

In the Hunter groundwater model it was assumed that the full entitlement is extracted at a uniform rate over the year at each bore. However, if the groundwater level drops below zero at the point, the extraction rate is reduced via a cubic function until it is zero when the groundwater level is 100 m below the point. This is rare and requires a confluence of parameters (low conductivity, porosity and rainfall) and the smooth cubic function is required to achieve rapid convergence of the numerical solver. In reality, extraction would cease once the watertable dropped below the screen of a bore, but continuing the water extraction in the model means the baseline and CRDP have the same bore extraction rates, which allows for a cleaner comparison of them. For example, consider a bore that extracts water for the entire baseline simulation. If a mine in the additional coal resource development caused drawdown at the bore, and if the bore ceased extracting water as soon as the groundwater level fell below the extraction point, then it would be difficult to compare the baseline and CRDP results, as the baseline would include an extracting bore, while the CRDP wouldn't.

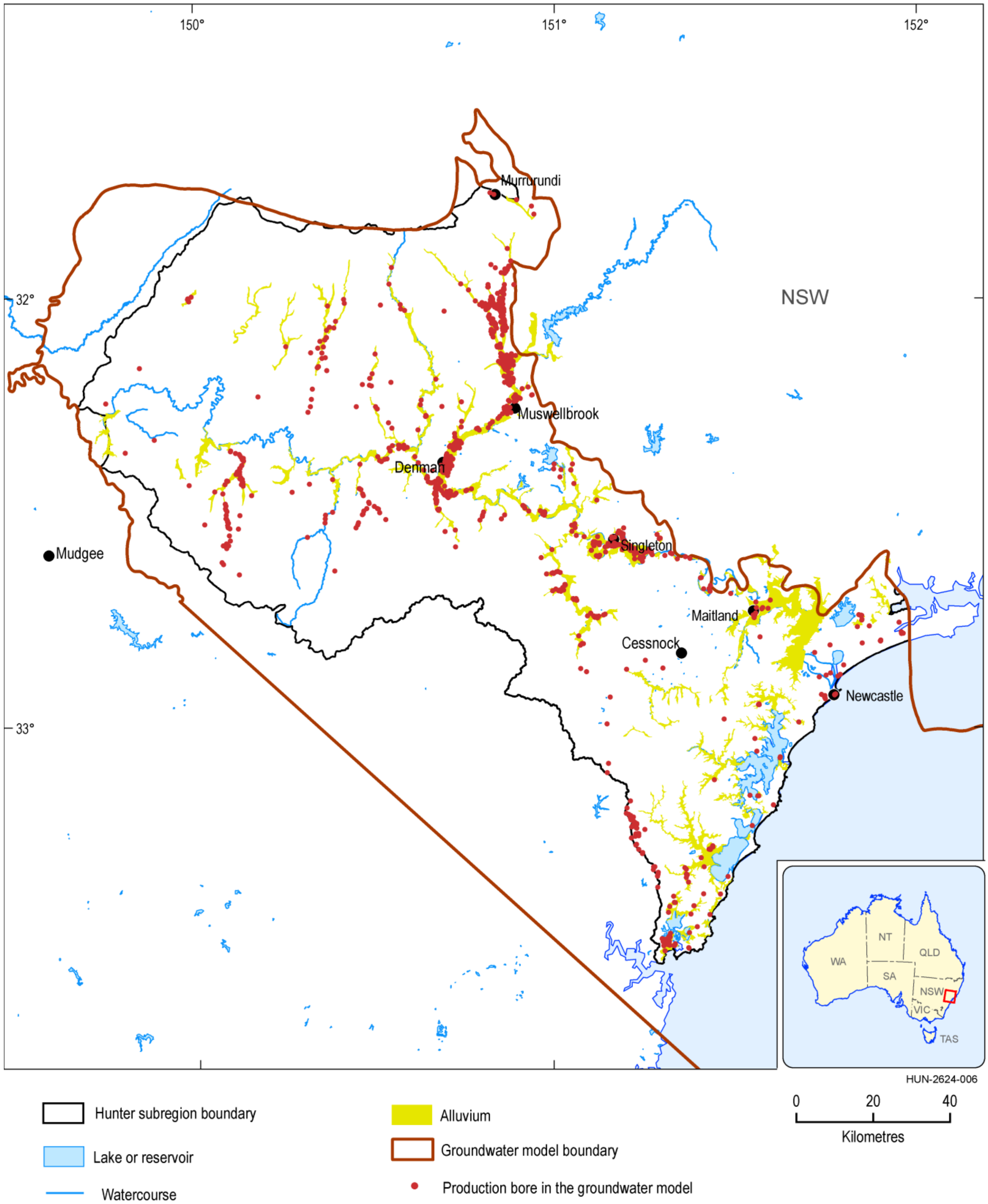

Figure 17 Production bores in the groundwater model

Data: Bioregional Assessment Programme (Dataset 9)

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2.6.2.5 Implementation of the coal resource development pathway

Summary

Groundwater modelling is undertaken for 58 coal resource development pathway (CRDP) mines, comprising 41 baseline and 17 additional coal resource developments. One baseline and five additional coal resource developments were not modelled due to lack of data or scale of proposed change.

The spatial extent of each mine working is represented in the model by its maximum footprint and does not vary over time. Each working is associated with a coal seam, which defines its depth. Footprints were obtained from a number of sources.

Flow rate time series are generated from historical data and forecast estimates of annual flow rates to represent groundwater extractions over the working life of the mine. Flow rates are varied in the uncertainty analysis by scaling the time series.

Hydraulic enhancement above longwall mines is implemented over the maximum mine footprint on the first day of mining. The change is assumed to be permanent. The magnitude of and depths over which hydraulic enhancement occur is uncertain and the parameters that govern these terms are varied in the uncertainty analysis.

A no-development simulation is run for 10^6 years to initialise the model, prior to undertaking modelling under baseline and CRDP.

The Hunter subregion has a long history of coal mining. Baseline coal mines and additional coal resource development were defined in Section 2.3.4 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018). There are 42 baseline mines and 22 additional coal resource developments included in the coal resource development pathway (CRDP), although due to insufficient data or insignificant changes in mine pumping rates from the additional coal resource development, 1 baseline mine and 5 additional coal resource developments were not included in the groundwater modelling. The potential impacts from these non-modelled mines are considered qualitatively in companion product 3-4 for the Hunter subregion (as listed in Table 2).

For the 58 modelled mines (41 baseline and 17 additional coal resource developments), each has to be defined in terms of its location, type of operation (open-cut or underground), area, depth (seam) and rates of groundwater extraction (also referred to as flow rates). A number of parameters also need to be defined to characterise changes in the hydraulic conductivity of units above and below the mine workings as a consequence of mining.

2.6.2.5.1 Spatial extent

For the groundwater modelling, a 'mine footprint' represents the area of mining only. That is, the footprint involves only the open pit or longwall panels, and does not include site facilities or other changes at the surface. Thus the mine footprints for groundwater modelling are not always the same as those used in the surface water modelling, which include all areas where surface water drainage is disrupted, such as from site facilities, water storages, drainage diversions, spoil heaps and roads (see companion product 2.1-2.2 (Herron et al., 2018), companion product 2.3 (Dawes et al., 2018) and companion product 2.6.1 (Zhang et al., 2018) for the Hunter subregion).

Mine workings, whether they are open-cut, longwall or bord-and-pillar mines, are represented by georeferenced polygons, which locate the 'mine' elements within the plan element mesh. As stated in Section 2.6.2.3.3.2, the plan mesh conforms, where possible, to the mine polygons.

Mine footprints were obtained from a number of sources, including existing digital data from some mining companies and the NSW Department of Trade and Investment, and footprints digitised specifically for the project from Landsat TM images of open-cut mines or from maps published in mine environmental assessment reports. Details of the source data can be found in Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018).

While a mine's footprint varies over the life of the mine, a constant footprint was used in the groundwater modelling, broadly corresponding to the maximum footprint. Given the coarse resolution of the regional-scale groundwater model (minimum pixel size of around 500 m), the finer detail of individual roadways, chain pillars, bords, etc. are not represented in the model. In most areas, even individual longwall panels are not resolved. Figure 18 illustrates how an AutoCAD representation of the Whybrow workings of the Bulga Coal underground mine supplied by Glencore Coal has been represented in the groundwater model. The coarse-scale resolution of the polygons is clearly adequate within the accuracy of the finite-element mesh.

In all, 98 mine footprint polygons were used to define the mining areas for the CRDP in the Hunter subregion for groundwater modelling. Many of these polygons overlap as they represent multi-seam mining operations, or open-cut operations exhuming old underground operations. The full extent of mining footprints is shown in Figure 20 in Section 2.3.4 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018).

Each mine working is associated with a working seam, which defines the approximate depth at which extraction occurs. As such, each polygon is also associated with a seam disc, which is the additional horizon representing a coal seam around mine workings that are included in the finite-element mesh (Section 2.6.2.3.3.1). Each polygon is superimposed upon its disc to yield a representation of the worked area in the model. Figure 9 illustrates multiple coal seam discs at Bulga coal mine.

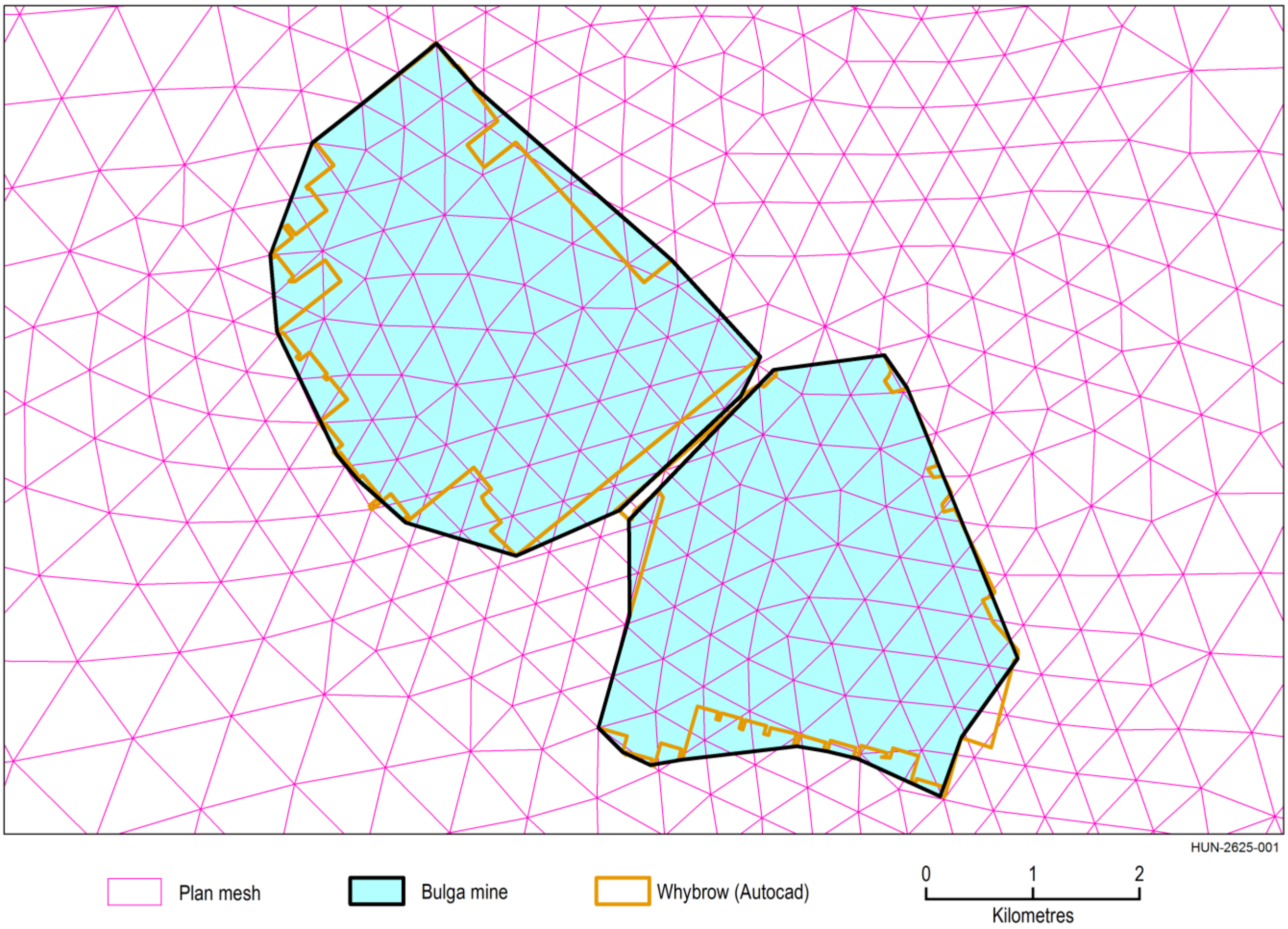

Figure 18 AutoCAD footprint of the Whybrow workings provided by Glencore Coal (brown) and the polygon generated from it (black and shaded) for Bulga Coal underground mine, overlain on the model mesh (pink)

Data: Bioregional Assessment Programme (Dataset 1); Glencore Xstrata (Dataset 2)

2.6.2.5.2 Water extraction

In order to model the removal of groundwater that seeps into mine workings, water is extracted from the model at all points within the polygon superimposed upon its seam disc. The rate of extraction is prescribed. This is in contrast to many groundwater models which are constructed to provide flow rate predictions. In that type of groundwater model, general-head boundary conditions are typically applied to the goaf area (void and broken rock left behind after coal extraction) of an underground mine, and the conductance is calibrated to match historical flow rates. For the Hunter subregion groundwater model, flow rates were obtained for: (i) years prior to 2015, from the reported values of mine water make in end-of-year mine reports, end-of-panel reports and environmental impact statements; and (ii) for years beyond 2015, from modelled estimates of mine water make found in environmental impact statements. A linear interpolation is used to estimate flow rates between the data points.

Figure 19 shows an example of rates of water extraction over the life of the Mount Arthur open-cut mine, based on actual and modelled rates. The full set of flow rate time series generated for baseline and CRDP mines is provided in Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018).

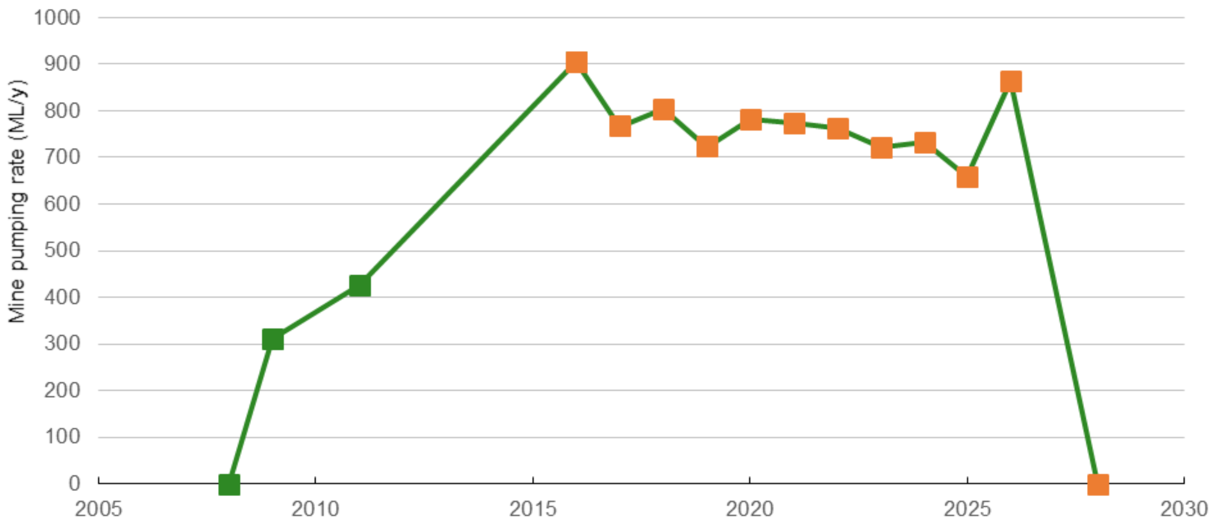

Figure 19 Time series of groundwater extraction for Mount Arthur open-cut mine

Green points indicate reported values, while orange points indicate future predictions.
Data: Bioregional Assessment Programme (Dataset 3)

Groundwater is extracted uniformly over the entire area defined by the polygon, even though in reality for longwall mines most water will seep out at the face and the panel perimeters. Specifically, if mine water extraction is *F* (ML/year) and *A* is the area (m^2) of the mine footprint, water is extracted at a uniform rate of *F/A* ML/year/m^2 over the entire footprint. This means longwall chainages (rates of extraction) and progressive pit excavation are not considered. However, to ensure numerical stability of the model, water extraction for a polygon is set to zero if the water head is below –100 m at the level of the seam disc. Negative 100 m was chosen because it is extremely rare to encounter such low heads since it requires a confluence of factors (for example, low hydraulic conductivity and porosity with high pumping rates), but yet it still allows the numerical solver to converge.

The void remaining after mining coal underground is not represented as a 'hole' in the model. Such holes are common in models coupled with geomechanics, and in models where very local-scale effects are being studied, such as assessing how much water is produced from the roof, floor and chain pillars. In the Hunter groundwater model, water is simply extracted from the polygons, as described above.

The rates of water extraction are varied in the uncertainty analysis (see Section 2.6.2.8). This is important since the reported historical flow rates are subject to errors, while future flow rates are necessarily predictions, informed by mine-scale groundwater modelling and assumptions about the hydrogeology and development of the mine, and are also uncertain.

2.6.2.5.3 Hydraulic conductivity enhancement

Mining relieves in situ stresses in the surrounding rock mass, causing deformation including fracturing. For example, in parts of the active caving zone of longwall mines, total strains can easily exceed 100%. The strain increments naturally alter the hydraulic properties of the surrounding rock, and it is generally assumed that the conductivity will increase by orders of magnitude in both the horizontal and vertical directions (Adhikary and Wilkins, 2012). This is because rock plastic deformation dilates existing micro and macro fractures and creates new ones. The rock-mass conductivity after caving and consolidation can be inferred from the response of piezometers or the measurement of water or gas flows within, above and below the goaf (Guo et al., 2014). It is always higher than the in situ value. This is the reason that the water make in a typical longwall mine will increase as panel width (and conductivity changes) increases, and, conversely, why a typical bord-and-pillar mine (with essentially very thin and short panels) makes less water than a typical longwall mine. Therefore, in the Hunter subregion groundwater model, the hydraulic conductivity of rock units above and below each mine working is assumed to be different from the in situ value.

In the Hunter subregion groundwater model, the hydraulic conductivity, K, above and below each mine working (i.e. above the polygon superimposed upon the seam disc), is enhanced according to:

$$K(x,y,z,t) = 10^{\Delta} K_0(x,y,z) \quad (5)$$

where K_0 is the base conductivity (both horizontal and vertical components), determined by layer number, lithology and depth, as described in Section 2.6.2.3; and Δ parameterises the conductivity change. $\Delta = 0$ before mining of the seam commences, and $\Delta = \Delta(h)$ at height, h, above the seam immediately after mining commences. This conductivity enhancement is assumed to remain after mining ceases, thus a separate ‘active phase’ (with Δ large) and ‘consolidation phase’ (with Δ smaller) above longwall mines is not included in the model (such phases would be important to include if the model were trying to predict mine water makes rather than treating them as an input parameter). However, Δ may be defined differently for each polygon. Δ is calculated using the following piecewise-linear function of the height above the mining seam, h:

$$\Delta = 0 \text{ for } h>Z\geq 0 \quad (6)$$

$$\Delta = 0 \text{ for } h<z<0 \quad (7)$$

$$\Delta = M(Z-h)/Z \text{ for } 0\leq h\leq Z \quad (8)$$

$$\Delta = m(h-z)/z \text{ for } z<h<0 \quad (9)$$

The general form of the relationship is illustrated in Figure 20 where it is clear that conductivity change is M orders of magnitude directly above the seam, and m orders of magnitude directly below the seam, and that the conductivity changes occur between z metres below the seam and Z metres above the seam.

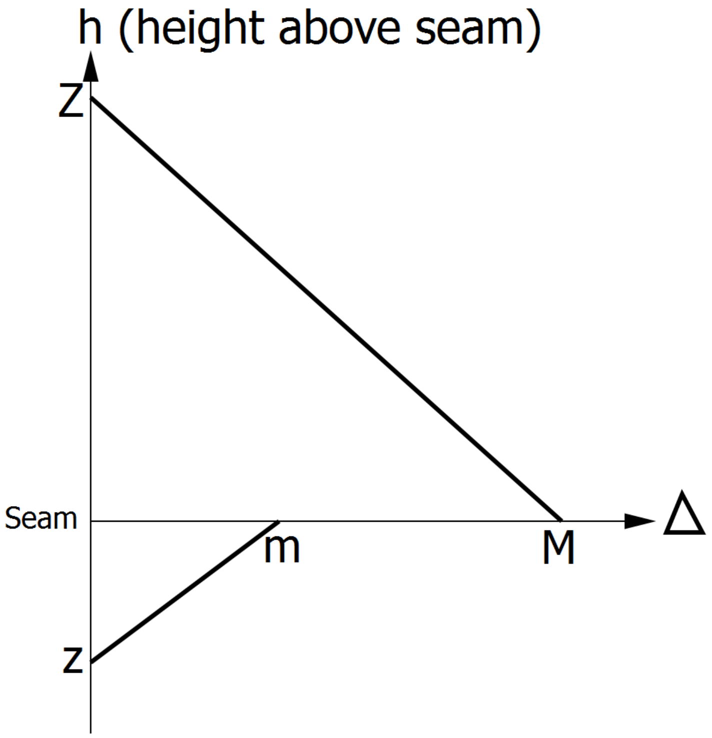

Figure 20 Assumed relationship between the conductivity-change parameter, Δ, and the height above the mining seam, *h*

As discussed in Adhikary and Wilkins (2012), longwall mining enhances the permeability greatly compared with bord-and-pillar mines, simply because the rock deformation caused by the latter is comparatively small. The effective conductivity in the immediate roof of longwall mines can be enhanced by up to 10 orders of magnitude. The values *M, m, Z* and *z* are varied in the uncertainty analysis around the values given in Table 5 for different mine types. The values in Table 5 are motivated by the numerical, experimental and observational studies performed by Adhikary and Wilkins (2012) and Guo et al. (2014).

The conductivity change (Δ) at a single point can be enhanced by many mine workings in multi-seam mining situations, with each enhancement assumed to be additive. To avoid precision-loss issues in the numerical solver when the hydraulic conductivity is increased by more than 20 orders of magnitude, an upper bound of $\Delta_{tot}<20$ is placed upon the total enhancement. Such large changes could occur in multi-seam mining situations as multiple mining operations contribute additively to the conductivity change.

Table 5 Model parameters for representing hydraulic conductivity enhancements for different mine types

Parameter	Longwall	Bord-and-pillar	Open-cut
M	9	2	0
Z	500	100	0
m	7	1	8
z	–250	–50	–90

Hydraulic enhancement is implemented in the groundwater model over the maximum footprint area of a longwall mine on the first day of mining. The enhancement is assumed to be permanent.

2.6.2.5.4 Simulations

For each parameter set in the uncertainty analysis, four simulations are undertaken as follows:

- A steady-state initialisation. This initialises the model for the three other simulations. No mining is performed (i.e. no groundwater extraction and no conductivity enhancement), nor is there any extraction of groundwater for non-mining uses. Rainfall recharge and evapotranspiration vary spatially, but are set at their average values for the period 1980 to 2012, so they are not temporally varying. The reference heads for the general-head boundary conditions are set at their hydrostatic values. This simulation is run for 10^6 years to reach approximate steady-state under these average conditions. Because of the adaptive time-stepping capability of MOOSE (2016) this simulation is computationally cheap, despite simulating 10^6 years of steady conditions.
- A no-development simulation. The heads at each finite-element node are initialised with their values from the steady-state simulation. No mining is performed. Groundwater is extracted via licensed bores. Rainfall recharge and evapotranspiration are spatially and temporally varying. The reference heads for the general-head boundaries are the heads from the steady-state simulation (not the reference heads from that simulation). This simulation runs from 1980 to 2102 on a monthly stress period.
- A baseline simulation. This is identical to the no-development simulation, except that baseline mines are made active (including the groundwater extraction and conductivity enhancement for those mines).
- A CRDP simulation. This is identical to the baseline simulation except that all additional coal resource developments are also made active.

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2.6.2.6 Parameterisation

Summary

The Hunter subregion groundwater model has 22 specific parameters, which can be broadly grouped into the following categories: land-surface flux parameters; general-head parameters; surface water – groundwater parameters; hydraulic properties; unsaturated flow parameters; and parameters associated with the hydraulic enhancement due to mining.

Details of hydraulic properties and unsaturated flow parameters are provided. Other parameters are discussed in other sections of the product. Values for fixed parameters are specified. Default values, multipliers and parameter ranges for those parameters varied in the uncertainty analysis are specified.

2.6.2.6.1 Hydraulic properties

The groundwater model needs to define porosity and vertical and horizontal hydraulic conductivity for every element in the model mesh. These properties might be expected to vary with lithology or geology. An analysis of 577 hydraulic conductivity measurements from the Hunter subregion found little to no correlation between lithology and hydraulic conductivity, nor between geologic layer and hydraulic conductivity (see Section 2.1.3 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)). However, there was a weak correlation with depth (see Figure 26 in Herron et al. (2018)). Companion submethodology M07 for groundwater modelling (Crosbie et al., 2016) proposes the use of a simple parameterisation of hydrostratigraphy in bioregional assessment (BA) groundwater model layers that treats the layers as homogeneous, but varies hydraulic properties with depth. In the absence of a good basis for varying hydraulic properties by lithology or geology, the parameterisation of the Hunter subregion groundwater model adopts this approach.

As described in Section 2.6.2.3.3.1, every point in the model domain can be defined in terms of a layer number (N = 1 to 11), a lithology (L = 1 to 7) and a depth, *d*, below the model topography. The horizontal hydraulic conductivity, *Kh*, the vertical hydraulic conductivity, *Kv*, and the porosity, *Φ,* are assumed to be of the form:

$$Kh = exp(-a_h d)\ Kh_{(L,N)} \qquad (10)$$

$$Kv = exp(-a_v d)\ Kv_{(L,N)} \qquad (11)$$

$$\Phi = exp(-a_\Phi d)\ \Phi_{(L,N)} \qquad (12)$$

where *a* is the exponential decay coefficient which varies each parameter with depth.

Reference horizontal conductivities, porosities and decay parameters are defined in Table 6, and were obtained by appropriately averaging data from Figure 26 and Figure 31 of Herron et al. (2018). It is not appropriate to directly use the raw conductivity data presented in Figure 26 in the groundwater model. This is because the measured data pertain to samples on the scale of centimetres (for lab measurements) to a few tens of metres (in-situ measurements). The regional groundwater model has a best resolution of 500 m, so some 'upscaling' of the raw data is necessary. Consider the problem of prescribing a suitable conductivity to a 500 m region of the groundwater model. Typically, there will be some regions of low conductivity within that region but there will also be regions of high conductivity, and water will flow preferentially through those highly conductive regions, almost entirely bypassing the regions of low conductivity. Therefore, the 500 m region will have an effective conductivity that is closer to the high conductivities shown in Figure 26. Of course, given the scatter of raw data in Figure 26, the conductivity of our 500 m region will be drawn from a probability distribution of conductivity values, but the mean of this probability distribution will be the (arithmetic) mean of the raw data. A classic review of this subject may be found in Renard and de Marsily (1997). This arithmetic mean is shown in Figure 26 as a function of depth, and leads to the value shown in Table 6.

Less data are available to constrain vertical conductivity. Aquitards typically occur as roughly horizontal layers of low conductivity in stratified geological systems such as the Hunter subregion. Such aquitards have little effect on horizontal water flow, since it flows relatively quickly through the surrounding aquifers, but have a greater effect on vertical flow, since the water must pass through the aquitard. This means that groundwater models typically use a vertical conductivity that is a small multiple of horizontal conductivity. A base multiplying factor of 0.1 is chosen in the Hunter groundwater model (and this is varied in the uncertainty analysis).

The alluvium layer (L = 7) is assumed to be more porous and conduct water more rapidly than the interburden layers (L = 1 to 6), reflecting its unconsolidated nature. Its thickness is represented as one finite element, which means at any point the conductivity of the alluvium is a single number and does not vary with depth. However because the thickness of the alluvium varies across the subregion, and conductivity is evaluated at the centroid of a 3D finite element, the effect of the decay parameter means a 20 m thick alluvium will have conductivity of 0.78 m/day, while a 10 m thick alluvium will have conductivity of 0.88 m/day. These differences are negligible. Thus the decay for the alluvium layer is unimportant since it is so thin in comparison with the overall model thickness.

Horizontal and vertical conductivities are assumed to decay at the same rate with depth.

Table 6 Reference hydraulic property values and decay parameters

Parameter	Units	Interburden layers (1 to 6)	Alluvium layer (7)
Horizontal hydraulic conductivity, $Kh_{(L,N)}$	m/day	0.5	1.0
Vertical hydraulic conductivity, $Kv_{(L,N)}$	m/day	0.05	1.0
Porosity, $\Phi_{(L,N)}$	dimensionless	0.1	0.2
Decay parameters, a_h , a_v	m^{-1}	0.025	0.025
Decay parameter, a_Φ	m^{-1}	0.01	0.01

In many groundwater models, the decay parameters a_h, a_v, a_Φ, and the functions $Kh_{(L,N)}$, $Kv_{(L,N)}$ and $\Phi_{(L,N)}$ would be calibrated by observation with water heads. Here, however, these are all varied in the uncertainty analysis as described in Section 2.6.2.7.2

In the coal resource development pathway and baseline simulations, the horizontal and vertical conductivities are further enhanced above underground mines and below both open-cut and underground mines.

2.6.2.6.2 Unsaturated flow

Single-phase unsaturated Darcy-Richards physics is used. A van Genuchten capillary suction function with index 0.4 and inverse-head 0.1 m^{-1} is used along with a relative permeability function of the form:

$$K = 3S^2 - 2S^3 \qquad (13)$$

where S is the water saturation. The capillary function and relative permeability function are kept fixed and are not part of the uncertainty analysis. The van Genuchten parameters are reasonable for rocks and soils (van Genuchten, 1980).

2.6.2.6.3 Summary of parameters in the groundwater model

There are 22 parameters in the groundwater model. They can be broadly grouped by model function into parameters relating to:

- Land-surface fluxes: two fixed parameters for defining evapotranspiration processes (see Section 2.6.2.4.2); there is also a recharge multiplier used in the uncertainty analysis to vary the recharge input.
- General-head boundary behaviour: one fixed parameter that is the conductance of all lateral boundaries (except the boundary to the Werrie Basin) and the ocean floor.
- Surface water – groundwater fluxes: four parameters that define the boundary conditions for the movement of water from groundwater to the river. River stage height varies with riverbed depth. The two leakage limiter parameters are fixed in the model (see Section 2.6.2.4.3).
- Hydraulic properties: nine parameters to define porosities and vertical and horizontal hydraulic conductivities with depth for the interburden (lithologies 1 to 6) and the alluvium (lithology 7) (Section 2.6.2.6.1).
- Unsaturated flow: two fixed parameters in the van Genuchten unsaturated flow equation (Section 2.6.2.6.2).
- Hydraulic enhancement: four parameters to characterise the magnitude of and depth over which hydraulic conductivity changes occur due to longwall mining (see Section 2.6.2.5.3).

Table 7 summarises the groundwater model parameters, including the reference values, ranges over which parameters are varied in the uncertainty analysis (see Section 2.6.2.8) and salient points. As identified above, a number of these parameters are dealt with in other sections of this product.

The range of conductivity and porosity values explored in the uncertainty analysis and its comparison with measured data is shown in Figure 26 and Figure 31 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018). As mentioned above, an upscaling analysis may be performed to yield a probability distribution for hydraulic conductivity, and the result of such an analysis is shown in Figure 21, which motivates the uncertainty bounds in Table 7. Figure 21 shows the probability distribution for the measured data in the depth interval 0 to 100 m. In this interval, conductivity measurements vary between 10^{-7} m/day and 30 m/day. The data have been binned into nine bins: the first lies between 10^{-7} m/day and 10^{-6} m/day, the second between 10^{-6} m/day and 10^{-5} m/day, and so on up to between 10^{1} m/day and 10^{2} m/day. Figure 21 shows that the data are roughly uniformly distributed into these bins, with slightly more likelihood of measurements occurring in the central bins than in the outer bins. Figure 21 also contains a probability distribution for the upscaled conductivity that is derived from the measured data, and its comparison with the uncertainty bounds for a 50 m depth from Table 7. Upscaling is discussed further in Renard and de Marsily (1997).

Conductivity enhancement above and below mines is discussed in Section 2.6.2.5.3, and the wide range of variation (5 orders of magnitude, and heights ranging between 100 m and 500 m above longwall workings) reflects the wide variation that may be experienced in different mining scenarios (Adhikary and Wilkins, 2012; Guo et al., 2014).

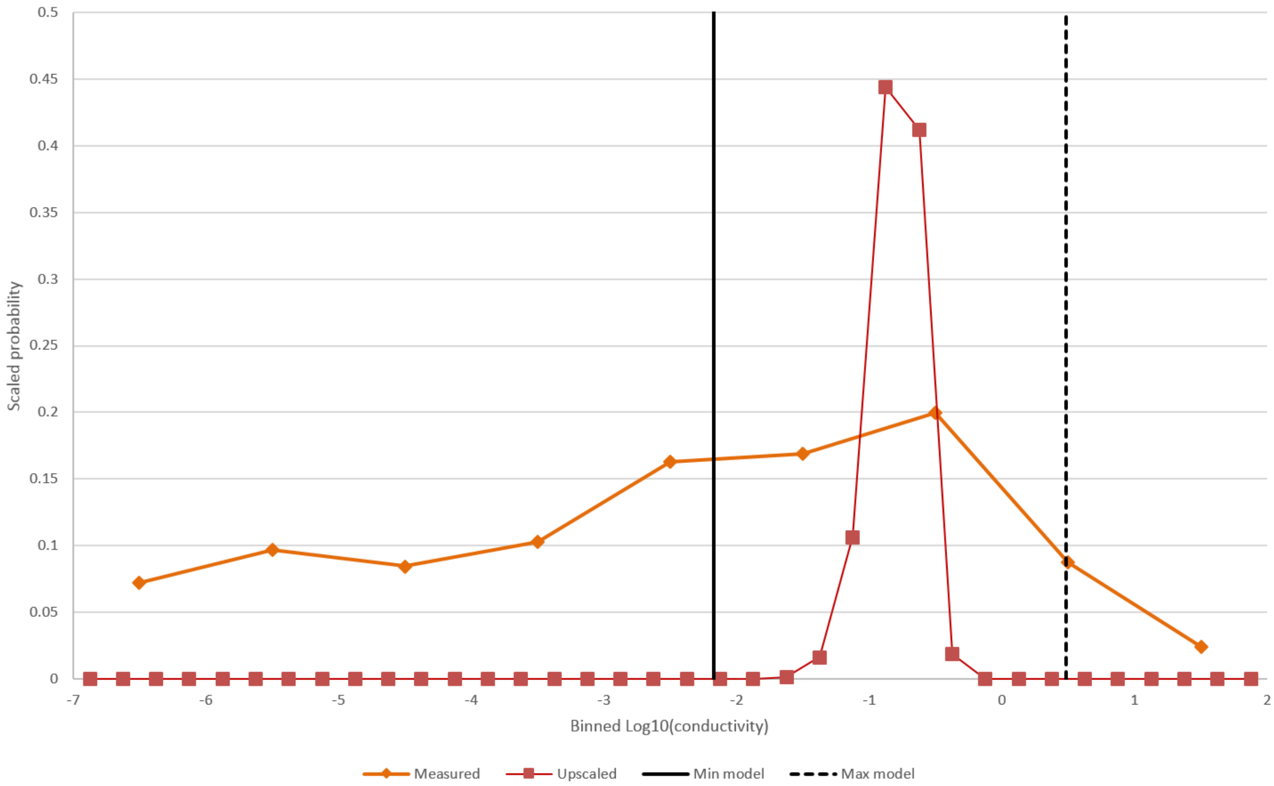

Figure 21 Scaled probability distributions for measured conductivity data in the depth interval 0 to 100 m, and the results of upscaling those data

Table 7 Groundwater model parameters: their reference values and the minimum and maximum values used in the uncertainty analysis

Process	Parameter	Units	Reference Value	Min	Max	Notes
Land-surface fluxes	ET extinction depth (*d*)	m	*d* = V/4	na	na	Fixed parameter. Depth below surface at which ET is assumed to cease. Calculated as a function of vegetation height, V. Throughout the Hunter subregion this varies between 0 m and 10 m.
	Watertable depth threshold for PET	m	–2	na	na	Fixed parameter. Watertable depth above which ET is approximated by PET.
	Recharge multiplier	na	1	0.5	1.5	Rainfall recharge to the groundwater system is multiplied by this quantity.
Outer boundary	General head conductance	$ML/y/m^3$	10^{-5}	na	na	General-head conditions are applied at the lateral boundaries (excepting the boundary to the Werrie Basin) and the ocean floor.
SW-GW fluxes	Riverbed conductance (*C*)	ML/m/y	320	32	3200	The riverbed conductance for points representing a 1 km section of river.
	Riverbed depth	m	5	0	10	This parameter may also be viewed as shifting the stage height of the rivers.
	River stage height (h_0)	m	3	na	na	Defaults to 3 m, but varies with riverbed depth
	Leakage limiter (*T*)	m	P: –1 E: 0	na	na	Fixed parameters. P = perennial: leakage does not increase when groundwater head is <1 m below river stage height E = ephemeral; *T* = 0 means no flow from river.
Hydraulic properties	Reference porosity – interburden ($\Phi_{1–6}$)	m^3/m^3	0.1	0.03	0.3	After multiplying by the decay parameter, porosity is constrained to always be greater than 0.0001 to ensure good convergence of the numerical model.
	Reference porosity – alluvium(Φ_7)	m^3/m^3	0.2	0.06	0.6	After multiplying by the decay parameter, porosity is constrained to always be greater than 0.0001 to ensure good convergence of the numerical model.
	Decay parameter for porosity (a_p)	na	0.01	0.005	0.015	An exponential decay function is used to vary porosity with depth.
	Horizontal conductivity – interburden (Kh_{1-6})	m/day	0.5	0.05	5	After multiplying by the decay parameter and applying mining-induced changes, an upper bound of 100 m/day and a lower bound of 10^{-6} m/day is placed on all conductivities.
	Horizontal conductivity – alluvium (Kh_7)	m/day	1.0	0.1	10	

Process	Parameter	Units	Reference Value	Min	Max	Notes
	Vertical conductivity – interburden ($Kv_{1–6}$)	m/day	0.05	0.005	0.5	
	Vertical conductivity – alluvium (Kv_7)	m/day	1.0	0.1	10	
	Decay parameter for *Kh* and *Kv* (a_h and a_v)	na	0.025	0.01	0.04	An exponential decay function is used to vary hydraulic conductivity with depth.
	Kv/*Kh*	na	0.1	0.01	1	Ratio of vertical to horizontal conductivity
Unsaturated flow	Capillary suction index	na	0.4	na	na	Fixed parameter. van Genuchten capillary suction index parameter for rocks and soil
	Inverse head	/m	0.1	na	na	Fixed parameter. van Genuchten inverse-head parameter
Hydraulic enhancement	Hydraulic conductivity multiplier above seam (*M*)	na	LW: 9 BP: 2	1.8 0.4	9 2	Order of magnitude increase in hydraulic conductivity. Bord-and-pillar (BP) mining has a lesser impact than longwall (LW) mining. Hydraulic enhancement occurs below, but not above open-cut (OC) mines.
	Hydraulic conductivity multiplier below seam (*m*)	na	LW: 7 BP: 1 OC: 8	1.4 0.2 1.6	7 1 8	Order of magnitude increase in hydraulic conductivity. Maximum height above and below the worked seam that hydraulic conductivity changes occur. Bord-and-pillar (BP) mining has a lesser impact than longwall (LW) mining. Hydraulic enhancement occurs below, but not above open-cut (OC) mines.
	Height of enhancement above worked seam (*Z*)	m	LW: 500 BP: 100	100 20	500 100	
	Depth of enhancement below worked seam (*z*)	m	LW: –250 BP: –50 OC: –90	–50 –10 –18	–250 –50 –90	Maximum depth below the worked seam that hydraulic conductivity changes occur.

BP = bord-and-pillar; E = ephemeral; ET = evapotranspiration; GW = groundwater; PET = potential evapotranspiration; P = perennial; LW = longwall; na = not applicable; OC = open-cut; SW = surface water

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2.6.2.7 Observations and predictions

Summary

Historical groundwater level and streamflow data are used to constrain groundwater model predictions. Through a rigorous quality control process, 64 of 583 groundwater monitoring sites are selected to constrain the numerical modelling. In the absence of reliable, regional estimates of surface water – groundwater flux, observed streamflow data are used to impose upper and lower bounds on the modelled surface water – groundwater flux.

At each model node in the model domain, the model simulates the time series of groundwater level for the baseline and coal resource development pathway (CRDP). One baseline mine and five additional coal resource developments were not modelled, so predictions do not represent changes from the full CRDP. The maximum difference in drawdown between the modelled CRDP and baseline, due to additional coal resource development (*dmax*), and the year of maximum change (*tmax*), are calculated as the difference between the two time series. At points along the prescribed stream network, the model also generates baseline and CRDP time series of the surface water – groundwater flux. These outputs become change in baseflow inputs to the river model and are encapsulated in the streamflow hydrological response variables reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

Predictions of the change in the surface water – groundwater flux arising from coal resource development indicate that increases in baseflow are possible. These are caused by hydraulic enhancement in the goaf above longwall mines, immediately following their collapse. A simple two-dimensional model illustrates how drawdown and hydraulic enhancement interact to produce a time series of baseflow increases and decreases. Local watertable increases have been reported in the literature, but there is no published account of baseflow increases.

A subset of ten groundwater model parameters is allowed to vary stochastically to form the basis for the sensitivity and uncertainty analysis. The groundwater levels and surface water – groundwater flux are most sensitive to depth of the river channel (*d_riv*), which determines the drainage level, the hydraulic properties (*Kh, K_lambda, KvKh*) and the recharge multiplier (*RCH*). The surface water – groundwater flux is also sensitive to riverbed conductance (*C_riv*).

The main prediction, *dmax*, the drawdown due to additional coal resource development, is sensitive to *Kh* as well, but is also sensitive to the baseline porosity parameter (*ne*) and the parameters that define the impact due to the additional coal resource development, such as *Q_mine* (the mine water extraction rate) and *K_ramp* (the magnitude of hydraulic enhancement). As the groundwater level and streamflow observations are not sensitive to these parameters, these parameters will not be constrained greatly in the uncertainty analysis.

2.6.2.7.1 Observations

2.6.2.7.1.1 Groundwater level

The HYDMEAS database (NSW Office of Water, Dataset 1) contains the observations of the regional groundwater monitoring network. Groundwater level measurements from 583 monitoring sites across the Hunter subregion (see Figure 19 in Section 2.1.3 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018)) were obtained. Of these, only 64 monitoring sites have surveyed spatial coordinates (easting, northing and elevation) and have been retained in the observation data set used to constrain the model parameters (Figure 22). These 64 sites have 431 groundwater level measurements, which span January 1983 to December 2012 and have between 1 and 27 observations in this period. It can be seen in Figure 22 that relatively few of these sites are close to the subregion's coal mining areas.

Local monitoring information, including monitoring data from mining companies, is not included in the analysis to avoid biasing the regional objective function with measurements predominantly affected by local hydrogeological conditions and stresses that are not captured in the regional model. Mining companies install monitoring wells in the vicinity of the mine sites to capture information about local hydrogeological conditions, surface water features or local lenses of more-permeable or less-permeable strata. Within a site-scale groundwater model, these local features can be represented with sufficient spatial detail and the historical stresses with sufficient accuracy for the groundwater-level observations to be used to infer local parameter values or constrain local predictions. In a regional-scale model, the representation of local features and stresses cannot be done at a resolution sufficient to match the information from local-scale observations. Regional-scale parameters will compensate for the missing spatial detail and the accuracy of the imposed historical stresses. As shown by Doherty and Welter (2010) and White et al. (2014), this can lead to a bias in the inferred parameter values, and in turn to biased predictions. Local information can be used in a regional context, if the tolerance of model-to-measurement misfit is increased to account for the missing local detail. This means in the vicinity of mines where, due to the historical pumping rates, hydraulic gradients are expected to be high, large discrepancies between modelled and observed groundwater levels should be expected and tolerated. Effectively, this reduces the information content of the local observations. Establishing an appropriate weighting or tolerance for local observations is site-specific and subjective. It requires an in-depth analysis of the accuracy of the local monitoring network as well as an estimation of the uncertainty in the historical pumping rates.

In order to limit the propensity of biasing regional parameter values through the incorporation of local-scale observations and inherently subjective weighting of these observations, local-scale information from mine groundwater monitoring networks is not used.

Section 2.6.2.8.1 provides the details of how these groundwater level observations are integrated into the objective function to constrain the groundwater model.

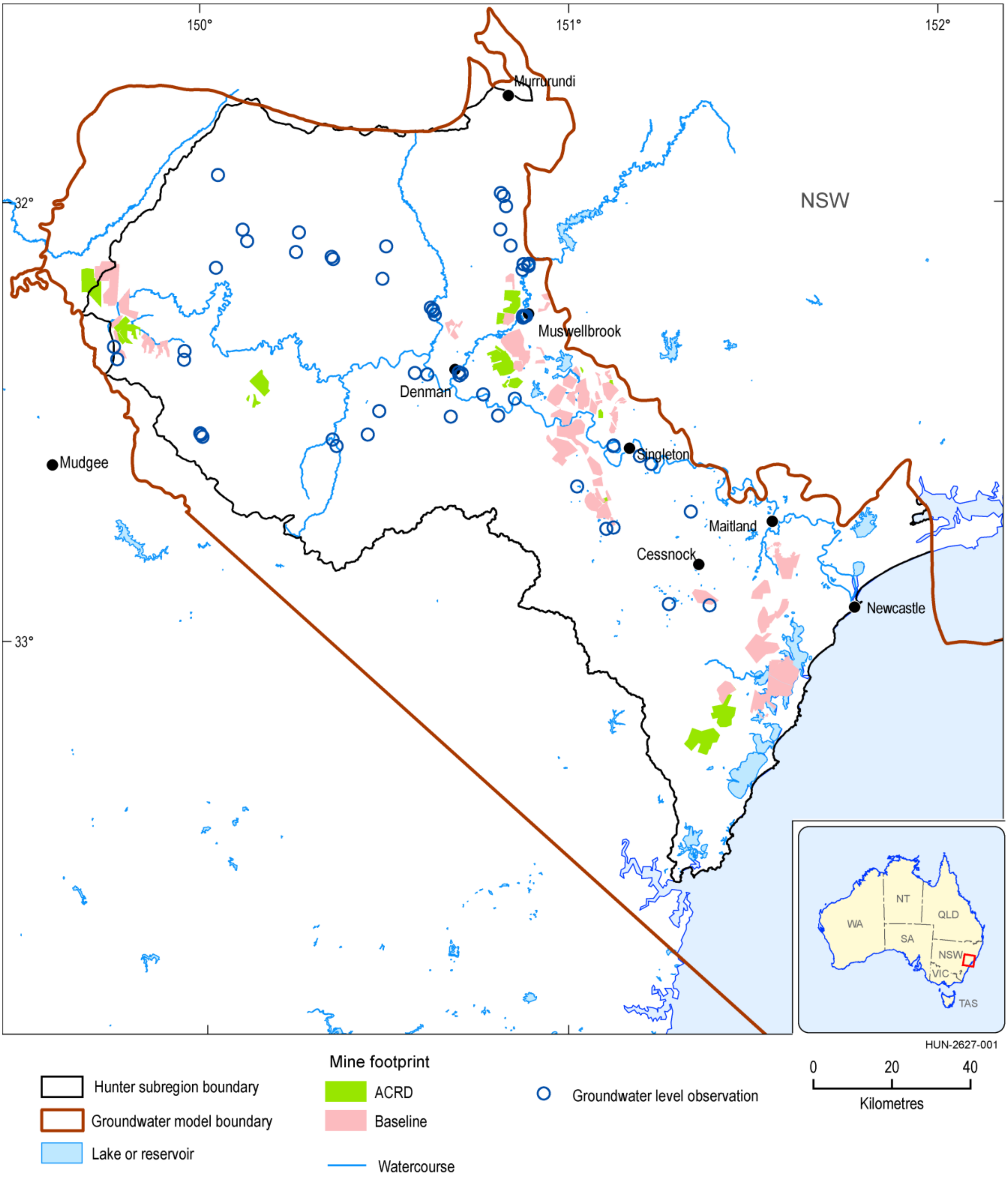

Figure 22 Groundwater level monitoring sites with surveyed coordinate and elevation data used to constrain the groundwater model

ACRD = additional coal resource development
CRDP = baseline + ACRD
Data: NSW Office of Water (Dataset 1)

2.6.2.7.1.2 Streamflow

The groundwater model was not designed to simulate total streamflow in the river system within its model domain, but rather to generate estimates of the surface water – groundwater flux (i.e. change in baseflow) at points along a prescribed stream network due to coal resource development. Constraining these fluxes requires regional estimates of the surface water – groundwater flux, which, as discussed in Section 2.1.5 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018), are not easy to determine.

As an alternative, long-term observed streamflow hydrographs have been used as proxy to constrain estimates of surface water – groundwater flux by the groundwater model. Parameter combinations that result in long-term historical surface water – groundwater fluxes in excess of the 70th percentile of total historical surface water flow were deemed unacceptable. Parameter combinations that result in long-term historical surface water – groundwater fluxes that are more negative than the negative of the 20th percentile of total historical surface water flow (i.e. streamflow losses greater than the 20th percentile of total streamflow) were also deemed unacceptable. The upper constraint is considered conservative as the regional estimate of baseflow contribution to the Hunter River system is between 22% and 66% of total streamflow (see Table 3 in Section 2.3.2.4 in companion product 2.3 for the Hunter subregion (Dawes et al., 2018)). The lower constraint is likewise conservative as it allows for locally losing conditions, while it excludes parameter combinations that give rise to regional losing river conditions.

Figure 23 shows the 10th, 20th, 50th, 70th and 90th percentiles of observed streamflow at selected gauge locations in the model domain used to constrain the groundwater model (see Figure 18). Section 2.6.2.8.1 provides more detail on how these streamflow observations are integrated in the objective function to constrain the groundwater model.

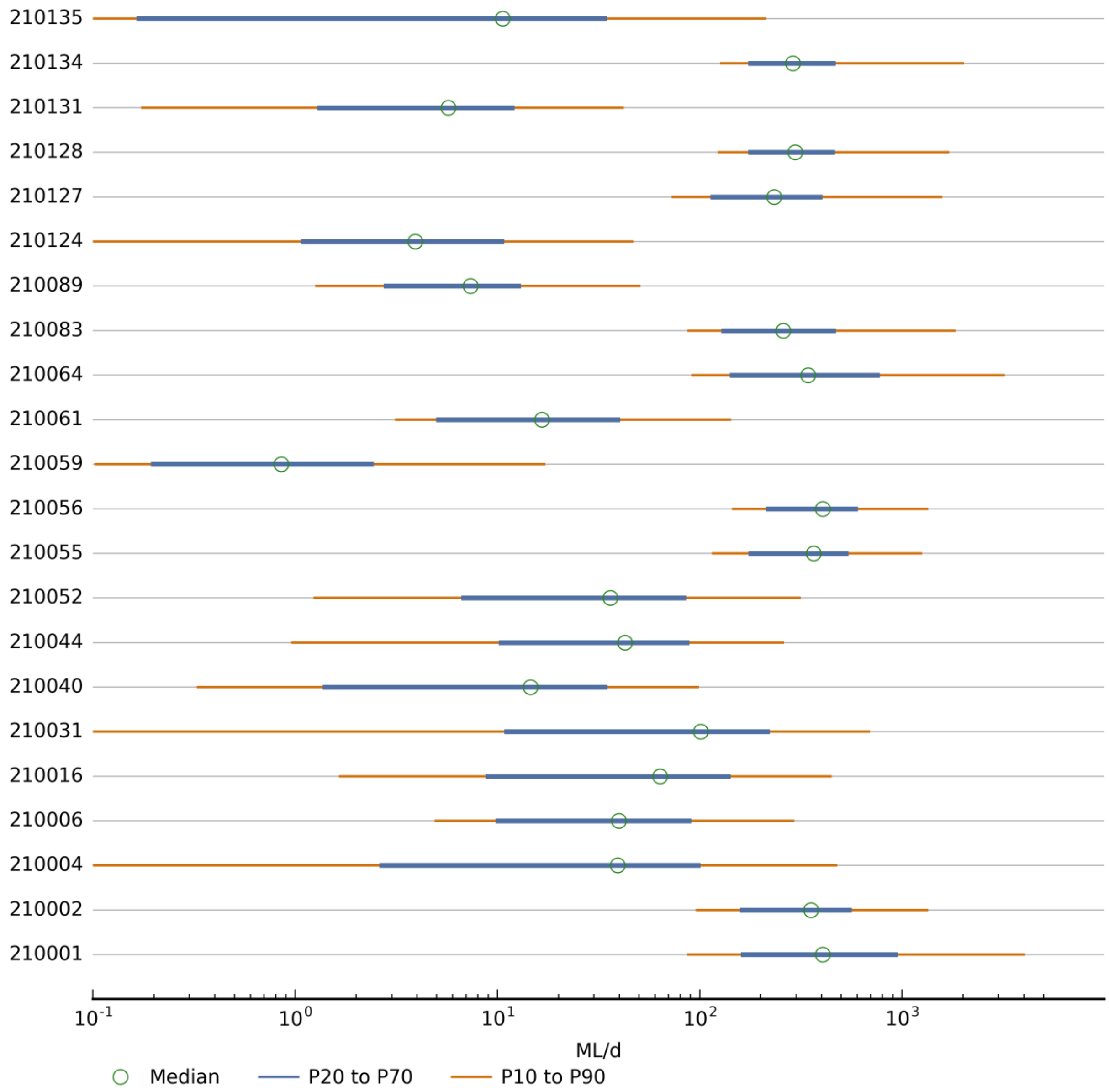

Figure 23 Percentiles of total flow at selected gauges in the model domain

Refer to Figure 32 in companion product 2.1-2.2 (Herron et al., 2018) for location of gauges.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.2.7.2 Predictions

2.6.2.7.2.1 Drawdown due to the additional coal resource development

As discussed in Section 2.6.2.1, one objective of the groundwater modelling is to provide probabilistic estimates of the drawdown of the watertable due to the additional coal resource development.

At each model node (shown in Figure 3), time series of groundwater level in the watertable aquifer are simulated for the baseline and CRDP, noting that one baseline and five additional coal resource developments were not modelled and results therefore do not provide a complete picture of the changes due to the additional coal resource development. The maximum difference in drawdown between the CRDP and baseline, due to additional coal resource development (*dmax*), and the year of maximum change (*tmax*), are calculated based on the difference between the two time series. This is illustrated in Figure 24 for two model nodes: probe66 and GW044912.

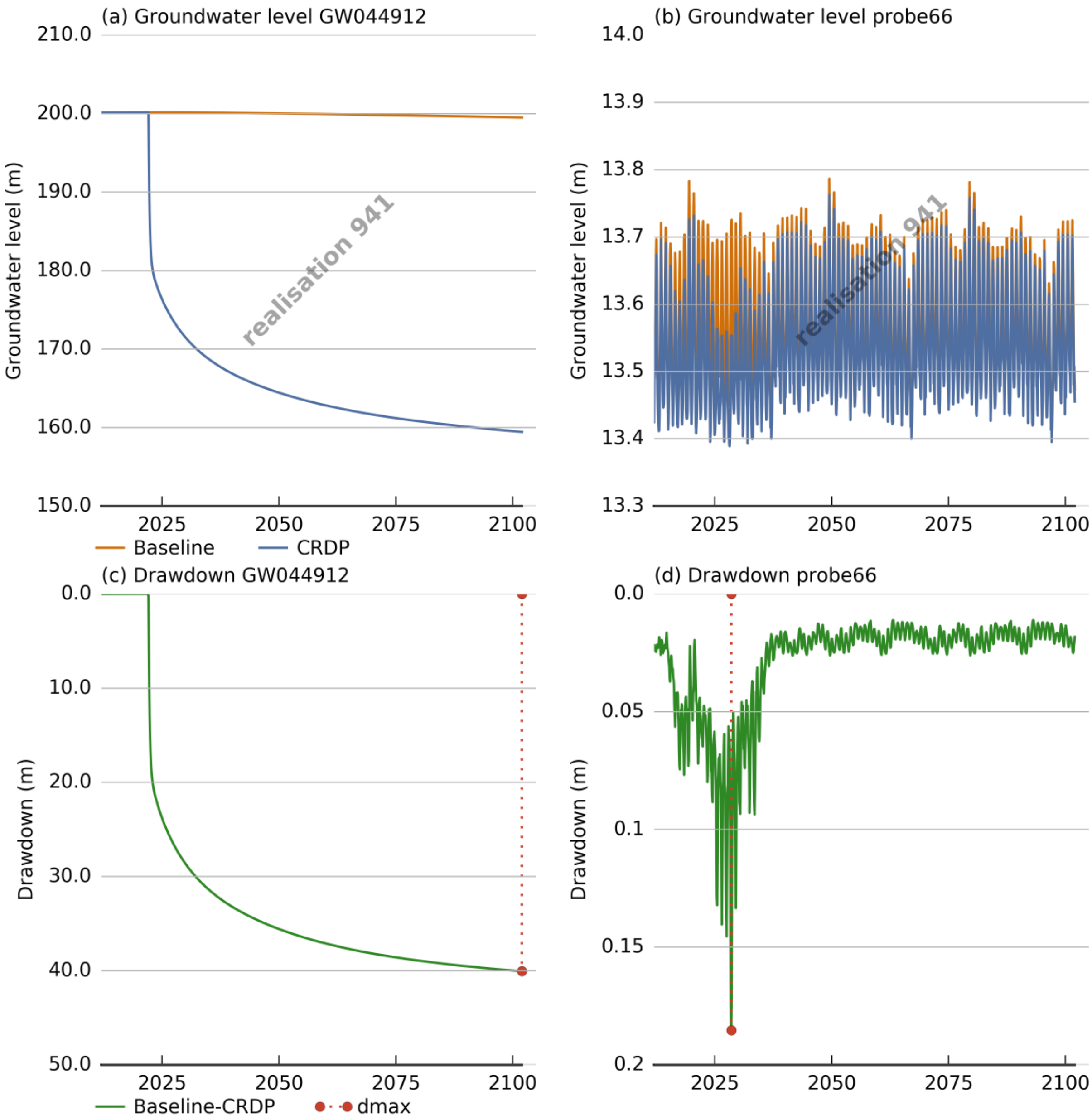

Figure 24 Example groundwater model output time series for model nodes GW044912 (a) and (c) and probe66 (b) and (d) for simulation 941

Groundwater levels in (a) and (b) are expressed as mAHD.
dmax = maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development (ACRD)
CRDP = baseline + ACRD
Data: Bioregional Assessment Programme (Dataset 2)

2.6.2.7.2.2 Change in surface water – groundwater flux due to the additional coal resource development

The difference in the surface water – groundwater flux due to the additional coal resource development is simulated for points along the groundwater model stream network shown in Figure 3 in Section 2.6.2.1. The surface water – groundwater fluxes upstream of each surface water model node in Figure 3 in Section 2.6.2.1 are aggregated at the node. The resulting flux time series are inputs to the surface water modelling, as documented in Section 2.6.2.1 and in greater detail in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

Generally, the extraction of water by coal mines causes baseflow to decrease. However, the modelling indicates that mining can also increase baseflow. This is due to hydraulic conductivity enhancement above underground mines and is explained in more detail here.

A simple two-dimensional groundwater model, also run using MOOSE and shown in Figure 25, was developed to illustrate the effect of conductivity enhancement and mine water extraction on baseflow and evapotranspiration. In the model, groundwater is recharged by rainfall and loses water via evapotranspiration at the surface, while the other boundaries are impermeable. A stream at the bottom of the hillslope receives groundwater as baseflow. The position of the watertable prior to mining is shown in Figure 25. It is deeper near the top of the slope, beyond the depth of evapotranspiration, but shallows towards the stream such that at some depth to watertable evapotranspiration becomes important. An underground mine is represented by a zone of conductivity enhancement (shown in red in Figure 25).

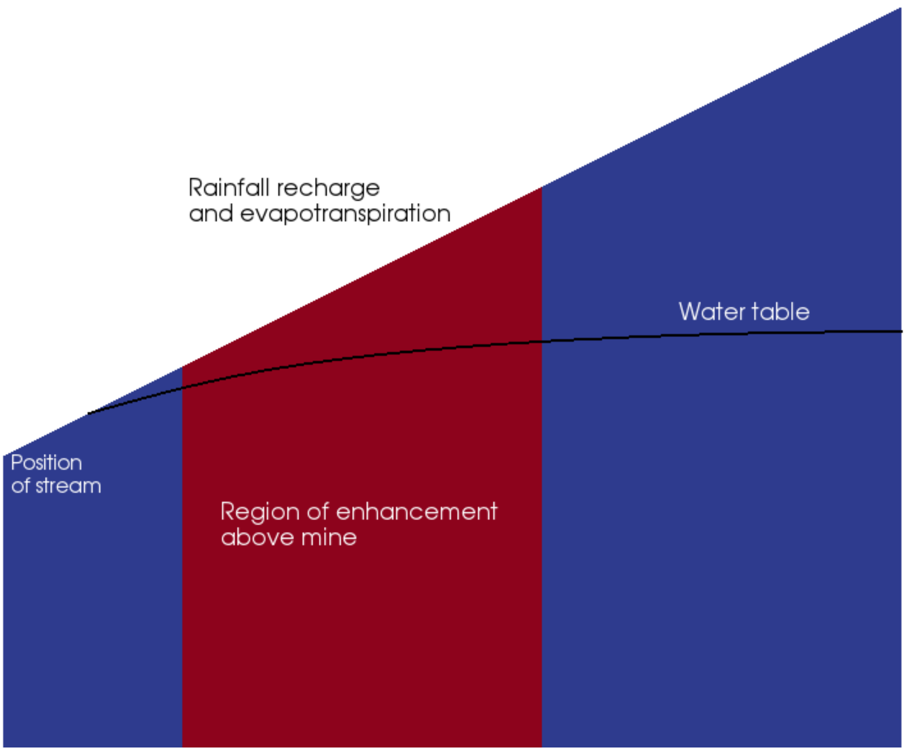

Figure 25 A two-dimensional groundwater model

The model is subjected to groundwater pumping from the mine, assumed to increase linearly from zero to some maximum rate over 50 years (dashed black line in Figure 26). Figure 26 shows the changes in baseflow to the stream over 120 years for a number of different schemes relative to a no-mine-pumping, no-hydraulic-enhancement baseflow (red line):

- Scheme 1: conductivity is enhanced above the entire mine footprint at the commencement of pumping (green line). This is the scheme used in the Hunter subregion groundwater model. It is incorrect on the local scale, as the collapsed zone with higher conductivity only occurs above mined longwall panels, not above unmined sections.
- Scheme 2: there is no conductivity enhancement, only mine pumping (orange line). This is similar to the effect of an open-cut mine.
- Scheme 3: conductivity is enhanced over the entire mine footprint at the commencement of mining, but there is no groundwater pumping (blue line).
- Scheme 4: the conductivity enhancement is phased in over time at a rate equal to the change in groundwater pumping over time by the mine (navy blue line). This is consistent with the expansion of the collapsed zone over time and with pumping rates being dependent on the area impacted by hydraulic enhancement.

In all schemes, the hydraulic conductivity enhancements are assumed to be permanent. In the pumping scenarios, pumping ceases at the cessation of mining (at t = 50 years).

The model does not represent potential changes in recharge from hydraulic enhancement. The physical subsidence of the land surface above longwall panels has not been included in the groundwater modelling, but may affect surface water routing (represented in the surface water modelling), groundwater flow and baseflow. Ponding in the subsided area could alter the local groundwater recharge pattern and have an effect on baseflow to streams.

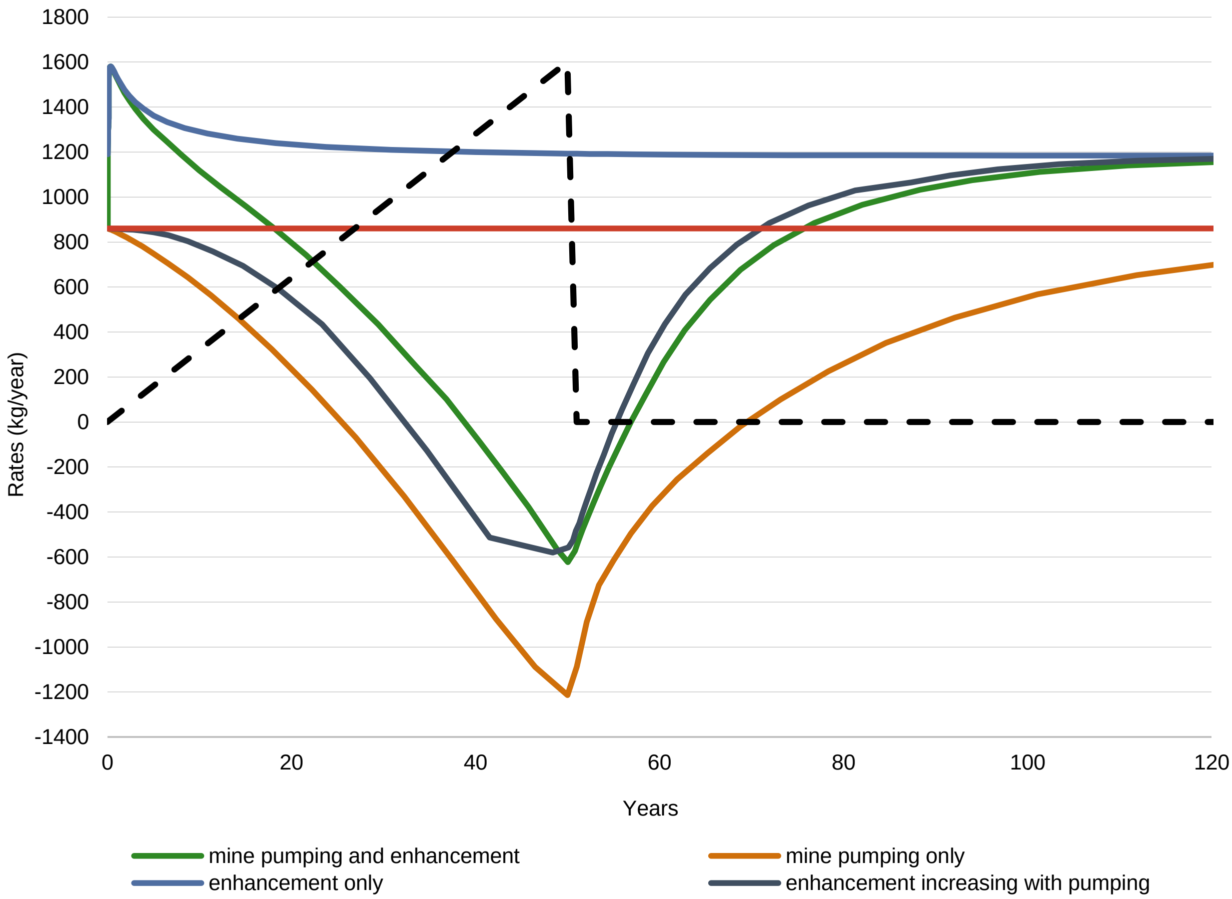

Figure 26 Baseflow for various mine pumping and conductivity enhancement schemes in the two-dimensional groundwater model

Data: Bioregional Assessment Programme (Dataset 3)

Figure 26 shows that when hydraulic enhancement is not represented in the model (scheme 2), pumping will cause baseflow to reduce for the duration of pumping, but will gradually recover once pumping ceases. Figure 26 also shows that when the full effect of hydraulic enhancement is introduced at the commencement of mining (schemes 1 and 3), this results in an initial 'slug' of groundwater to the stream. The hydraulic enhancement causes stored groundwater to flow more rapidly in the direction of the stream, which causes an increase in the pressure head at the interface with the non-hydraulically enhanced area, leading to more baseflow to the stream. As pumping increases (scheme 1), this slug of baseflow is offset by watertable lowering above the mine and the creation of a hydraulic gradient towards the mine, which reduces the flow of groundwater to the stream. In the absence of pumping (scheme 3), the initial slug decays to a new equilibrium baseflow that is greater than the starting baseflow.

When the hydraulic enhancement is phased in as mining progresses (scheme 4), the initial baseflow slug can be offset by the effects of drawdown and there may be minimal impact on baseflow early on.

In schemes 1, 3 and 4, the final baseflow after mining has ceased is higher than the pre-mining baseflow. This is explained by reference to Figure 27, which shows the position of the watertable before mining (in black) and after hydraulic enhancement (in green). Above the mine, the watertable is almost horizontal because the higher conductivity above the mine means the rock is almost like a 'tub' containing water. In the Figure 27 example, much of the area has experienced a lowering of the watertable, which means there is less evapotranspiration from those areas. Since the rainfall recharge is unchanged, net recharge is increased, leading to more baseflow under the new steady state. This increased baseflow might possibly be saline.

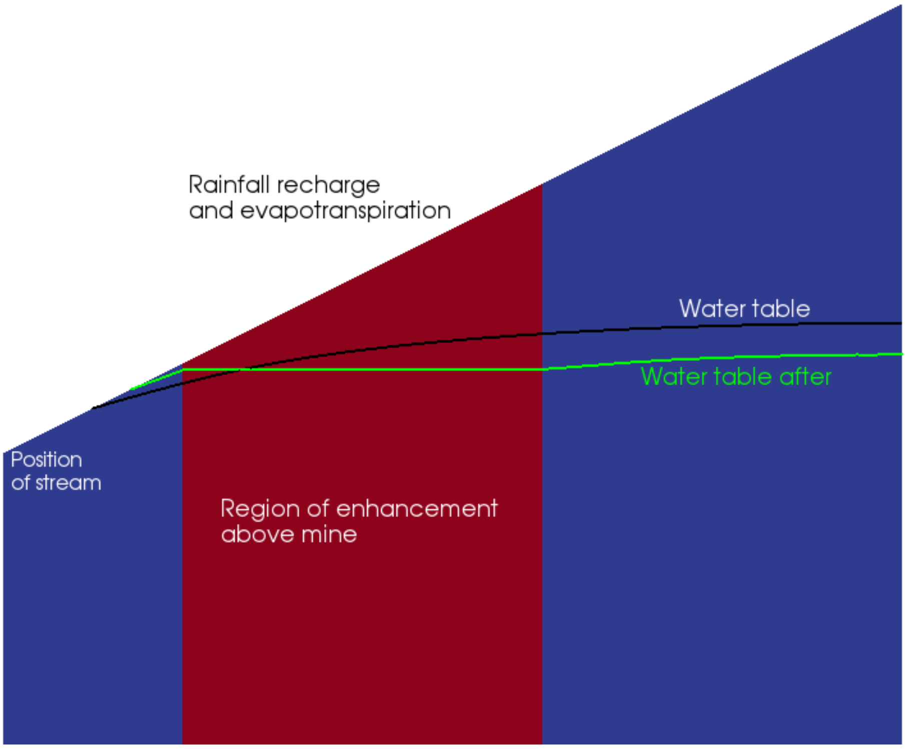

Figure 27 Position of the watertable before and after mining

This simple model illustrates the possibility for increased baseflows following mining. In site-specific, three-dimensional situations with realistic topography and complicated hydrogeology, and with temporal changes in rainfall and evapotranspiration, and with realistic longwall excavation patterns and retreat rates, the situation is much more complex for a stream at the local scale. Any section of any stream could follow any combination of schemes 1, 2, 3 and 4. Moreover, the models do not consider any change to porosity (storage) and water head due to the volumetric expansion of the overburden. These will naturally decrease the initial 'slug' of water, but will play no role in the long-term behaviour of baseflow.

Baseflow itself is difficult to measure, but related effects have been measured by Walker (1988) who conducted a study to assess the impact of longwall mining on shallow groundwater and found that after mining, the groundwater levels in 60% of observation wells equalled or exceeded the pre-mining levels.

In summary, there are three ways that baseflows can increase due to mining:

- In the short term, water stored in the interburden can be released as the groundwater finds a new equilibrium (this is modelled in the Hunter subregion groundwater model).

- When the groundwater's new phreatic surface is deeper than prior to mining, resulting in less evapotranspiration for the same recharge (this is modelled in the Hunter subregion groundwater model).
- In the longer term, when a new equilibrium is established, the enhanced conductivity means that: (i) groundwater moves faster (this is modelled); and (ii) rainfall recharge is potentially higher (this is not modelled).

Various studies undertaken by CSIRO Energy of underground fluid flows coupled with rock deformation caused by longwall mining suggest increases in baseflow due to hydraulic enhancement are unlikely at distances greater than two times the width of the longwall panel from the longwall panel – i.e. it is a local effect.

To deal with the initial slugs in baseflow response that resulted from initiating hydraulic enhancements above longwall mines on day 1 of mining, the surface water – groundwater exchange flux simulations were modified to remove baseflow increases prior to being input into the AWRA-R model (reported in companion product 2.6.1 surface water modelling for the Hunter subregion (Zhang et al., 2018)). This also removed any longer-term baseflow increases resulting from hydraulic enhancement and changes in groundwater level, thus results reported in the surface water modelling represent only the changes caused by decreases in the flux of groundwater to streams, and it is these changes that are carried through to the impact and risk analysis in companion product 3-4 for the Hunter subregion (as listed in Table 2).

2.6.2.7.3 Design of experiment and sensitivity analysis

As outlined in Section 2.6.2.1, the groundwater model is evaluated for a wide range of parameter combinations chosen in a systematic and efficient way that we refer to as the design of experiment (see companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016)). The results of these model runs, the simulated equivalents to the observations described in Section 2.6.2.7.1 and the predictions described in Section 2.6.2.7.2, are used to train statistical emulators, which replace the original model in the uncertainty analysis. Each parameter is sampled across a wide range to ensure sufficient coverage of the parameter space. The design of experiment model runs also allow a comprehensive sensitivity analysis to be undertaken. Such an analysis provides insight into the functioning of the model and aids in identifying which parameters the predictions are most sensitive to and if the observations are able to constrain these parameters.

Table 8 lists the ten parameters that were varied in the sensitivity and uncertainty analysis and how they relate to the hydraulic properties, stresses and boundary conditions of the groundwater model. The 'Section' column provides the section number in this product where the parameter is discussed, while the 'Notes' column provides more detail on the implementation of the parameters. The 'Min' and 'Max' columns provide the range over which the parameter is sampled. Not all the model parameters were carried through to the uncertainty analysis. Rationalising the number of parameters was undertaken to reduce the total number of simulations needed to characterise modelling uncertainty. Where a number of parameters are used to define a process in the model, it is possible to fix some and vary others to obtain a satisfactory characterisation of the range of possible outcomes. The use of multipliers, such as *ne*, *Kh* and *K_ramp*, ensures that all model parameters related to the hydraulic properties in the model are varied systematically during the uncertainty analysis. The unsaturated-flow parameters and the river stage height are not varied in the uncertainty analysis as their effect on predictions is strongly correlated with other included parameters. For example, the effect on predictions of varying river stage height can largely be determined through varying riverbed depth addition. Likewise, changes in unsaturated-flow properties are linked to the saturated-flow properties, which means the uncertainty in the unsaturated-flow properties is reflected in the uncertainty of the saturated-flow properties. The general-head conductance and depth control on evapotranspiration are not included in the uncertainty analysis as initial model runs indicated that these parameters have a very limited effect on predictions. This is explored for evapotranspiration-extinction depth in more detail in Section 2.6.2.8.2.16.

Table 8 Parameters included in the sensitivity and uncertainty analysis

Parameter	Description	Section	Min	Max	Notes
Q_mine	Mine water extraction multiplier	2.6.2.5	0.5	1.5	All groundwater extraction rates by mines are multiplied by this quantity.
C_riv	Riverbed conductance multiplier	2.6.2.4	0.1	10	The riverbed conductance is multiplied by this quantity.
d_riv	Riverbed depth addition (m)	2.6.2.4	–5	5	Depth of the river points defined as: $d = topo - 5m - d\_riv$ The depth of the river points thus varies from 0 to 10 m below topography.
RCH	Rainfall recharge multiplier	2.6.2.4	0.5	1.5	Rainfall recharge is multiplied by this quantity.
ne_lambda	Decay parameter for porosity (*a_p*)	2.6.2.6	0.005	0.015	The baseline porosity is 0.1 for lithologies 1 to 6, and 0.2 for lithology 7. It is multiplied by the multiplier, and the exponential decay is used to find the porosity at a certain depth. However, porosity is constrained to be always greater than 0.0001 to ensure convergence of the numerical model.
ne	Baseline porosity multiplier	2.6.2.6	0.3	3	
K_lambda	Decay parameter for horizontal and vertical conductivity (a_h and a_v)	2.6.2.6	0.01	0.04	The same exponential decay parameter is chosen for horizontal and vertical conductivity. The baseline horizontal conductivity is 0.5 m/day for lithologies 1 to 6, and 1 m/day for lithology 7. The baseline vertical conductivity is 0.05 m/day for lithologies 1 to 6, and 1 m/day for lithology 7. An upper bound of 100 m/day and a lower bound of 10^{-6} m/day is placed on all conductivities. See Section 2.1.3 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018) for a comparison with measured data.
Kh	Horizontal hydraulic conductivity multiplier	2.6.2.6	0.1	10	
KvKh	Ratio *Kv/Kh*	2.6.2.6	0.01	1	
K_ramp	Conductivity enhancement multiplier	2.6.2.5	0.2	1	All parameters, *M*, *m*, *Z* and *z* introduced in Section 2.6.2.5.3 are multiplied by this quantity.

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

Within the available time frame and with the available computational resources, the modelling team was able to evaluate 1500 parameter combinations. Although the coverage of a ten-dimensional parameter space is limited with 1500 simulations, visual inspection of the parameter combinations evaluated showed that there was adequate coverage of all parameters and no bias or gaps in the sampling of the parameter hyperspace.

Section 2.6.2.7.4 describes the development of the emulators with these model results. A part of developing the emulators is verifying that the sampling density is sufficient to train the emulators with an acceptable mismatch between simulated and emulated prediction values. The following sections describe the sensitivity of the observations and predictions to the ten parameters.

2.6.2.7.3.1 Simulated equivalents to observations from the design of experiment

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

Figure 28 shows how the predicted groundwater levels at observation bore GW080967 in November 2005 vary with parameter values. The sensitivity index for each parameter is also shown. The green line indicates the observed groundwater level.

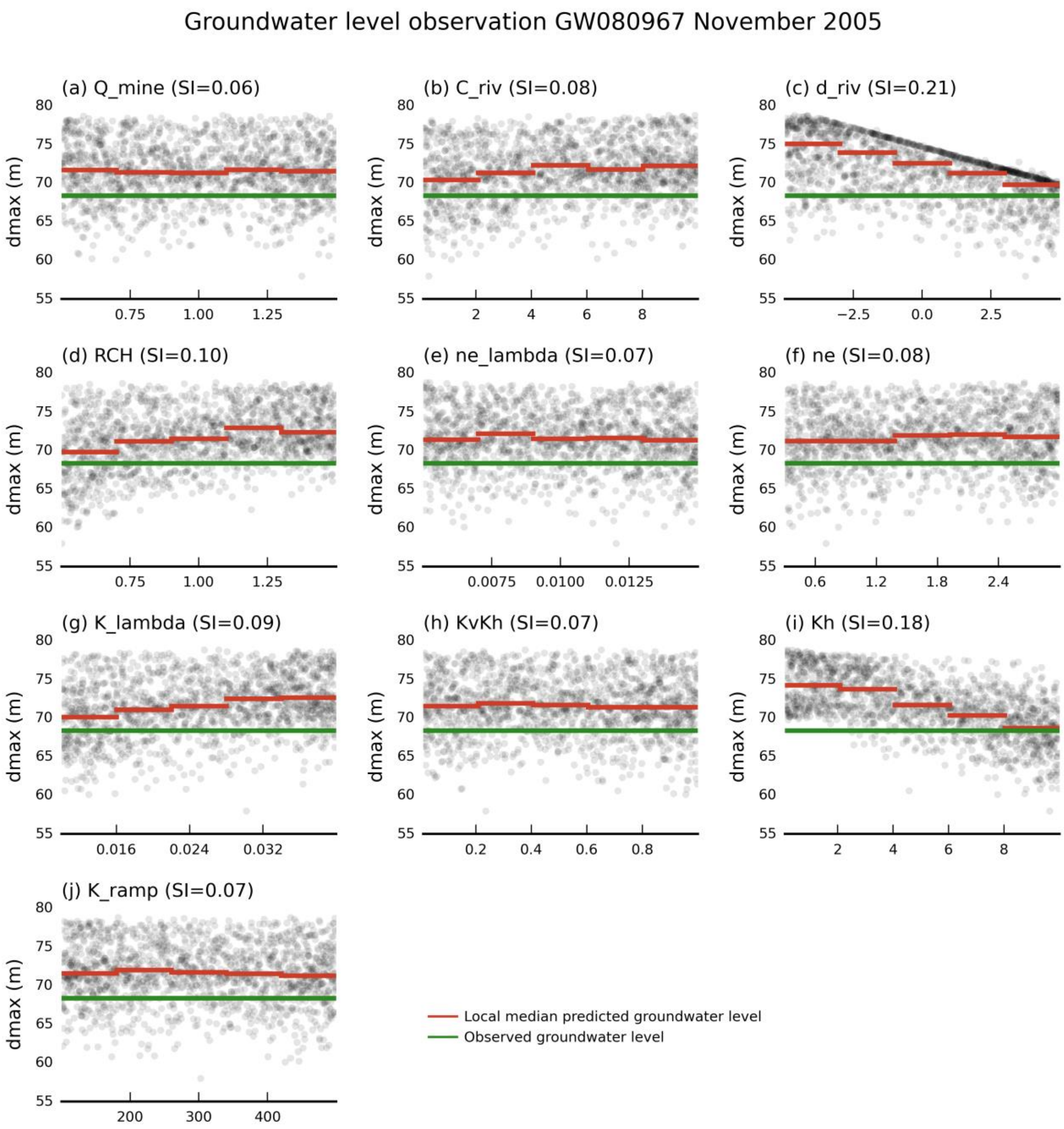

Figure 28 Scatterplots of the parameter values versus the simulated groundwater level at observation location GW080967 in November 2005 for all evaluated design of experiment model runs

For each parameter, the corresponding sensitivity index (SI) is provided in the title. The sensitivity index is a relative metric in which high values indicate sensitive parameters and low values indicate less sensitive parameters. The red line indicates the local median of simulated values over the parameter ranges spanned by the line segment. The green line is the observed groundwater level. dmax = maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development (ACRD)
Data: Bioregional Assessment Programme (Dataset 2)

It is clear that a wide range of parameter values result in predicted groundwater levels matching the observed groundwater level at this location. However, only a few parameters noticeably affect the predicted groundwater levels:

- *d_riv*: the depth of river model nodes below topography where a *d_riv* equates to a depth below topography of 0 m and a *d_riv* of 5 m equals a depth of 10 m below topography

- *Kh*: the horizontal hydraulic conductivity multiplier
- *RCH*: the multiplier for spatially variable recharge
- *K_lambda*: the depth-decay parameter for horizontal and vertical hydraulic conductivity.

The depth below topography of the river model nodes controls the drainage level in the groundwater model and therefore imposes an upper boundary on the simulated groundwater levels, even at this observation location which is more than 15 km from the nearest river model node. For *d_riv* values less than 1 m, however, the parameter no longer controls groundwater levels. The hydraulic properties, *Kh* and *K_lambda*, both have a large influence. Higher hydraulic conductivities (high *Kh* and low *K_lambda*) result in lower simulated groundwater levels. The recharge multiplier, *RCH*, has a secondary effect, in which higher recharge values result in higher groundwater levels.

Figure 29a shows boxplots of the sensitivity indices for all available simulated equivalents to groundwater level observations. The same parameters identified as influential on the groundwater level at observation location GW080967 in November 2005 appear to be important for simulated equivalents at other groundwater level observation sites.

The simulated equivalents to groundwater level observations are not sensitive to *Q_mine, C_riv, ne_lambda, ne* and *K_ramp*. This is not surprising for *Q_mine* and *K_ramp* as they affect the mine pumping rates and hydraulic conductivity enhancement after longwall mine collapse, and will mostly affect future rather than historical simulated groundwater levels. The relative insensitivity of groundwater level predictions to the riverbed conductance (*C_riv*) and porosity (*ne_lambda* and *ne*) does not mean these variables have no effect, rather it indicates the effect of these parameters is small compared to other parameters and is too small to be distinguished based on a design of experiment with 1500 evaluated parameter combinations.

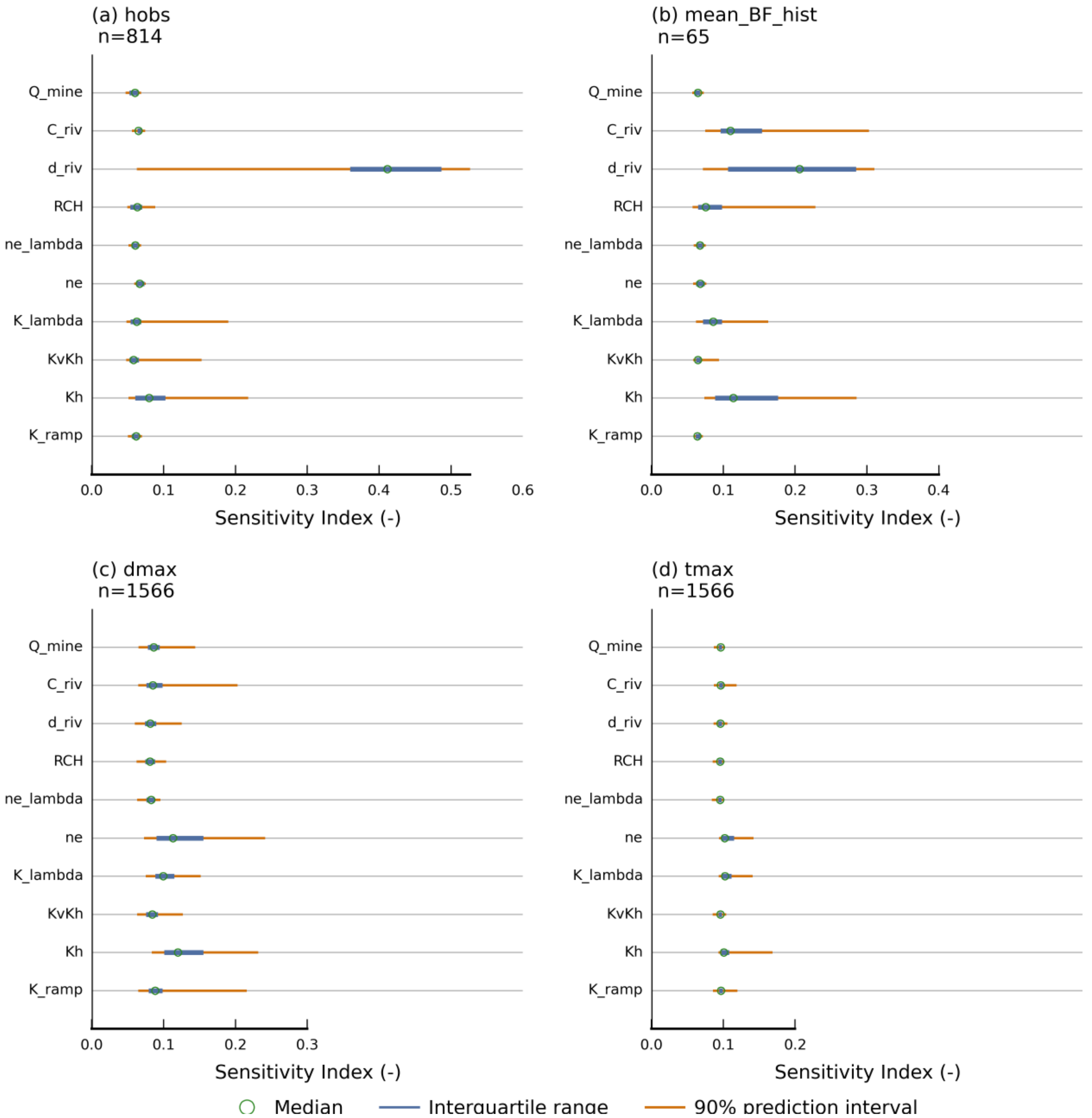

Figure 29 Boxplots of sensitivity indices for (a) all available groundwater level simulated equivalents to observations, (b) average historical simulated baseflow, (c) drawdown (dmax) and (d) year of maximum change (tmax) for all evaluated design of experiment parameter combinations

Data: Bioregional Assessment Programme (Dataset 2)

2.6.2.7.3.2 Simulated historical average surface water – groundwater flux

Figure 30 shows scatterplots of the parameter values versus the simulated average historical surface water – groundwater flux at gauge location 210083 for all of the evaluated design of experiment model runs. By far the most sensitive parameter is the depth of the river model nodes below topography (*d_riv*). The average historical baseflow increases almost linearly until the river model nodes are about 4 m below topography (*d_riv* equal to –1 m). For larger values of *d_riv*, however, the historical average baseflow remains almost constant and baseflow is positive. For positive baseflow values, the simulated baseflow appears to vary linearly with hydraulic properties (*K_lambda* and *Kh*), riverbed conductance (*C_riv*) and recharge (*RCH*). Figure 29b confirms that these parameters are influential for the other gauge locations as well.

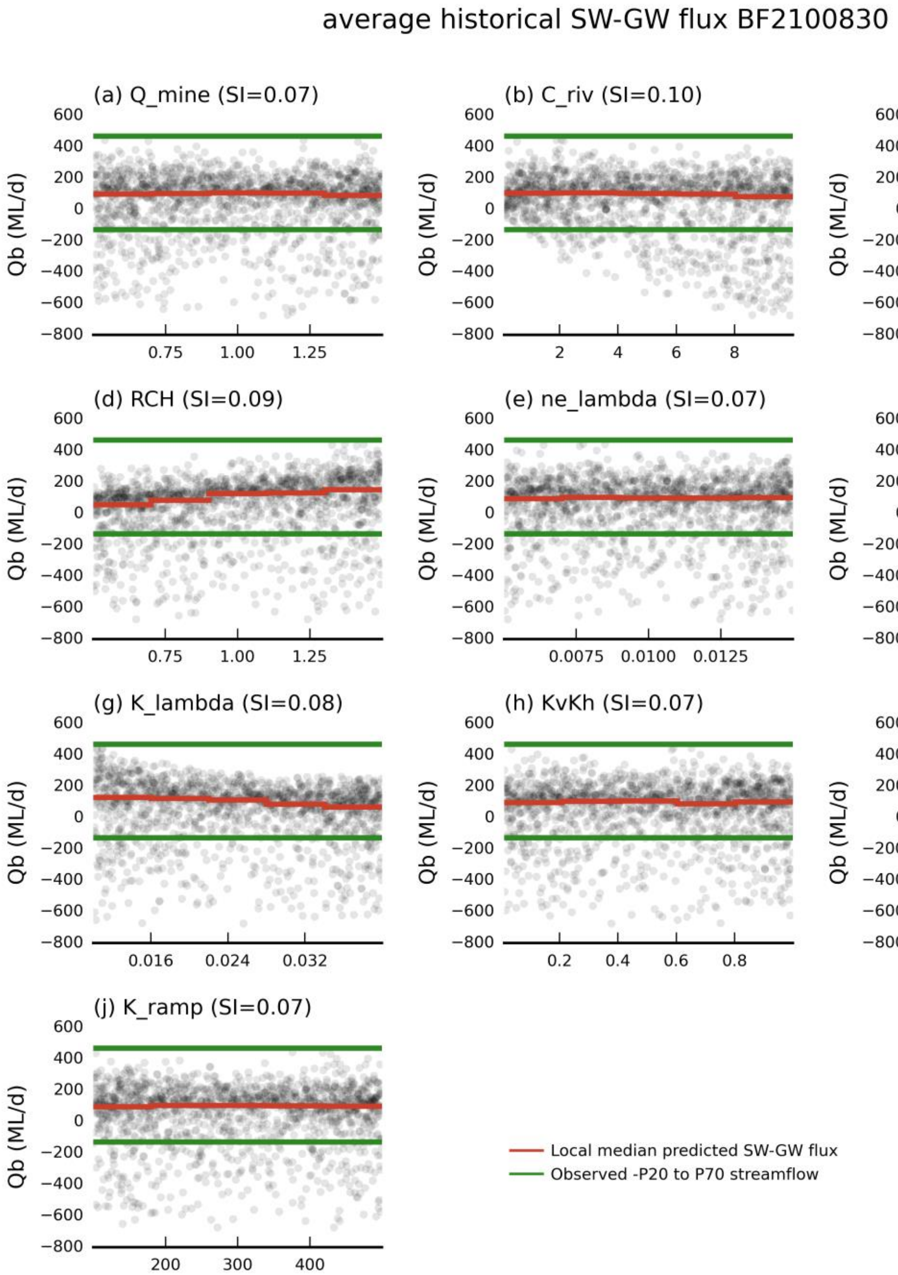

Figure 30 Scatterplots of the parameter values versus the simulated average historical surface water – groundwater flux at gauge location 210083 for all evaluated design of experiment model runs

For each parameter, the corresponding sensitivity index (SI) is provided in the title. The sensitivity index is a relative metric in which high values indicate sensitive parameters and low values indicate less sensitive parameters. The red line indicates the local median of simulated values over the parameter ranges spanned by the line segment. The green lines indicate the observed negative of the 20th percentile and the 70th percentile.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.2.7.3.3 Drawdown predictions (dmax) and year of maximum change (tmax)

Figure 31 shows scatterplots of the parameter values versus predicted maximum drawdown at model node probe_66 for all evaluated design of experiment model runs. The dominant parameter is *Q_mine*, the multiplier on the mine pumping rates. Increasing pumping rates lead to increases in drawdown. The hydraulic properties *Kh* and *K_lambda* are the next most important parameters. An increase in hydraulic conductivity (*Kh* increases and *K_lambda* decreases) leads to decreases in maximum drawdown. The *K_ramp* parameter, the enhancement of hydraulic conductivity after longwall mine collapse, shows a non-linear response, with the *dmax* values most sensitive for *K_ramp* values less than 200 m. The porosity parameters, *ne* and *ne_lambda*, have a small effect on the predicted drawdown, where increased porosity leads to smaller predicted drawdowns.

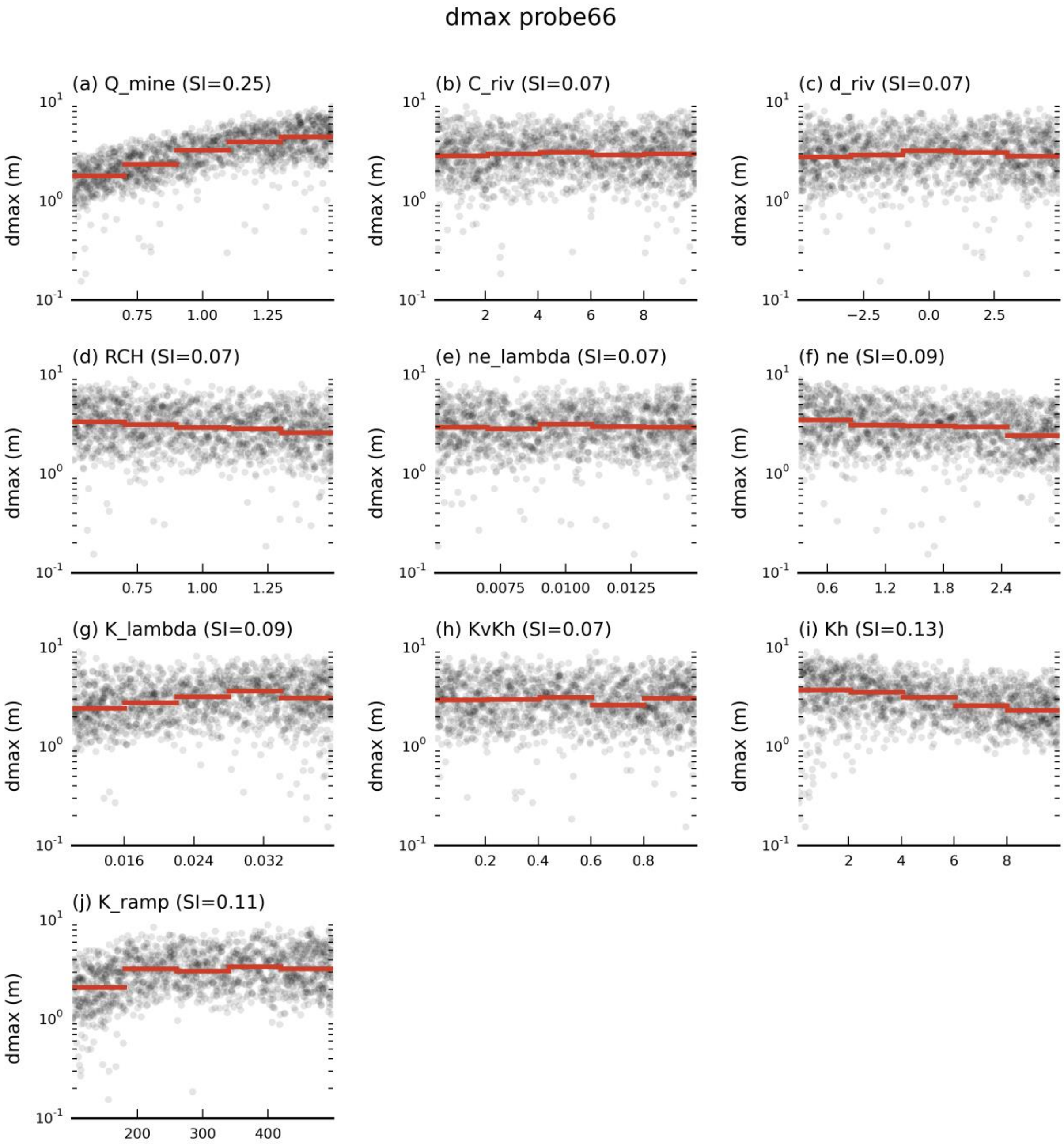

Figure 31 Scatterplots of the parameter values versus the predicted drawdown (*dmax*) at model node probe_66 for all evaluated design of experiment model runs

For each parameter, the corresponding sensitivity index (SI) is provided in the title. The sensitivity index is a relative metric in which high values indicate sensitive parameters and low values indicate less sensitive parameters. The red line indicates the local median of simulated values over the parameter ranges spanned by the line segment.
Data: Bioregional Assessment Programme (Dataset 2)

Figure 29c confirms these trends at the other model nodes, but provides a more nuanced understanding of the model behaviour. The two most important parameters across all model nodes are *Kh* and *ne*, followed by *C_riv*, *K_ramp* and *Q_mine*. The wide ranges in sensitivity index for some parameters reflect spatial variability in parameter sensitivity. For example, model nodes close to the river network are more sensitive to the riverbed conductance *C_riv* than model nodes away from the river network.

Figure 29d shows the sensitivity indices for the year of maximum change. Although the ranges of the sensitivity indices for *ne*, *Kh* and *K_lambda* are larger than for other parameters, there is no parameter that clearly dominates the year of maximum change. This indicates a large random component in this prediction as illustrated in Figure 24b and Figure 24d. A small change in either time series will have a negligible effect on the predicted drawdown, but can potentially drastically shift the year of maximum change.

2.6.2.7.4 Emulators

The purpose of a statistical emulator is to provide a computationally efficient surrogate for a computationally expensive model. These emulators provide a way to quantify the predictive distribution for a prediction of interest, given a new set of parameters for which the model was not run. Thus regional-scale model estimates can be updated at a site with information that better reflects local-scale conceptual models of the geology and hydrogeology. The predictions of interest are the groundwater hydrological response variables, *dmax* and *tmax.* Changes in the surface water – groundwater flux are incorporated into the streamflow modelling as changes in baseflow and inform the surface water hydrological response variables, reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

As outlined in the uncertainty analysis workflow (Figure 5 in Section 2.6.2.1), an emulator is created for each objective function (see Section 2.6.2.8.1) and for each prediction of drawdown due to additional coal resource development and year of maximum change. The objective function emulators are used in the Markov chain Monte Carlo sampling of the prior parameter distribution to create a posterior parameter distribution for each prediction. These posterior parameter distributions are subsequently sampled with the emulator for that prediction to produce the predictive distribution of drawdown and year of maximum change due to additional coal resource development at each model node.

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

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

- design of experiment parameter combinations
- design of experiment model output

- transform of parameters
- transform of output.

The set of 1500 parameter combinations that were evaluated and their corresponding model results are used to train the individual emulators for each prediction.

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

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

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

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

The accuracy of the emulator, the degree to which the emulator can reproduce the relationship between the parameters and the prediction, depends greatly on the density of sampling of parameter space. This section examines whether the set of 1500 evaluated parameter combinations provides sufficient information to train ten-dimensional emulators. As it is beyond the scope of this product to examine this for all the emulators created, the suitability of the number of parameter combinations is illustrated using the fraction of gauges for which the average historical baseflow is between the negative 20th percentile and the 70th percentile of observed total streamflow. Emulating this quantity is especially challenging as this fraction is a non-linear function of several interacting parameters.

Figure 32 shows the correspondence between the modelled and emulated fraction of the baseflow objective function (see Section 2.6.2.8.1) using an emulator trained with 100, 500, 1000 and 1500 samples. The performance is poor for emulators trained with 100, 500 and 1000 samples; however, the performance is adequate for the emulator trained with 1500 samples.

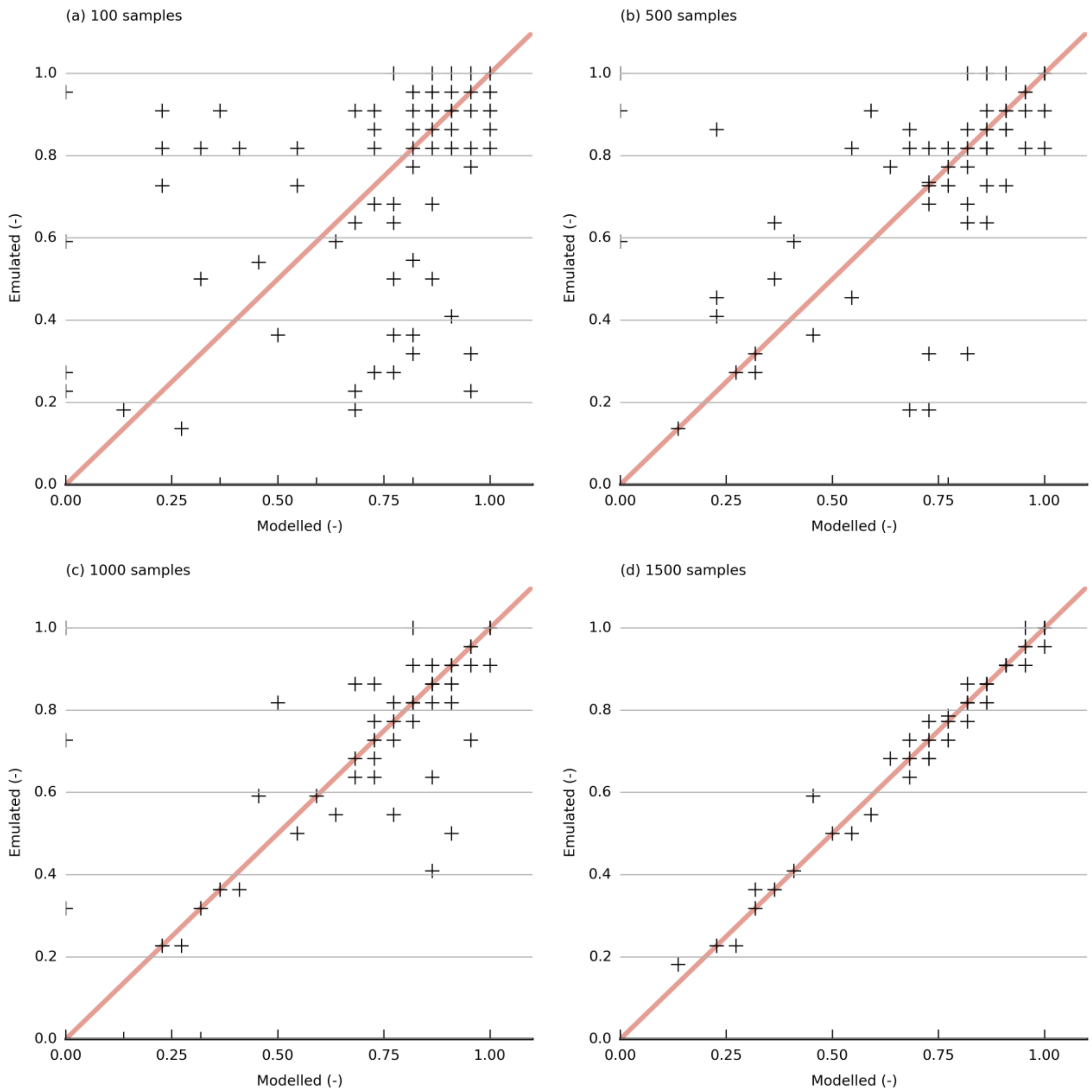

Figure 32 Scatterplots of modelled versus emulated values of the fraction of gauges for which the average historical baseflow is between the negative 20th percentile and the 70th percentile of observed total streamflow for emulators trained with different training set sizes

Data: Bioregional Assessment Programme (Dataset 2)

Figure 33 shows this evolution in a more quantitative way by visualising the mean absolute error between modelled and emulated values produced by emulators trained with training sets that vary from 100 to 1500 in increments of 100. This fraction is used as an objective function in the uncertainty analysis (see Section 2.6.2.8.1) in which parameter combinations are accepted if the fraction is in excess of 0.9. The mean absolute error of an emulator trained with 1500 samples is 1%. By using an emulator with this accuracy in the Markov chain Monte Carlo sampling, the risk of wrongly accepting or rejecting a parameter combination is very small. Emulators with this level of accuracy also provide confidence that predictions obtained with the emulators are very close to predictions generated with the original model.

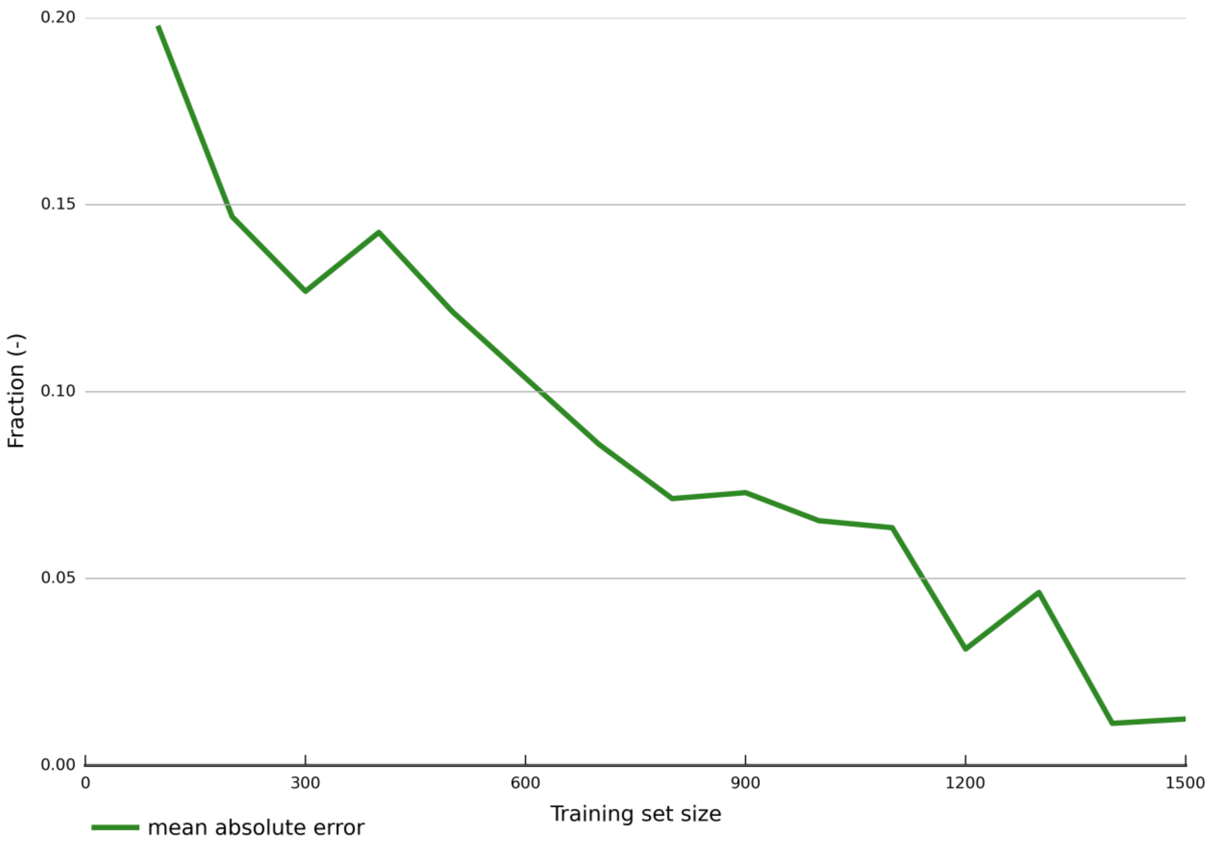

Figure 33 Convergence of mean absolute error between modelled and emulated values of the fraction of gauges for which the average historical baseflow is between the negative 20th percentile and the 70th percentile of observed total streamflow

Data: Bioregional Assessment Programme (Dataset 2)

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Dataset 3 Bioregional Assessment Programme (2017) HUN GW Model baseflow increase v01. Bioregional Assessment Source Dataset. Viewed 10 January 2017, http://data.bioregionalassessments.gov.au/dataset/3fd4ec6c-f49f-4ad3-b718-379932d63617.

2.6.2.8 Uncertainty analysis

Summary

The uncertainty analysis is consistent with the approach described in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016). The same ten parameters investigated in the sensitivity analysis are considered in the uncertainty analysis of the groundwater model for the Hunter subregion.

Prior distributions for each parameter assume a uniform distribution, with no covariance of parameters. Groundwater level observations from a limited set of observation sites and observed streamflow data are used to constrain the parameter space. Parameter sets for groundwater levels are considered acceptable when they result in average groundwater level predictions that are within 10 m of observed historical averages at observation sites within 15 km of the prediction site. Results indicate that at many sites groundwater level predictions are not very sensitive to model parameters and provide little constraint on the prior distributions. In some areas, no parameter combinations were able to predict groundwater level observations. This most likely is due to local-scale factors not included in the regional modelling.

Acceptable parameter sets for modelled surface water – groundwater fluxes are those in which the average of the simulated historical surface water – groundwater flux is between the negative 20th percentile and 70th percentile of observed streamflow.

A number of parameters are constrained by the observation data: depth of riverbed, recharge, ratio of vertical to horizontal hydraulic conductivity, horizontal hydraulic conductivity and *K_lambda*. The other parameter values could not be constrained.

The posterior parameter sets must pass the acceptance thresholds defined for groundwater level and surface water – groundwater flux, except where the objective function for groundwater levels is less than 0.1 and only the latter acceptance threshold is required. Markov chain Monte Carlo sampling is repeated until 10,000 acceptable parameter sets are obtained to characterise the uncertainty of predictions of drawdown – maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development (*dmax*) and year of maximum change (*tmax*).

More than three-quarters of the output locations have *dmax* less than 2 m; two-thirds have *dmax* less than 0.2 m. Additional drawdown is localised around the additional coal resource development mines. At a distance of about 20 km from the mine sites, there is only about a 5% probability of the *dmax* exceeding 0.2 m. In general, the *tmax* occurs relatively quickly in the immediate vicinity of the mines, but progressively later with increasing distance from the mines.

Local geological and hydrogeological information from the proposed Wallarah 2 mining area is used to demonstrate how the results from the regional parameter set can constrained to better represent the local situation. The use of local information reduces the extent of the predicted drawdown in the Wyong River catchment relative to the regional result set.

As in any modelling exercise, a number of assumptions and model choices have had to be made. A formal and systematic discussion of the rationale behind these assumptions in terms of data and resource availability and technical constraints as well as the perceived effect on the predictions highlighted that the largest sources of uncertainty in the predictions are the assigned mine pumping rates and the parameterisation of hydraulic properties. The latter issue is confounded as the available regional observation data set has limited potential to constrain the parameters the predictions are most sensitive to.

2.6.2.8.1 Factors included in formal uncertainty analysis

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

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

The prior parameter distributions are constrained by observations with the ABC methodology to generate posterior parameter distributions. The posterior parameter distributions are then used to generate the final set of predictions from which the uncertainty of drawdown due to additional coal resource development (i.e. maximum difference in drawdown between the CRDP and baseline) (*dmax*) and year of maximum change (*tmax*) predictions can be characterised. The process of constraining the prior parameter distributions by observations is described and discussed in Section 2.6.2.8.1.2, while the resulting posterior predictive distributions are detailed in Section 2.6.2.8.1.3.

The uncertainty analysis is focused on predictions of *dmax* and *tmax* due to the additional coal resource development. The surface water – groundwater fluxes generated along the river network within the groundwater model domain are inputs to the Hunter river model (see companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)) and included in the characterisation of uncertainty of streamflow predictions in that product. Results from the groundwater modelling are summarised as a water balance across the entire modelling domain in companion product 2.5 for the Hunter subregion (Herron et al., 2018a).

2.6.2.8.1.1 Prior parameter distributions

The model parameters in the sensitivity and uncertainty analysis are not varied directly, but rather through a set of offsets, multipliers or coefficients of depth-dependent relationships. The initial values of the model parameters and the ranges of the offsets, multipliers and coefficients listed in

Table 8 are based on information available about the groundwater systems, summarised in companion product 2.1-2.2 (Herron et al., 2018b) and companion product 2.3 (Dawes et al., 2018) for the Hunter subregion. The ranges of parameter values reflect the uncertainty in characterising the system due to spatial variability and incomplete knowledge of the system.

The information available was not deemed sufficient to justify any other distribution than a uniform distribution. The prior parameter distributions of the parameters listed in Table 8 are all uniform distributions with ranges corresponding to the minimum and maximum values given in the table. No covariance between parameters is specified as insufficient information is available to specify such covariance. Assuming no correlation between parameters is a conservative assumption as it will result in wider predictive intervals.

2.6.2.8.1.2 Posterior parameter distributions

The posterior parameter distributions are obtained through a Markov chain Monte Carlo sampling of the prior parameter distributions with a rejection sampler based on the ABC methodology. The rejection sampler only accepts a parameter combination, randomly drawn from the prior parameter distribution, if a model run with these parameters satisfies a predefined objective function threshold. The objective functions for the groundwater model summarise its performance in predicting groundwater levels and baseflow rates against observations of groundwater levels and baseflows estimated from streamflow observations. An example of an objective function is the mean absolute difference between observed and simulated groundwater levels. The ABC methodology requires not only definition of an objective function, but also the threshold value above which the parameter set is deemed to be acceptable. Ideally, this threshold is based on an independent estimate of the observation error.

For the Hunter subregion two types of such observations are available to constrain the parameters for the predictions (see Section 2.6.2.7.1):

- groundwater level observations
- observations of total streamflow.

The sensitivity analysis (Section 2.6.2.7.3) showed that both groundwater level predictions and surface water – groundwater flux are dominated by the drainage level assigned to the river model nodes (*d_riv*), while predictions of *dmax* due to the additional coal resource development are mostly sensitive to mine pumping rates and the hydraulic properties, and not to *d_riv*. The sensitivity analysis also showed considerable variation in the sensitivity indices, reflecting spatial variability in both the observations and model predictions.

To accommodate this, the model parameters for the predictions of *dmax* and *tmax* at each model node are constrained individually using an objective function (OF) that consists of two components: (i) a spatially weighted sum of the residuals between observed and simulated groundwater levels, and (ii) a baseflow constraint based on historical streamflow data, defined as:

$$OF_{BF} = \frac{1}{n_{gauge}} \sum_{i=1}^{n_{gauge}} f(Q_{b,i}) \quad \begin{cases} f(Q_{b,i}) = 0 \text{ if } -Q_{P20,i} \nless Q_{b,i} \nless Q_{P70,i} \\ f(Q_{b,i}) = 1 \text{ if } -Q_{P20,i} < Q_{b,i} < Q_{P70,i} \end{cases} \qquad (14)$$

In this equation, $Q_{b,i}$ is the average historical simulated surface water – groundwater flux at gauge i, n_{gauge} is the number of gauges with observations of total streamflow, and $Q_{P20,i}$ and $Q_{P70,i}$ are the 20th and 70th percentile of observed streamflow over the historical record at gauge i respectively. Any parameter combination that results in an OF_{BF} value of less than 0.9 is deemed unrealistic and excluded from the posterior parameter distribution. In other words, only parameter sets which simulate an average historical surface water – groundwater flux between the negative of the 20th percentile of observed streamflow and the 70th percentile of observed streamflow at 90% of the gauges are retained.

River systems in the Hunter subregion are predominantly gaining (see companion product 2.1-2.2 (Herron et al., 2018b) and companion product 2.3 (Dawes et al., 2018) for the Hunter subregion). However, estimates of the groundwater contribution to total streamflow vary widely and are influenced by the estimation method (e.g. digital baseflow separation, salt balance, environmental tracers). Unless the uncertainty in the estimated surface water – groundwater flux can be characterised robustly and independently, the adoption of a very precise objective function based on the mismatch between the observed and simulated surface water – groundwater fluxes is not justified (Kavetski et al., 2006). Here, a less stringent objective function has been defined to eliminate unrealistic parameter combinations. Based on estimates of baseflow for Hunter subregion streams (see companion product 1.1 (McVicar et al., 2015) and companion product 2.3 (Dawes et al., 2018) for the Hunter subregion), it is considered unlikely that the long-term average groundwater contribution to total streamflow is more than the 70th percentile of the streamflow hydrograph. High percentiles generally correspond to high flows dominated by direct runoff from rainfall. While the system is described as predominantly gaining, some reaches are ephemeral and will at times be losing streamflow. It is unlikely that the average loss from surface water to groundwater averaged over the historical period (1983 to 2012) would exceed the 20th percentile of total streamflow for that period. Streamflow losses greater than this are inconsistent with the magnitude of river losses from the regulated river system.

The first component of the objective function consists of a distance-weighted sum of the residuals between observed and simulated groundwater levels. Thus, an observation close to a prediction location has greater potential to constrain that prediction than an observation further away. The objective function takes this into account by weighting the difference between observed and simulated values of groundwater level based on the distance between the prediction location and the observation and the distance of the observation point to the nearest blue line network – that is, the mapped major river network. The additional criterion for predictions of change in groundwater level in layer 1 is therefore defined as:

$$O_j = \sum_{i=1}^{k} \frac{r_i}{n_i} \left(1 - \tanh\left(\frac{d_i}{w}\right)\right) \left(h_{o,i} - h_{s,i}\right)^2 \qquad (15)$$

where O_j is the criterion for prediction *j*, $h_{o,i}$ is the *i*th observed groundwater level and $h_{s,i}$ is the simulated equivalent to this observation. r_i is the distance (in km) of observation i to the nearest blue line network while d_i is the distance (in km) between observation i and prediction j. Coefficient w controls the distance at which the weight of observation i drops to zero. To account for transient observations, the weights are divided by n_i, the number of observations at the observation location. The tanh function allows the weight of an observation to decrease almost linearly with distance and to gradually become zero at a distance of approximately $3w$. This is illustrated in Figure 34 for different values of w.

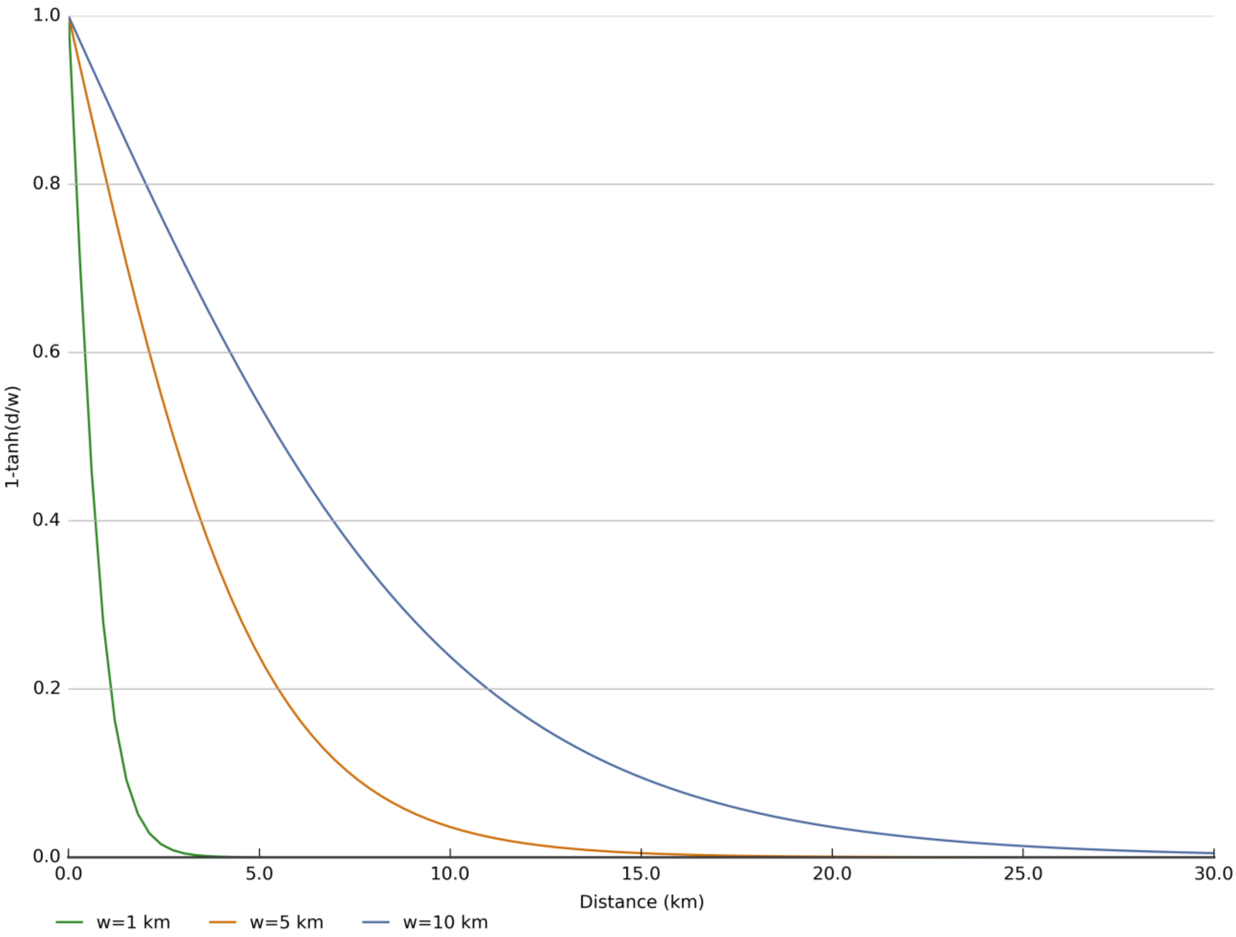

Figure 34 Weights of observations in objective function of the distance between observation and prediction for different values of *w*

d = distance between observation and prediction (km); w = shortest distance between observation location and blue line network (km)
Data: Bioregional Assessment Programme (Dataset 1)

Ideally, the distance weighting function is chosen based on a spatial analysis of the available groundwater level observations. The sparsity of observations, especially transient observations, did not allow such an analysis. In the uncertainty analysis of the groundwater model for the Hunter subregion the value of w is set equal to 5 km, which means that an observation has a weight of zero if the distance between the prediction and the observation is more than 15 km (a pragmatic choice by the project team).

The threshold T_j for each prediction is defined as:

$$T_j = \sum_{i=1}^{k} \frac{r_i}{n_i}\left(1 - \tanh\left(\frac{d_i}{w}\right)\right)(10)^2 \qquad (16)$$

This means any parameter combination that results in an average difference between observed and simulated groundwater level equal to or less than 10 m is deemed acceptable. In a traditional calibration this corresponds to a normalised root mean squared error of 2% for groundwater level observations that span a range of about 500 m (Bioregional Assessment Programme, Dataset 1). In other words, each parameter combination that is accepted in the Monte Carlo analysis, will lead to a groundwater model with a normalised root mean squared error of no more than 2%.

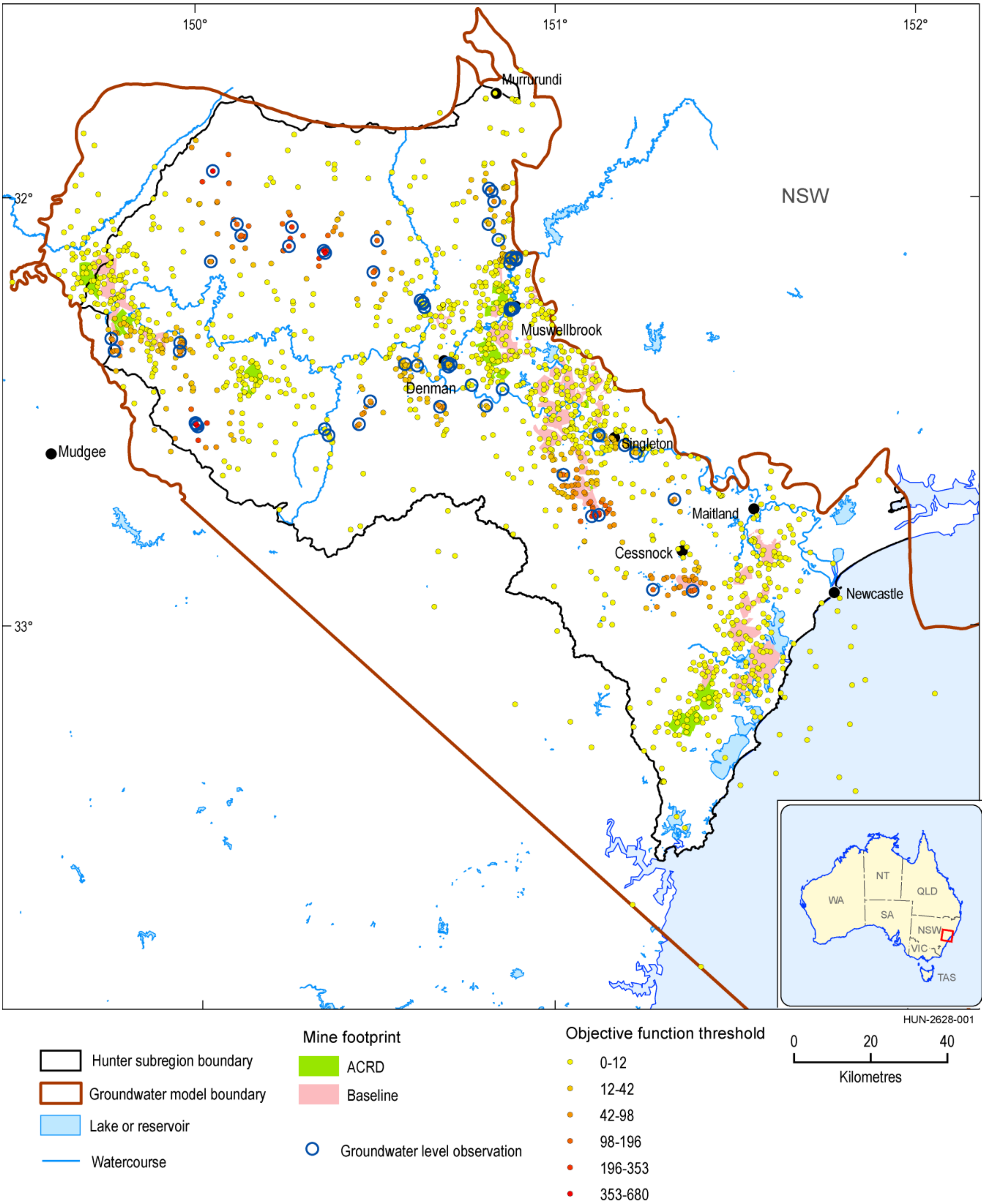

Figure 35 Groundwater level objective function threshold

Data: Bioregional Assessment Programme (Dataset 1)

Figure 35 shows the acceptance threshold for the groundwater level objective function for each model node. The value of the threshold is not that important: high values indicate a prediction is within the zone of influence of one or more observations, and this means the parameter distribution used for that prediction can potentially be constrained by groundwater level observations; low values indicate predictions far removed from any observation, which therefore have a low potential to be constrained.

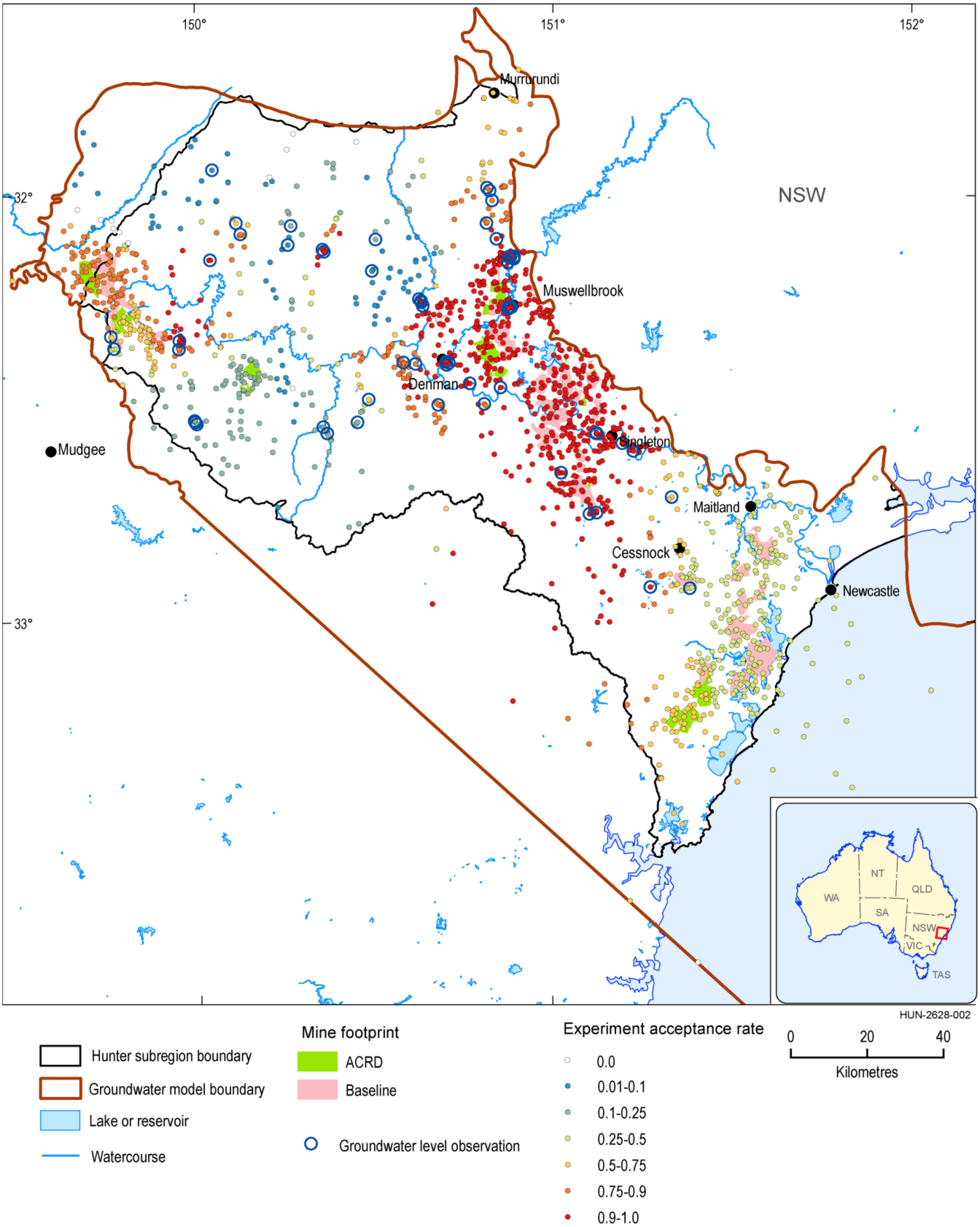

Figure 36 Fraction of parameter combinations evaluated in the design of experiment that meet the acceptance threshold

Data: Bioregional Assessment Programme (Dataset 1)

Figure 36 shows the fraction of evaluated parameter combinations of the design of experiment that meets the groundwater level acceptance criterion. Values in excess of 0.9 indicate that most parameter combinations evaluated in the design of experiment produce groundwater level predictions that agree with the observations in that region (within the specified acceptable range). In other words, the simulated groundwater levels in these regions are not very sensitive to the parameter values. In the groundwater model for the Hunter subregion, the high acceptance rates along the Hunter River alluvium are probably caused by proximity to surface water boundaries. Simulated groundwater levels close to the model domain's river network are affected by the river boundary conditions, rather than the parameter values.

Very low acceptance rates indicate that only a limited number of parameter combinations produce simulated groundwater levels that correspond to observed values at the observation locations. As parameter bounds in the design of experiment are deliberately chosen to be wide, low acceptance values indicate localised shortcomings of the conceptual model – that is, either it is not possible to get an acceptable correspondence between observed and simulated values, or some of the observations are not representative of the regional groundwater flow system. In some extreme cases, the acceptance rate is equal to zero, which occurs in the north of the subregion and east of Mudgee. The latter are predictions within overlapping zones of influence of two observation locations for which the simulated values cannot simultaneously agree with both observed groundwater levels. Although this can relate to shortcomings of the spatially uniform parameter multipliers within a layer, it is also likely due to the boundary conditions, the local conceptualisation, or even artefacts or errors in the observation database.

Figure 36 can be used as a proxy for the conceptual model uncertainty of the groundwater model. Very high acceptance rates indicate insensitivity to parameter values, although the groundwater level predictions broadly agree with observations. Low values, on the other hand, indicate regions where the groundwater model is unlikely to make acceptable groundwater level predictions and the conceptualisation is locally inadequate. Although the extent and shape of these regions is determined by the weighting function, the presence of these zones indicates that for some sets of observations the model is not able to simultaneously match the observations within the prescribed error threshold. A detailed forensic examination of both the observation database and the groundwater model to attribute the mismatch to either observation uncertainty or conceptual model issues has not been carried out.

In the Markov chain Monte Carlo sampling, random parameter combinations are selected from the uniform prior parameter combinations. These parameter combinations are evaluated with the emulator for the objective function for groundwater levels for that prediction location and with the emulator for the surface water – groundwater flux objective function. Only if a parameter combination yields objective function values that meet both thresholds is the parameter combination accepted in the posterior parameter combination for this prediction of *dmax* and *tmax*. For predictions where the acceptance rate of the groundwater level observation objective function of the design of experiment parameter values is less than 0.1, the objective function for groundwater levels is not used. As explained earlier, low acceptance rates can be an indication of conceptual model issues or observation error. If only a small fraction of parameter combinations leads to acceptable groundwater levels, it is likely that the observation is over-fitted and the uncertainty under estimated. By using only the baseflow objective function to constrain parameter sets for predictions with a groundwater level acceptance rate of less than 0.1, over-fitting and underestimating uncertainty are avoided.

The Markov chain Monte Carlo sampling is repeated until 10,000 samples are accepted in the posterior parameter combinations. This number was chosen to be as large as was computationally possible within the time frame of the project. Verification that 10,000 samples is sufficient to obtain robust estimates of the 5th, 50th and 95th percentiles of *dmax* and *tmax* is provided in the next section.

The histograms in Figure 37 show the 5th, 50th and 95th percentiles of the 1566 posterior parameter combinations (one for each prediction). Parameters are uniformly sampled so those not constrained by the observations will have the 5th and 95th percentiles close to the minimum and maximum of the prior distribution, while the 50th percentile will be close to the centre of the distribution. The posterior distributions for parameters *Q_mine*, *C_riv*, *ne_lambda*, *ne* and *K_ramp* are very similar to their prior distributions and are therefore not constrained by the observations. The posterior distributions of *d_riv*, *RCH*, *K_lambda*, *KvKh* and *Kh* differ from their priors. The general trends are for the depth of riverbed below topography to be deeper (*d_riv* more positive), recharge to be higher and the hydraulic conductivity to be lower (higher *K_lambda* and lower *Kh*) and more isotropic (higher *KvKh*).

Figure 38 shows the spatial distribution of the median of the posterior parameter distributions from which a number of spatial patterns emerge:

- the south-east region, close to Newcastle, trends to higher recharge and lower *Kh*, indicating groundwater levels are under estimated
- the south-west region indicates lower recharge and higher *Kh*, indicating groundwater levels are over estimated
- clusters of higher or lower *d_riv* indicate localised underestimation or overestimation of groundwater levels.

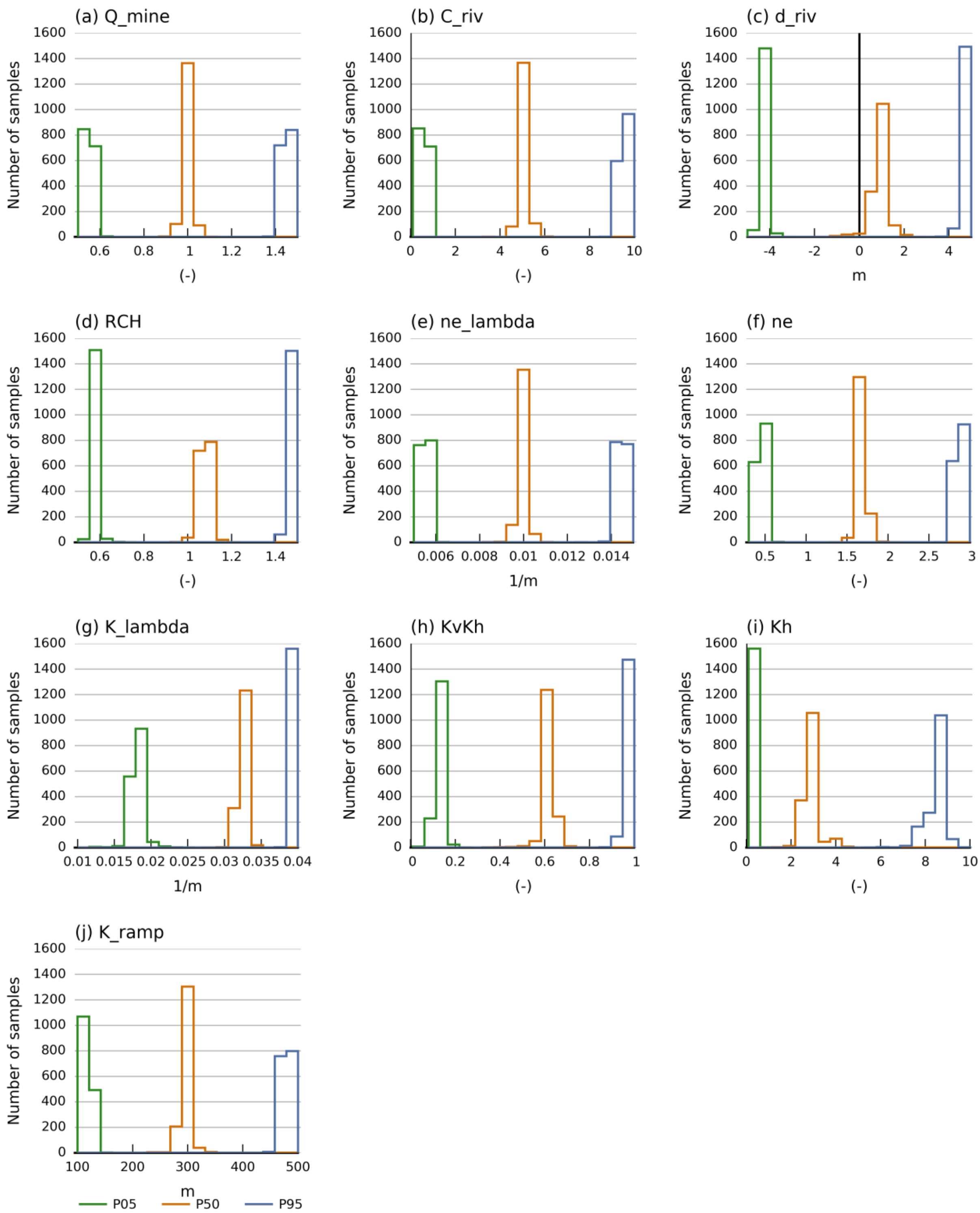

Figure 37 Histograms of the 5th, 50th and 95th percentile of posterior parameter combinations

The prior distributions for each parameter are uniform. A posterior parameter distribution that is not constrained by the available observations (such as *C_riv*) will have the 5th percentile close to the minimum of the parameter range, the 50th percentile close to the middle and the 95th percentile close to the maximum. Posterior parameter distributions of parameters that are constrained by the available observations will deviate from that, as for example shown for *Kh*.
Data: Bioregional Assessment Programme (Dataset 1)

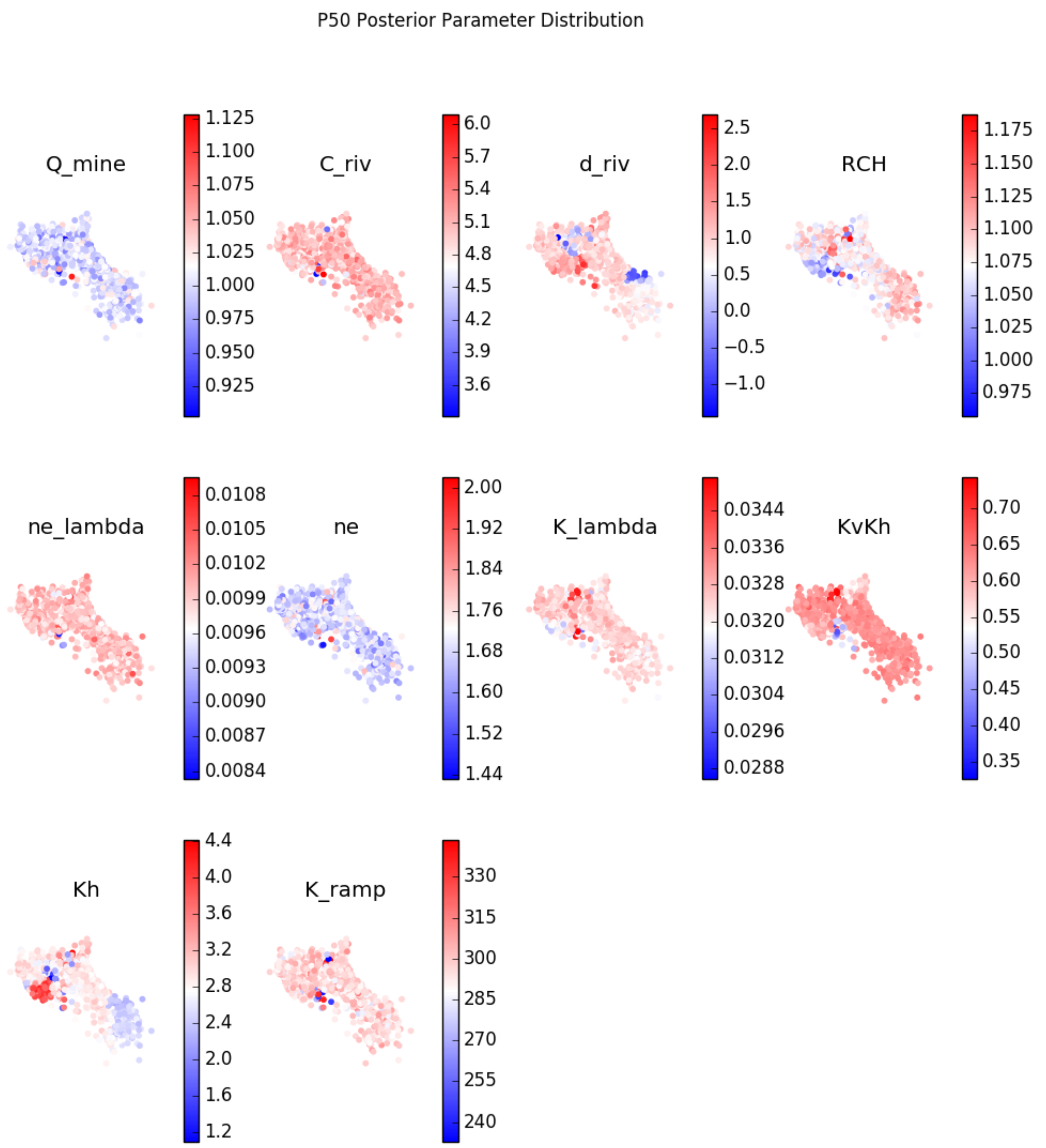

Figure 38 Spatial distribution of the median of the posterior parameter distributions

Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.8.1.3 Predictions

At each of the 1566 model nodes, an emulator is trained to predict *dmax* and *tmax* using the 1500 evaluated parameter combinations during the design of experiment. Each of the 10,000 parameter combinations in the posterior parameter distribution for each prediction is evaluated with the corresponding emulator to produce 10,000 predictions of *dmax* and *tmax*. Results are summarised using the 5th, 50th and 95th percentiles. Figure 39 shows how the 95th percentile of *dmax* evolves with increasing sample size for two prediction locations, probe66 and GW044912. At both locations the 95th percentile of *dmax* stabilises after about 6,000 samples.

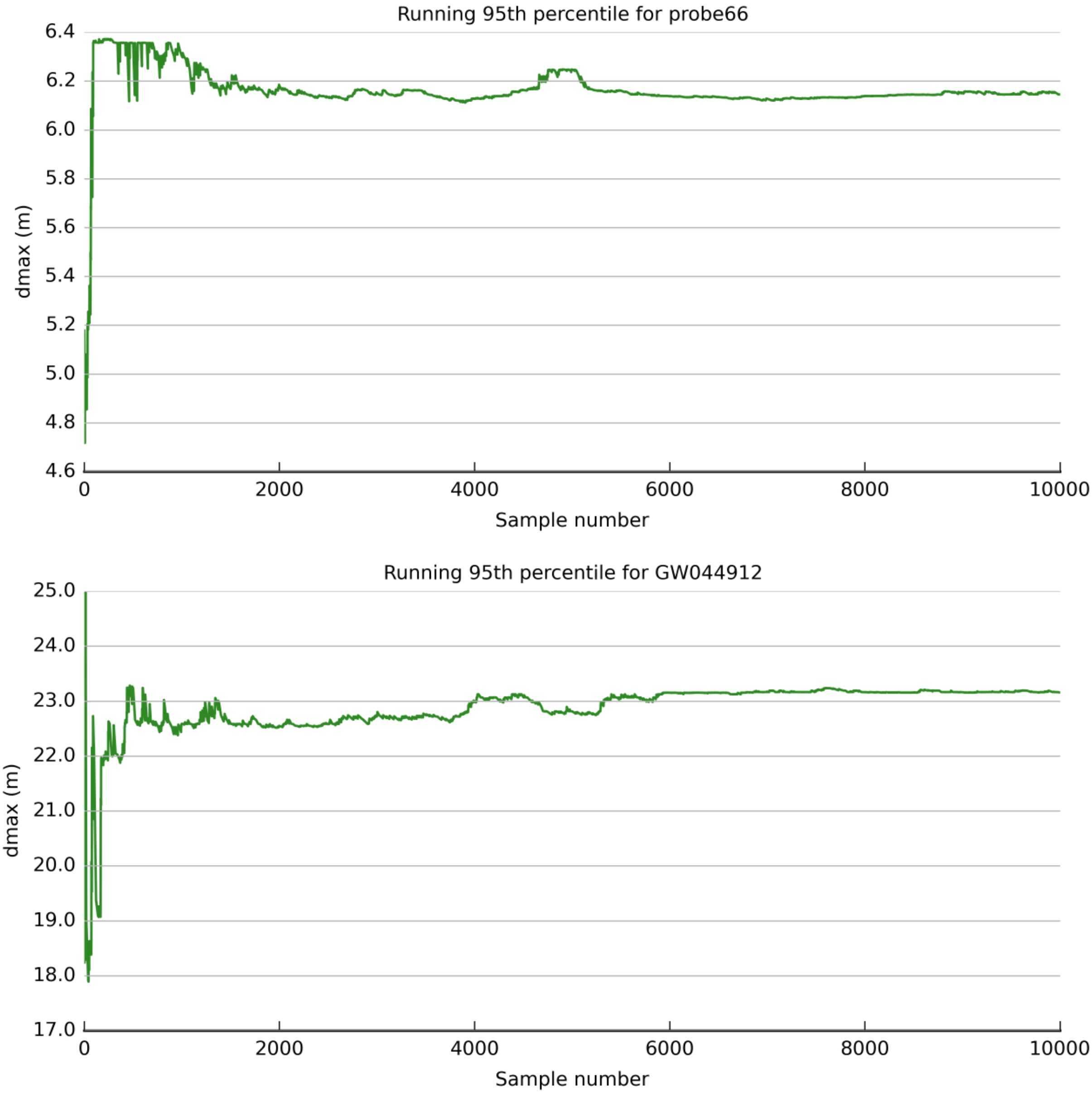

Figure 39 Convergence of the 95th percentile of drawdown (*dmax*) at probe66 and GW044912 for increasing numbers of samples in the posterior parameter distribution

dmax= 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)

Figure 40a and Figure 40b show the histograms of the 5th, 50th and 95th percentile of *dmax* and *tmax* for the 1566 predictions. A $\log_{10}$ scale is used on the y-axis as the hydrological change is very skewed. More than three-quarters of the output locations show *dmax* less than 2 m; more than two-thirds of output locations have *dmax* less than 0.2 m. Figure 40c provides increased resolution of the number of predictions with *dmax* between 0 m and 2 m. At about 20 output locations, the median of drawdown is larger than 10 m, with no median drawdowns in excess of 40 m. The 95th percentile of *dmax* is larger than 40 m for about ten output locations with the maximum 95th percentile equal to 75 m.

The histograms of *tmax* (Figure 40b) show that the median *tmax* is evenly distributed throughout the simulation period. The 5th percentiles of *tmax* are slightly skewed to earlier in the simulation period, whereas the 95th percentiles are skewed to later in the simulation period. A very large proportion of model nodes have a *tmax* equal to 2102. This is the value assigned to all output locations for which *dmax* is equal to 0 m or *dmax* is not realised within the simulation period.

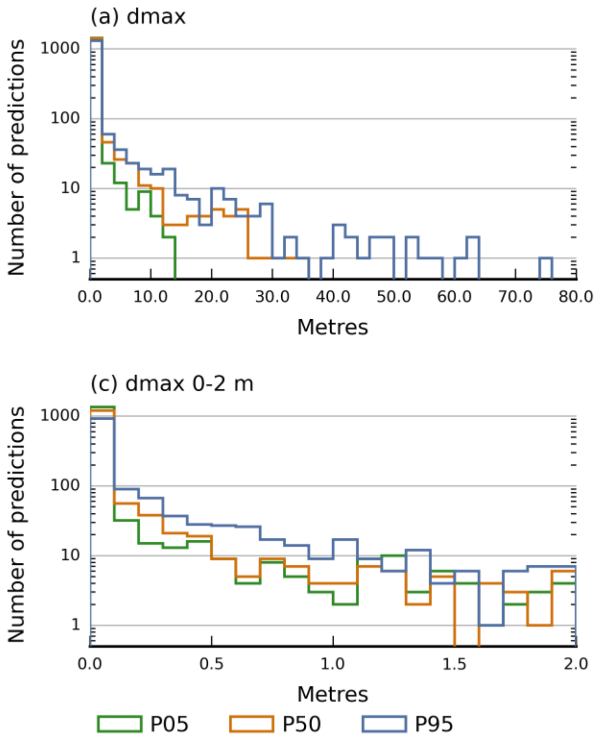

Figure 40 Histograms of the 5th, 50th and 95th percentile of (a) drawdown and (b) year of maximum change; plot (c) shows the maximum drawdown in the range from 0 m to 2 m

dmax = maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development
tmax = year of maximum change
The 5th percentile of *dmax* is not entirely visible as it is covered by the line for the 50th percentile. A *tmax* value of 2102 is assigned to all predictions in which the *dmax* is not realised during the simulation period or the *dmax* is equal to 0 m.
Data: Bioregional Assessment Programme (Dataset 1)

Results from the groundwater model nodes were spatially interpolated to obtain valid posterior distributions at other locations across the modelling domain. A Delaunay Triangulation (DT) was generated in the R package ‘tripack’ (Renka et al., 2015). For any new location within the DT, the quantiles of maximum drawdown at the nodes of the triangle enclosing the new location are linearly interpolated to the new location. A forward-backward cubed-root transform is applied during the interpolation process to improve performance over potentially non-linear surfaces. The maps in Figure 41 and Figure 42 show the probability of *dmax* exceeding 0.2 m and 2 m respectively in the Hunter subregion. In each figure, the two smaller maps show the probability of drawdown under baseline and CRDP, while the larger map shows the probability of the drawdown due to the additional coal resource development. It can be seen that the hydrological changes are localised around the mine footprints and that the probability of exceeding both thresholds is higher under the CRDP.

For the purposes of defining the groundwater zone of potential hydrological change, that is the area in which the magnitude of predicted drawdowns from the additional coal resource development is deemed significant in terms of potentially impacting groundwater-dependent landscape classes and assets, a greater than 5% probability of *dmax* exceeding 0.2 m has been adopted. In Figure 41, this is shown by the change from purple to white. At its maximum, this zone does not extend more than about 20 km from the mining developments.

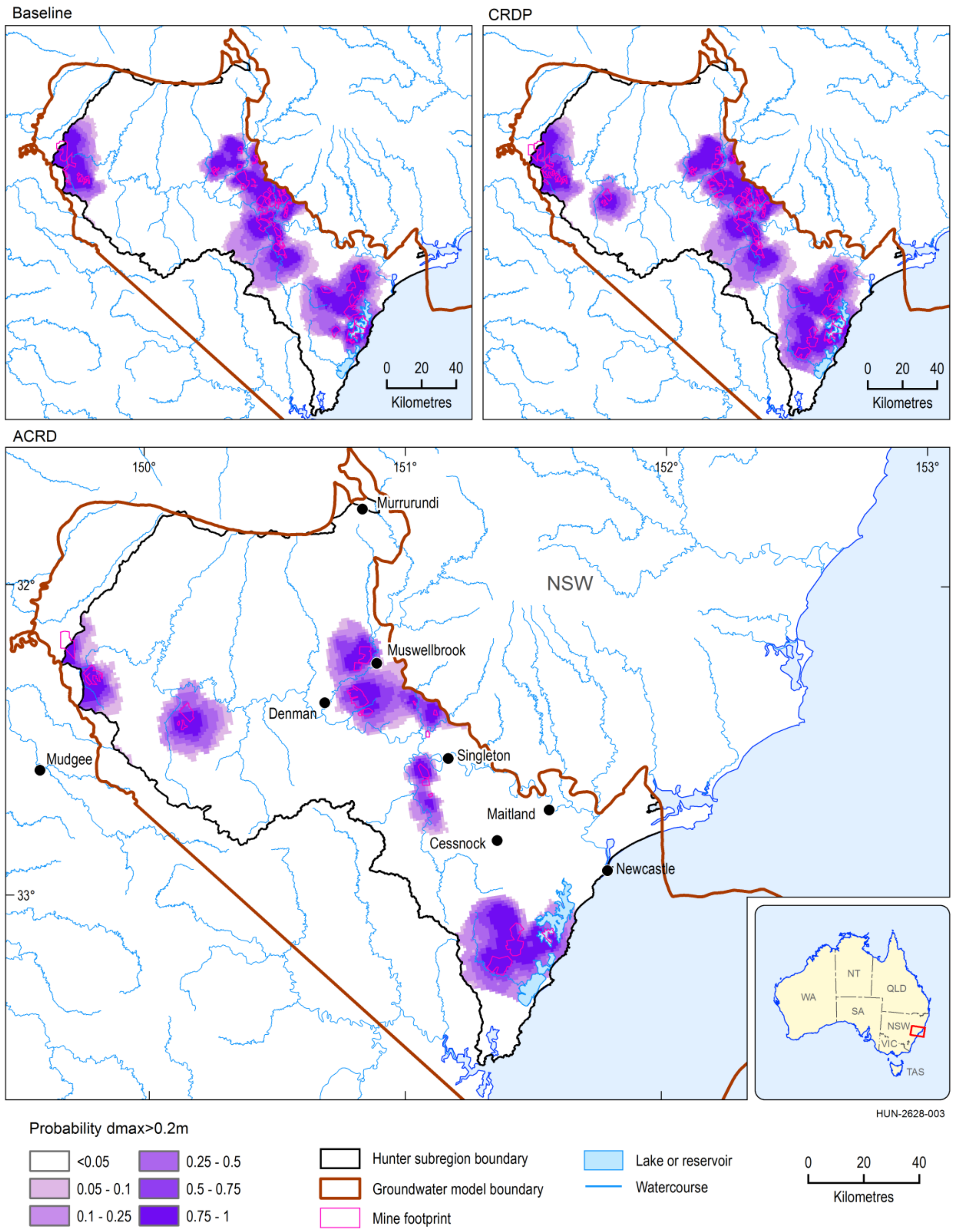

Figure 41 Probability of drawdown exceeding 0.2 m under baseline and coal resource development pathway (CRDP), and the difference in results between baseline and CRDP, which is the change due to the additional coal resource development (ACRD)

dmax = maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures.
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.
Data: Bioregional Assessment Programme (Dataset 1)

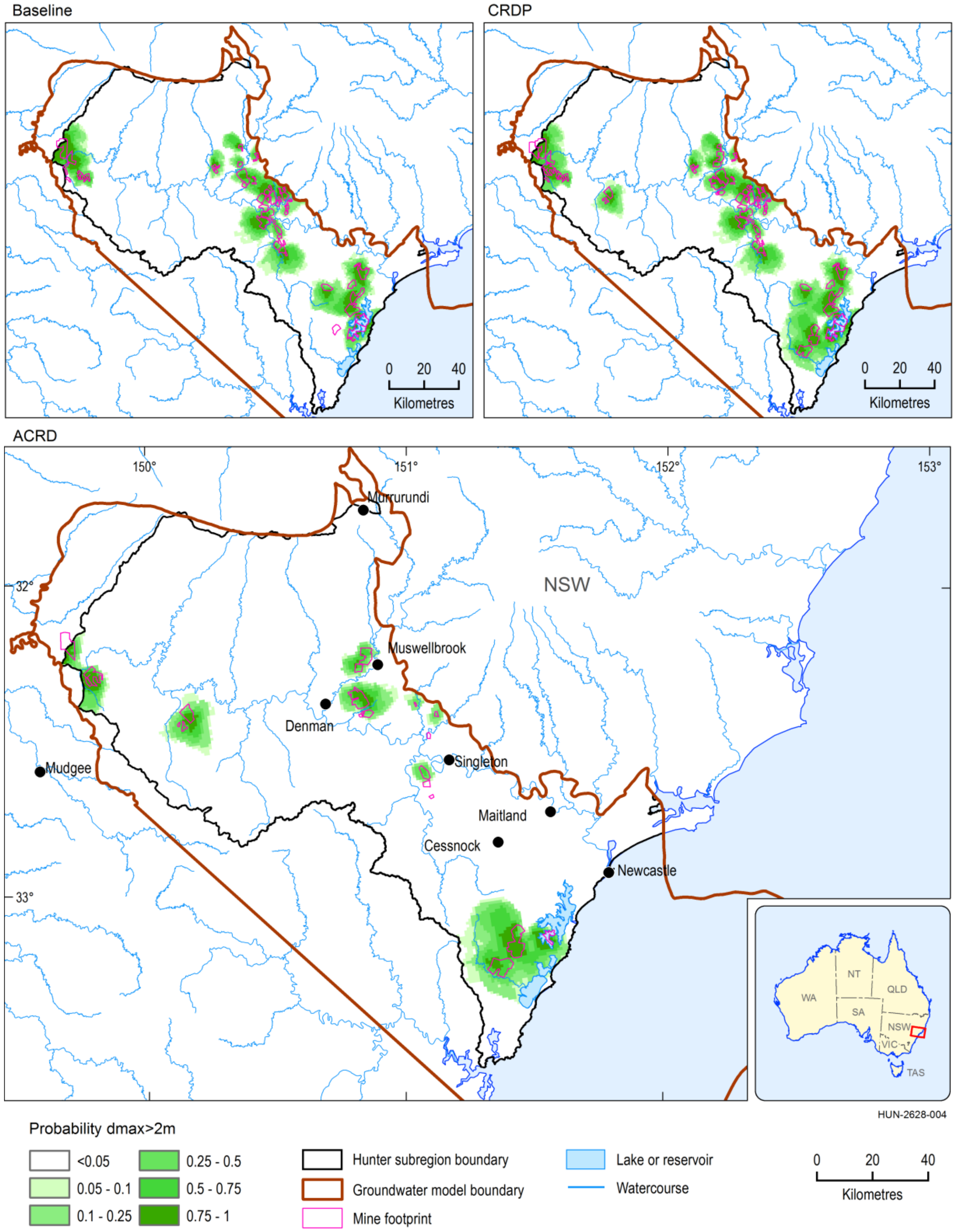

Figure 42 Probability of drawdown exceeding 2 m under baseline and coal resource development pathway (CRDP), and the difference in results between baseline and CRDP which is the change due to the additional coal resource development (ACRD)

dmax = maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures.
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.
Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.8.1.4 Comparison with results from other models

Section 2.6.2.2 provides a list of groundwater models that have been developed on behalf of various mining companies in the Hunter subregion for the purposes of estimating mine water make and modelling the impacts of pumping on local groundwater levels. These groundwater models are typically site scale, have a fine grid resolution and are underpinned by site-specific knowledge of the lithology, geophysics and hydrogeology of the model domain that is held by the mine. They are also deterministic models, which means they provide a single estimate of hydrological change based on a single parameter combination that is considered optimal, whereas the Hunter subregion groundwater modelling package is designed to provide probabilistic ensembles of predictions, based on a range of likely parameter combinations. The primary predictions from the Hunter subregion groundwater model are *dmax* (i.e. the maximum difference in drawdown between baseline and CRDP) and *tmax*, whereas the mine-scale models are designed to provide changes in groundwater levels and fluxes at selected times in the future. Further complicating direct comparisons between model outputs are the differences in conceptualisation, boundary conditions and, critically, the implementation of coal resource development.

Given these points of difference, it is not warranted to make direct comparisons between results from these local-scale models and from the groundwater model developed for the Hunter subregion.

However, Figure 43, Figure 44 and Figure 45 show the 5th, 50th and 95th percentiles respectively of *dmax* at the regional watertable under baseline and CRDP (relative to no coal resource development), and *dmax* at the regional watertable due to additional coal resource development (the difference in results between CRDP and baseline). These maps provide the range of drawdown predictions from the numerical modelling and can be used as reference to compare individual local-scale model results.

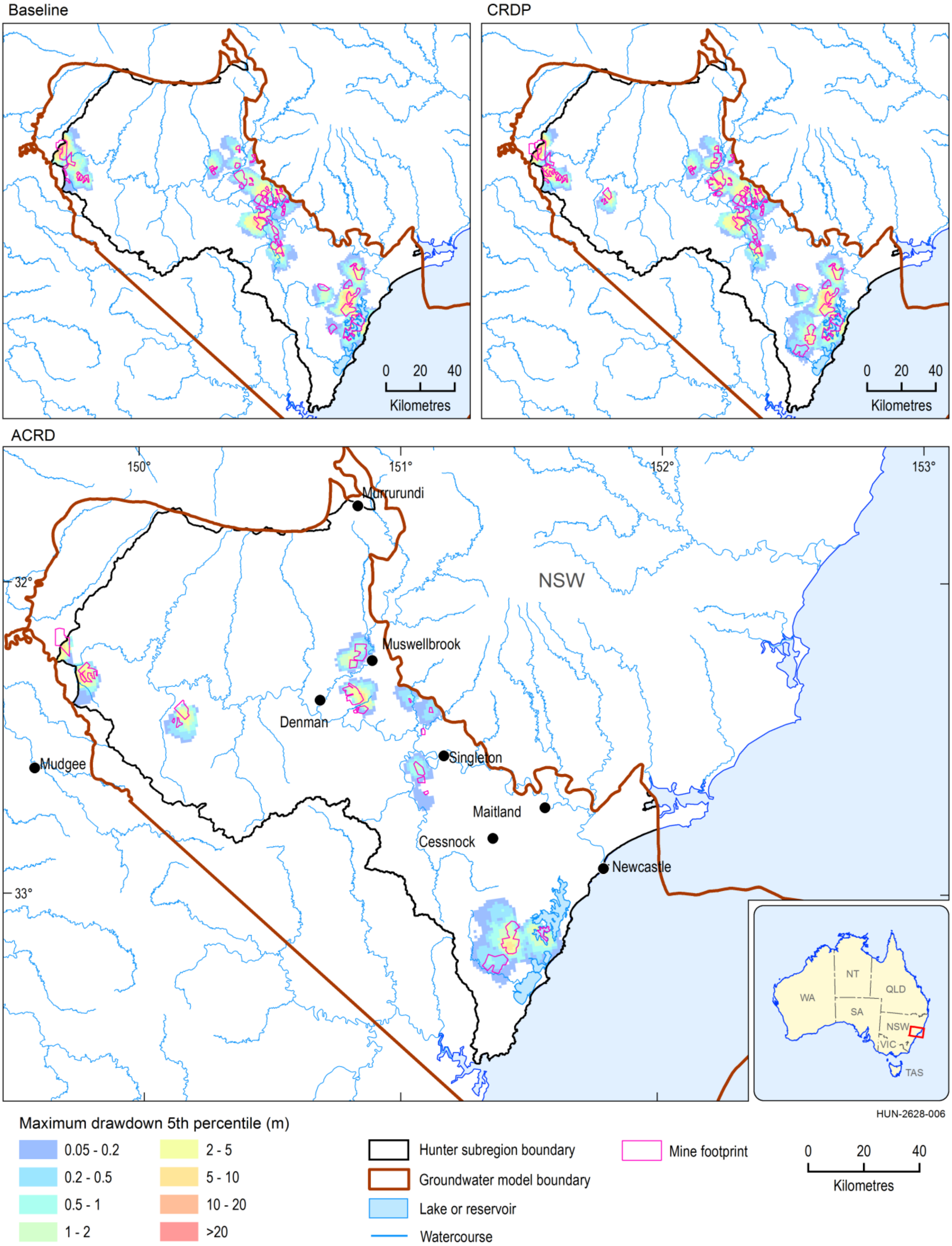

Figure 43 5th percentile of *dmax* at the regional watertable under baseline and coal resource development pathway (CRDP), and the change due to the additional coal resource development (ACRD)

dmax = maximum drawdown, 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)

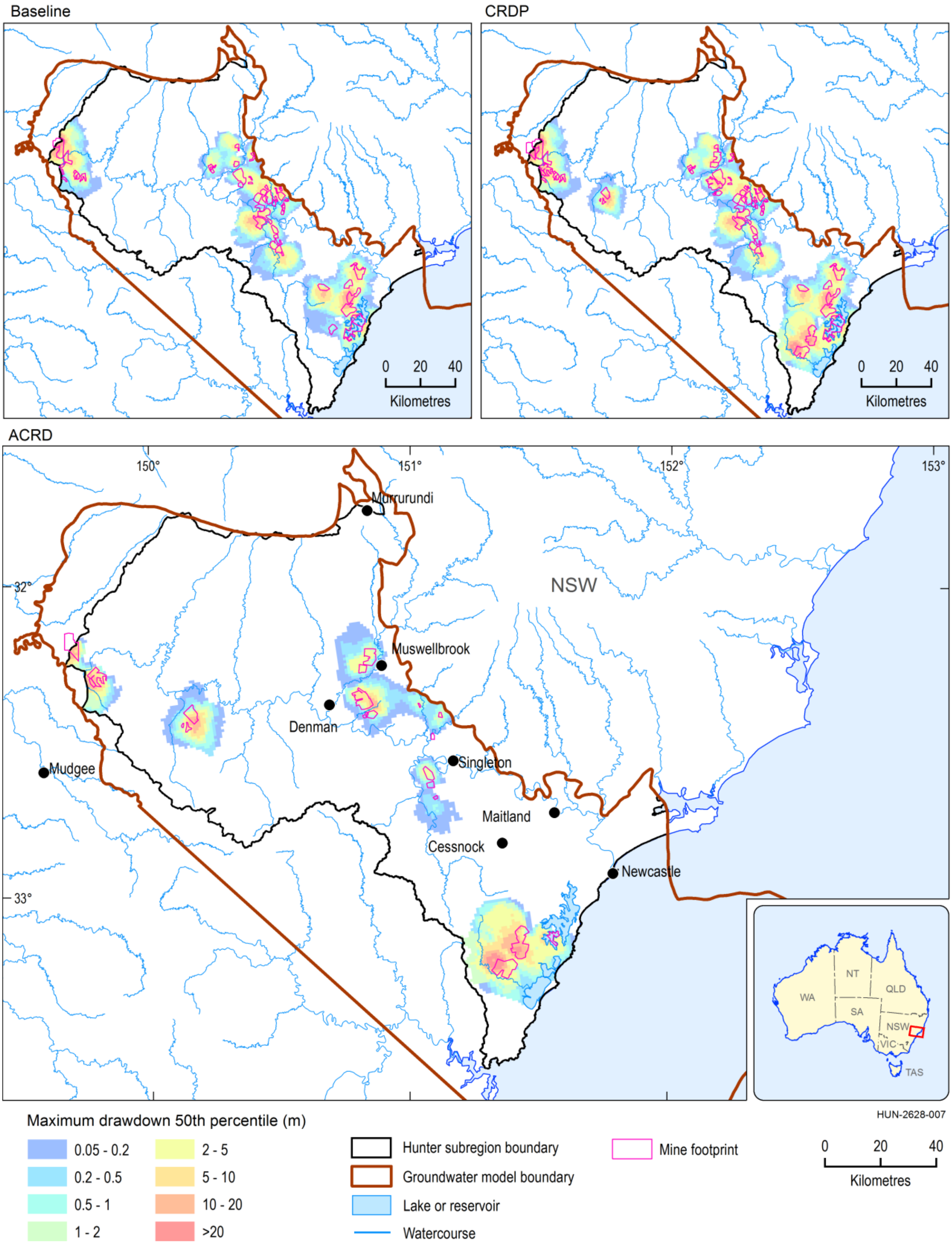

Figure 44 50th percentile of *dmax* at the regional watertable under baseline and coal resource development pathway (CRDP), and change due to the additional coal resource development (ACRD)

dmax = maximum difference in drawdown due to the additional coal resource development (ACRD), obtained from the time series of differences between CRDP and baseline. Drawdowns under the baseline and the CRDP are relative to drawdown with no coal resource development.
Data: Bioregional Assessment Programme (Dataset 1)

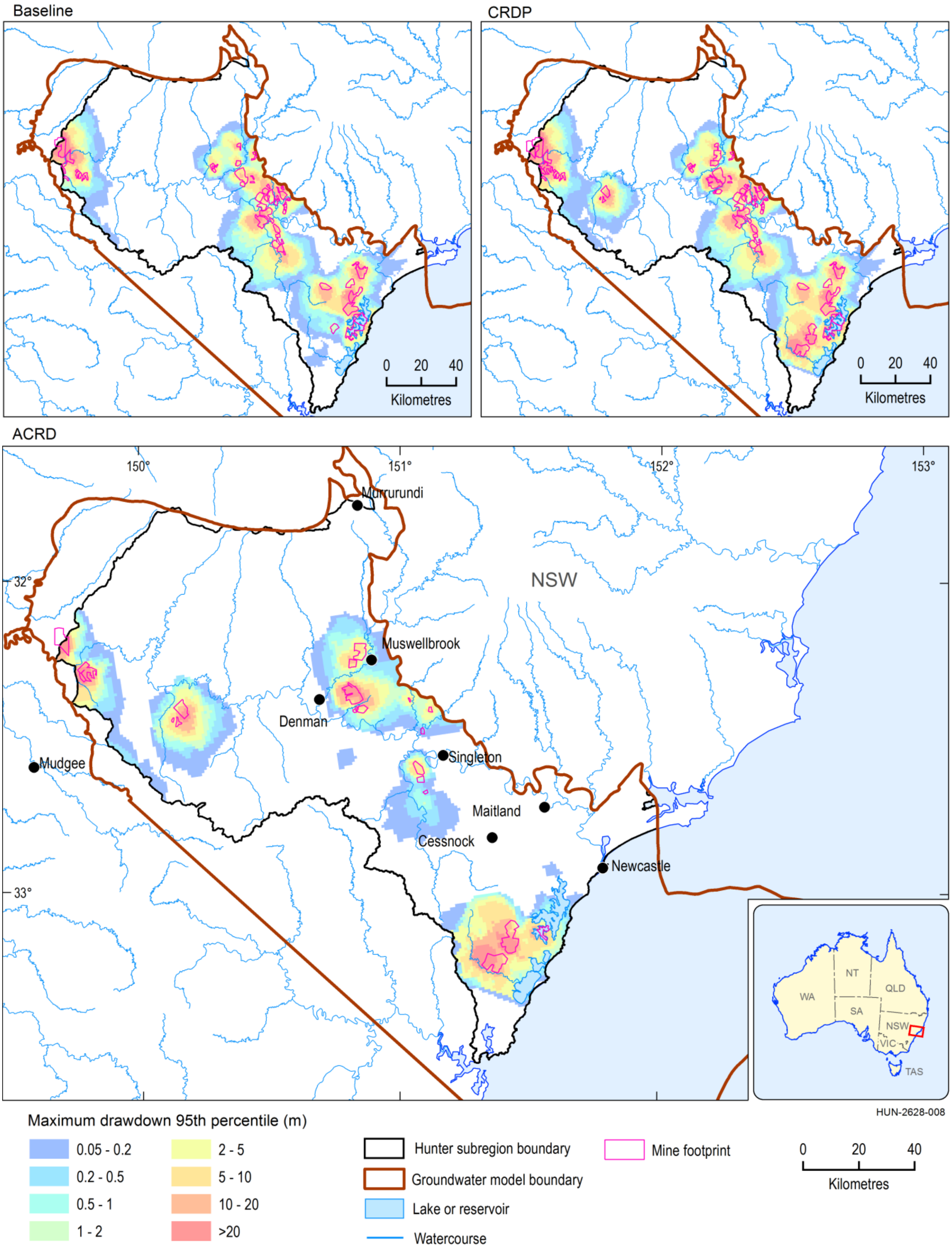

Figure 45 95th percentile of *dmax* at the regional watertable under baseline and coal resource development pathway (CRDP), and the change due to the additional coal resource development (ACRD)

dmax = maximum drawdown, 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)

While a direct comparison with results of local-scale models is not warranted, the database of model runs created during the design of experiment permits a rapid assessment of the effect of local geological and hydrogeological information on the predictions for an area. This is illustrated here for the proposed Wallarah 2 mine.

The Wallarah 2 development is chosen because results from the surface water and groundwater modelling, based on the regional parameterisation, indicate potentially large hydrological changes in the Wyong River catchment, which are attributable predominantly to this development. However, local geological and hydrogeological information indicate that for some parameters, the range represented in the regional modelling is too wide and a locally more accurate prediction can be obtained through constraining the results from the regional model.

The Wallarah 2 proposal is a greenfield underground coal mine west of Wyong. Groundwater modelling undertaken for the Environmental Assessment assumes that the horizontal and vertical hydraulic conductivities of the overburden layers are sufficiently low that groundwater depressurisation due to mining would not propagate through to the watertable (Mackie Environmental Research, 2013). The Wallarah 2 groundwater modelling also assumes that hydraulic enhancement above the longwall panels will not extend into the top 120 m of overburden, thus near-surface hydraulic conductivities will be unaffected by mining. The NSW Planning Assessment Commission critically examined the available data and modelling and concluded that the available data and modelling are consistent with a low-permeable interburden and that propagation of depressurisation to the watertable aquifer is likely to be limited (Shepherd et al., 2014).

The prior parameter distributions specified in Section 2.6.2.8.1.1 represent a conservative range of parameters, designed to account for hydrogeological conditions at the regional scale varying from a tight, impermeable overburden to a more permeable interburden. The hydraulic conductivity data from the proposed Wallarah 2 mining area shows that hydraulic conductivity decreases more rapidly with depth than is the case in the regional dataset (Figure 46; Bioregional Assessment Programme, Dataset 2). The range of the parameters controlling the horizontal hydraulic conductivity, Kh and K_lambda is adjusted such that the upper limit of horizontal K values reflects the locally measured values.

In addition, the ratio of vertical to horizontal hydraulic conductivity is limited to 0.5. This means that the vertical hydraulic conductivity is at most half of the horizontal hydraulic conductivity. A final local adjustment is the hydraulic enhancement after longwall mine collapse. In the regional parameterisation the hydraulic enhancement extent varies from 100 m to 500 m above a mine. Based on the geomechanical analysis in Mackie Environmental Research (2013), the upper limit of this range is limited to 250 m.

Figure 47 shows the effect on the contours of *dmax* of this local parameterisation for the Wyong area. There is a considerable reduction of the area enclosed by the 0.2 m contour for the 50th percentile map where maximum *dmax* values do not exceed 2 m. At the 5th percentile no *dmax* values in excess of 0.2 m are present. At the 95th percentile with local parameterisation there is still drawdown simulated, but the magnitude and extent is less than what is simulated as median value in the regional parameterisation.

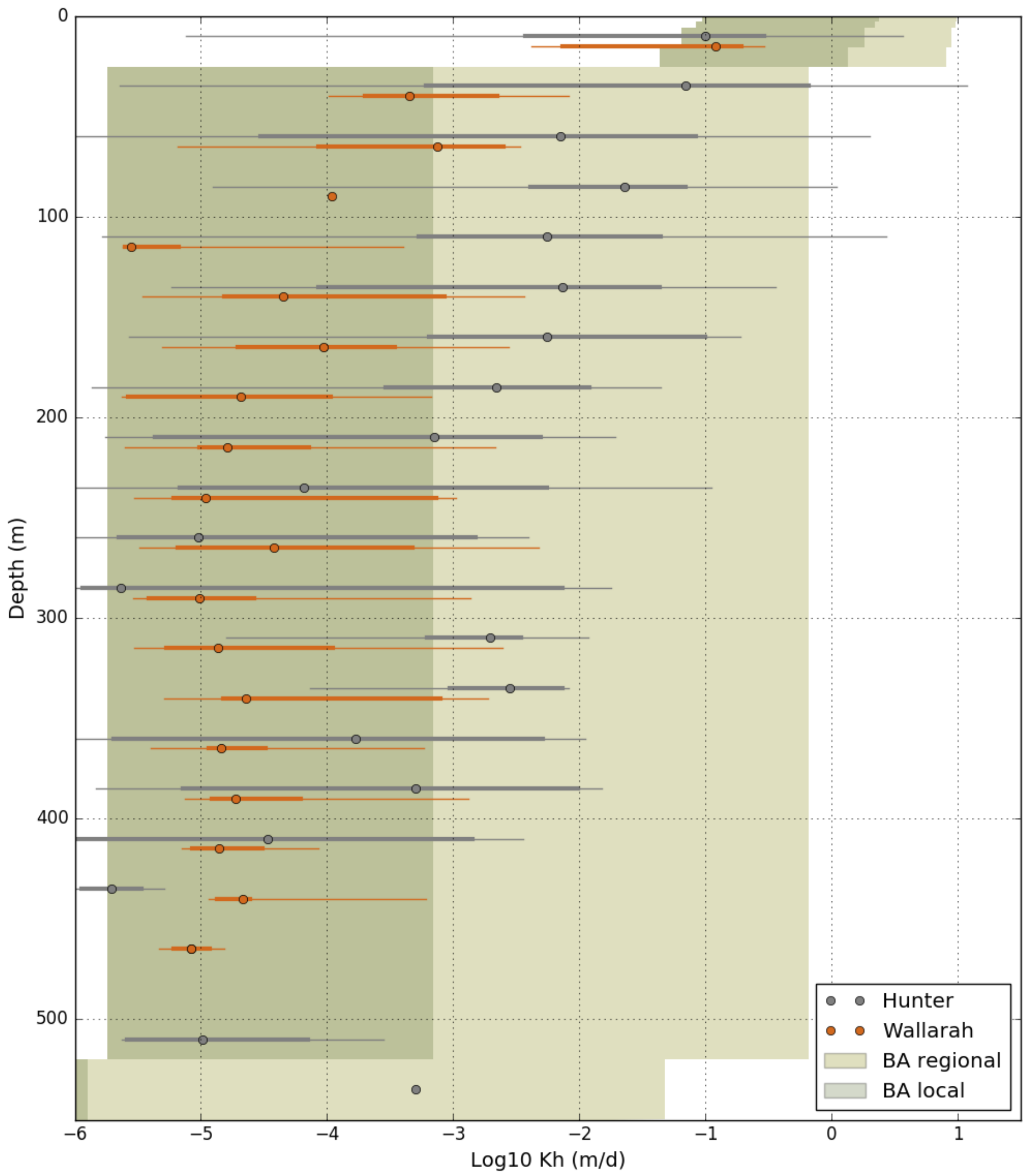

Figure 46 Horizontal hydraulic conductivity with depth based on regional data (grey boxplots) and Wyong River catchment data (orange boxplots)

Boxplots show the range of Kh values from the regional dataset (Bioregional Assessment Programme, Dataset 2) and the Wallarah 2 groundwater assessment (Mackie Environmental Research, 2013) grouped by 25 m depth intervals. The area of lighter shading represents the range of Kh values at this location in the BA groundwater model for the regional parameterisation. The dark shading indicates the range of Kh values updated with local information, where the lower limit is left unchanged, but the upper limit is more constrained.

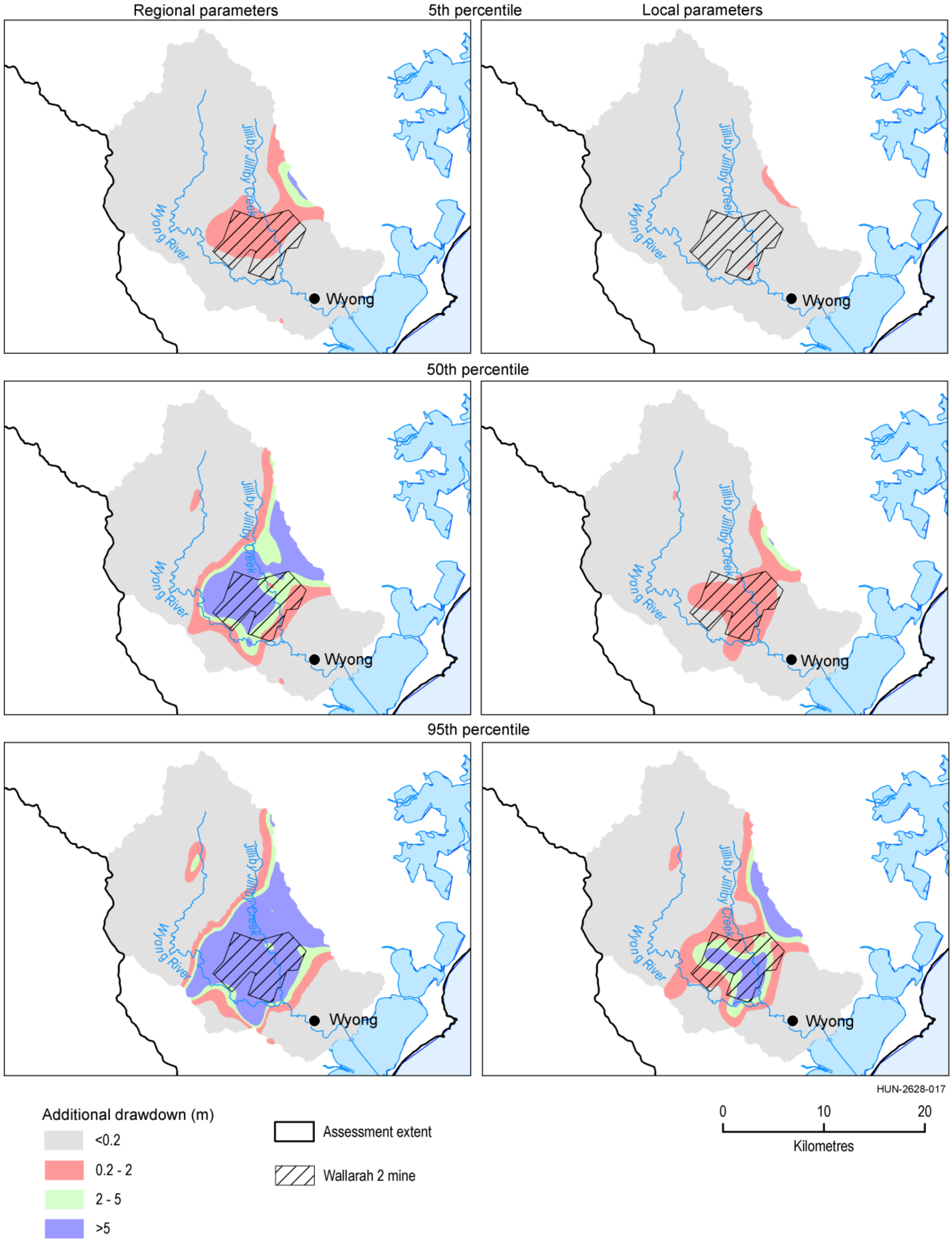

Figure 47 5th, 50th and 95th percentiles of *dmax* with regional parameterisation (left column) and local parameterisation (right column)

The drawdown area has been clipped to the Wyong River catchment boundary. *dmax* = maximum drawdown, 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)

The Wallarah 2 example illustrates how the stochastic results of a conservative parameterisation can be updated in a straightforward way based on local information.

Cautious comparisons can also be made between the Hunter subregion BA drawdown results and the potential impact zone defined in the Mid Hunter Groundwater study (EMM, 2015). Key differences between this study and the Hunter subregion BA modelling are discussed in Section 2.6.2.2. In the EMM (2015) study, analysis of modelled drawdowns from site-scale groundwater modelling at a number of open-cut mining sites in the Hunter Coalfield led to the adoption of a generalised 4 km buffer around mining areas to define the potential surface water impact zone (drawdowns >1 m). In Figure 48, a 4 km buffer has been generated around each of the baseline, CRDP and additional coal resource developments to delineate the zone within which drawdowns are assumed to be >2 m using the EMM (2015) approach. It can be seen that a generalised 4 km buffer provides a useful first approximation of the >2 m drawdown zone. When compared to the >2 m drawdown area from the BA model results, 4 km underpredicts the extent of this area in some areas and overpredicts it in others. In particular, the drawdowns from underground mines in the Newcastle Coalfield are underpredicted, although when local hydrogeological and geological data are used to constrain regional model results around Wallarah 2 (as shown in Figure 47), a 4 km radius overpredicts the potential impact zone. The difference between the Newcastle Coalfield and the two other coalfields, may be because the buffer was defined based on the results from modelling open-cut mines only and/or because physical differences between the Newcastle and Hunter coalfields mean the 4 km buffer is not appropriate in areas beyond where it was derived. The BA groundwater model also results in asymmetric drawdown zones around mines, which reflects the spatial variability across the model domain (e.g. from topography; the alluvium and stream network; thickness of overburden). Because a one-size-fits-all buffer approach does not take account of cumulative impacts, the buffer approach tends to underpredict the >2 m drawdown area under the CRDP in the Hunter Coalfield, but overpredict this area for just the additional coal resource development. In other words, a generalised buffer is not sensitive to the intensity of coal resource development.

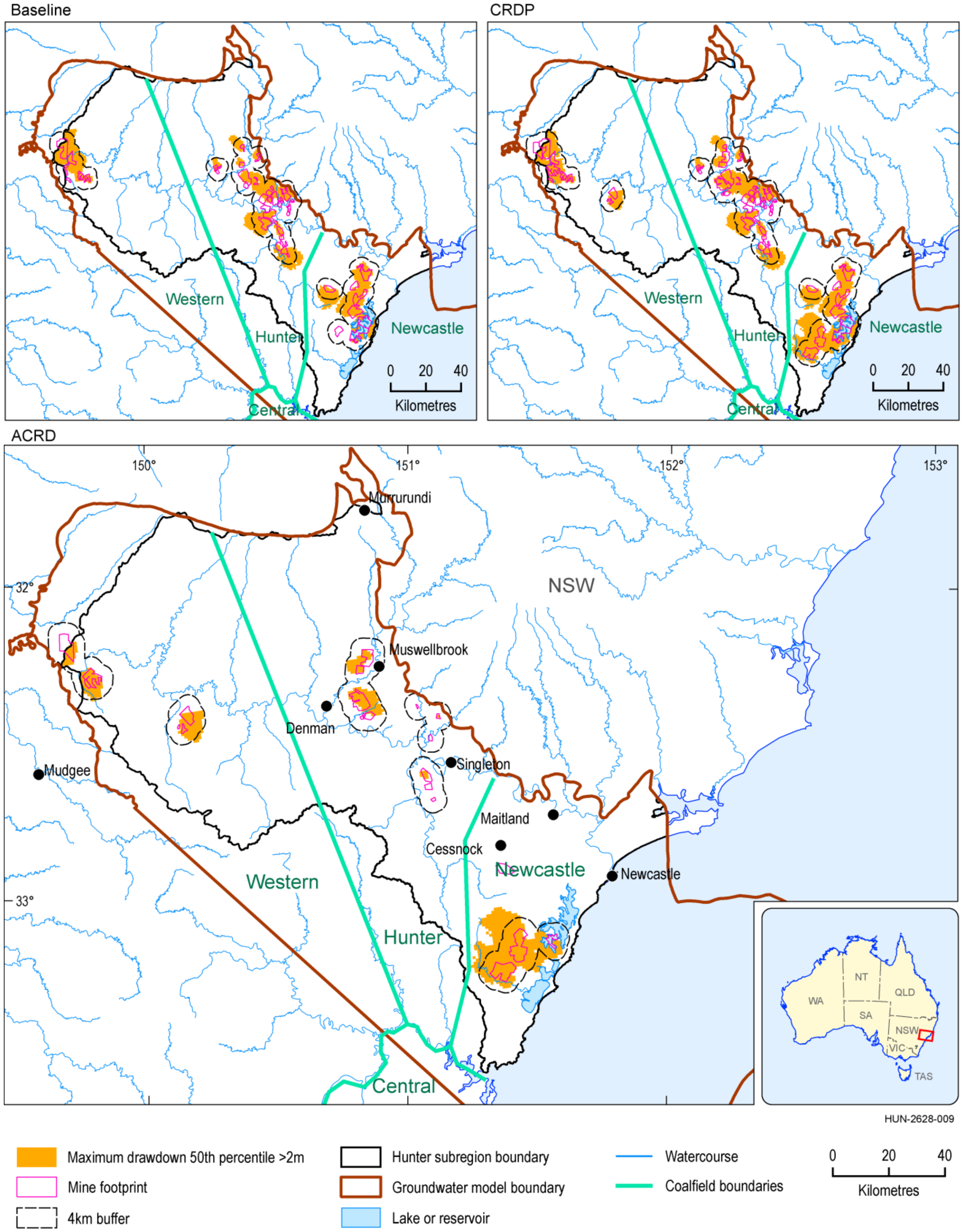

Figure 48 Generalised 4 km buffer over the 50th percentile of *dmax* at the regional watertable under baseline and coal resource development pathway (CRDP), and the difference in results between baseline and CRDP which is the change due to the additional coal resource development (ACRD)

dmax = maximum drawdown, 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)

2.6.2.8.2 Factors not included in formal uncertainty analysis

The major assumptions and model choices underpinning the Hunter subregion groundwater model are listed in Table 9. Many of these are not included in the formal uncertainty analysis. Each assumption is rated against four attributes: data, resources, technical and effect on predictions. These ratings have been assigned based on expert opinion of the Assessment team. A more detailed discussion of each assumption, including the rationale for the rating, follows.

The data column is the degree to which the question 'If more or different data were available, would this assumption/choice still have been made?' would be answered positively. A low rating indicates the assumption is not influenced by data availability – that is, the same assumption would be made with more or different data; a high rating indicates the assumption would be revisited if more data were available.

The resources rating reflects the extent to which resources available for the modelling, such as computing resources, personnel and time, influenced the assumption or model choice. A low rating indicates the same assumption would have been made with unlimited resources; a high rating indicates the assumption is driven by resource constraints.

The technical rating reflects the extent to which the assumption is influenced by technical issues. A high rating is assigned to assumptions and model choices that are driven by computational or technical limitations of the model code. These include issues related to spatial and temporal resolution of the models.

The most important rating summarises the effect of the assumption or model choice on model predictions. These ratings reflect a qualitative assessment by the Assessment team. The following discussion of each assumption confirms that those having a medium or high effect on predictions are consistent with the precautionary principle – that is, that the effect on predictions is towards overestimation rather than underestimation of the impact.

Table 9 Qualitative uncertainty analysis of the groundwater model of the Hunter subregion

Number	Assumption/model choice	Data	Resources	Technical	Effect on predictions
1	Selection of parameters for sensitivity and uncertainty analysis	Low	High	Low	Medium
2	Specification of prior parameter distributions	High	Low	Low	Medium
3	Spatially uniform hydraulic properties	Medium	Medium	Medium	Medium
4	Depth dependence of hydraulic properties	High	High	Low	High
5	Hydraulic enhancement after longwall mine collapse	High	Low	Low	Medium
6	Mine footprints represented as time invariant polygons	Low	Medium	Medium	Medium
7	Representation of surface water – groundwater interactions	High	Medium	Medium	Medium
8	Distance-based weighting of observations	Medium	Medium	Low	Low
9	Constraining parameters with groundwater level observations	High	Medium	Low	Medium
10	Constraining parameters with streamflow observations	High	High	Medium	Medium
11	Zonal recharge from chloride mass balance	High	Low	Low	Low
12	Lateral boundaries	High	Medium	Low	Medium
13	Simulation period from 2012 to 2102	Low	High	Medium	Low
14	Resolution and geometry of mesh	High	Medium	Low	Medium
15	Horizontal and vertical extent of alluvium	Low	Medium	Low	Low
16	Evapotranspiration extinction depth	High	Low	Low	Medium
17	Van Genuchten parameters	High	Low	Low	Low
18	No representation of faults	High	Medium	Low	Medium
19	No historical mines	High	High	Low	Low
20	Non-mining groundwater extraction rates	Low	Low	Low	Low

2.6.2.8.2.1 Selection of parameters for sensitivity and uncertainty analysis

The Hunter subregion groundwater model has many parameters (Table 7) of which ten were considered in the uncertainty analysis (Table 8). This selection was based on initial runs of the groundwater model, the experience of the BA groundwater modelling team and recognition that it is possible to fix some parameters and vary others to obtain a satisfactory characterisation of the range of possible outcomes (see Section 2.6.2.7.3).

Selection was not based on the availability of data as a parameter range can be defined for each parameter from local information or the literature. The data attribute therefore scores low. The resource attribute is, however, scored high. Every additional parameter included in the uncertainty analysis requires additional model runs to adequately sample the parameter space for development of robust emulators (Sahama and Diamond, 2001). A pragmatic choice was made to limit the analysis to the ten selected parameters to ensure sufficient resolution with the available computing resources. The resources attribute is therefore scored high. There are no technical issues with including more parameters, hence the attribute is scored low.

The initial, exploratory runs indicated that the parameters predictions are most sensitive to include the ten selected parameters. However, due to non-linearities between parameter values and predictions, the sensitivity of predictions to a parameter can depend on the value of the parameter (Hill and Tiedeman, 2007). Therefore the possibility that the excluded parameters could have an effect on predictions in other parts of their feasible parameter range cannot be ruled out. The effect on predictions is therefore scored medium. The number of model runs required to include all parameters in the uncertainty analysis are, however, too large to be evaluated within the timeframe allowed for modelling within this project.

2.6.2.8.2.2 Specification of prior parameter distributions

The prior parameter distributions are chosen to be uniform within the ranges selected by the modelling team, based on the information available for the Hunter subregion and equivalent analogue basins in Australia and the world.

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

The effect of the choice of parameter distributions is potentially important as many of the parameters the predictions are sensitive to are not greatly constrained by the available observations. The posterior parameter distributions for these parameters are very similar to the prior distributions. The effect on predictions is therefore rated medium.

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

2.6.2.8.2.3 Spatially uniform hydraulic properties

The hydraulic properties are implemented as spatially uniform horizontally, although they are varied with depth (see next section).

Insufficient data are available to characterise spatial variability at a regional scale, although in the vicinity of existing and proposed mines some information is available. The data availability attribute therefore receives a medium score.

The level of spatial detail that can be accommodated in a numerical model is governed by the horizontal and vertical discretisation, but will always require upscaling. Upscaling is a challenging technical task and there are a wide variety of techniques available to scale from point measurements to wider areas for use in numerical modelling (Renard and de Marsily, 1997). The technical column is rated medium.

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

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

For groundwater quantity predictions at the regional scale, *Australian groundwater modelling guidelines* state that the representative elementary volume is valid and can be applied to capture spatial variability in hydraulic properties by using equivalent values (guiding principle 7.3; Barnett et al., 2012).

Although introducing spatial heterogeneity might have an effect on the extent of predicted changes in groundwater level in the immediate vicinity of the mines, at larger scales the effect is minimal (see companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016)).

2.6.2.8.2.4 Depth dependence of hydraulic properties

The hydraulic properties of the groundwater system are varied with depth rather than by lithology.

The data attribute is rated high. Analysis of the available hydraulic property data indicated no systematic variations of hydraulic conductivity with lithology or stratigraphy (see Section 2.6.2.6.1 and Section 2.1.3.2 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b)). This is likely due to high spatial variability in hydraulic conductivity measurements generally, but can also be due to the uncertainty in the lithology within the geological model, and the coarseness of the geological model. In the vicinity of some mines, local geological information indicates that local aquitards exist, which could be introduced into the model in a similar way to the seam discs. Although local information is available, considerable resources are required to integrate this in a consistent manner in a regional model. Section 2.6.2.8.1.4 does, however, provide an example of how local-scale information can be integrated for selected predictions. The resources attribute is rated high. The technical attribute is rated low as it is relatively straightforward to implement different parameterisations.

The effect on predictions is rated high as the predictions of drawdown are very sensitive to the hydraulic properties and the observation data have limited potential to constrain the hydraulic property parameters. The current parameterisation, without regionally extensive aquitards, will overestimate the vertical propagation of drawdown to the watertable, while underestimating the lateral extent of drawdown in the coal seams and adjacent confined aquifers. The assumption is nevertheless deemed conservative, as the prime groundwater related variable of interest for receptor impact modelling is the drawdown at the watertable, not the drawdown in the coal seams and adjacent aquifers.

2.6.2.8.2.5 Hydraulic enhancement after longwall mine collapse

The hydraulic properties above mined coal seams are changed after mining commences to represent the effects of longwall mine collapse.

The data attribute is rated high as the process is well described, but data on hydraulic properties after longwall mine collapse are scarce.

Both the resources and technical attributes are rated low, as it is trivial to implement hydraulic enhancement differently. The hydraulic conductivity enhancement due to underground mining is modelled by a ramp function. The enhancement is applied to the entire area above and below the mine polygon immediately upon commencement of mining. The actual enhancement from each mine working is dynamic, advancing with the mining face and consolidating in the goaf region. If the phasing of each mine working were included, a more accurate representation of the groundwater in regions close to the mines would be obtained.

The effect on predictions is rated medium, as hydraulic enhancement is locally important for prediction above or close to the mine footprints. Further away from the mines, the enhancement is less important. Related to the hydraulic enhancement is the potential for an increase in recharge in areas affected by subsidence and longwall mine collapse. This feature is not implemented; however, an increase in recharge would likely counter the drawdown due to the additional coal resource development. By not including this enhanced recharge, drawdown due to the additional coal resource development is likely to be overestimated.

2.6.2.8.2.6 Mine footprints represented as time invariant polygons

The underground mines are represented as time invariant polygons, as discussed in Section 2.6.2.5. These polygons are an approximation of the maximum mine footprint and the progression of mining is not captured.

The data attribute is rated low, whereas the resource and technical attributes are rated medium. This reflects that this method of representing the mines is driven by the low spatial resolution of the regional modelling. Detailed information on mine footprints is available and, especially for the historical developments, the timing of mining is also often available, but extracting the data is time and resource consuming. The spatial resolution of the regional groundwater model is not sufficient to capture this detail. Similarly, the regional geological model does not represent individual coal seams.

The effect on predictions is rated medium as the regional drawdown due to additional coal resource development is controlled more by the mine pumping rate and the hydraulic properties than the exact outline of the mined area.

2.6.2.8.2.7 Representation of surface water – groundwater interactions

Surface water – groundwater interactions are implemented through a boundary condition in the groundwater model (Section 2.6.2.3). The parameter *d_riv* controls the depth of the riverbed below the surface elevation of the model mesh element, hence the drainage level. River stage is kept constant throughout the simulation period, so *d_riv* also contains river stage height information. The parameter *C_riv* describes the riverbed conductance, which is assumed to be uniform throughout the Hunter subregion.

The data attribute is rated high. Surveyed information of riverbed elevation is not available for most of the river network. Although there is a reasonable network of river gauges measuring river stage, these need to be interpolated between gauge locations and extrapolated upstream of headwater gauges to regionalise the point information. Although the available high-resolution digital elevation models partly alleviate the need for surveyed riverbed elevations, a river channel depth still needs to be assumed. Similarly, very few estimates of riverbed conductance are available, and measuring this parameter throughout the Hunter subregion to enable realistic spatial variation in the model is impractical.

The resources attribute is rated medium as a detailed analysis of the currently available stream geometry information would enable better representation of the spatial variation in drainage level. Introducing spatially varying *C_riv* would be fairly simple. The technical attribute is also rated medium as the resolution at which the stream can be represented depends on the mesh resolution.

The effect on the predictions is rated medium. The sensitivity analysis (Section 2.6.2.7.3) found that the simulated groundwater levels and surface water – groundwater fluxes are sensitive to the drainage level, but the predictions of the *dmax* are much less sensitive to these parameters. For model nodes close to rivers, *dmax* can be sensitive to *C_riv* but for other points, *C_riv* is unimportant. An improved representation of the river boundary will therefore not directly result in a greatly reduced uncertainty in the predicted drawdowns. However, a more accurate, independently specified boundary condition will reduce the conceptual model uncertainty which can improve the potential for the groundwater level and streamflow observations to constrain other model components.

2.6.2.8.2.8 Distance-based weighting of observations

Related to the previous assumption is the weight assigned to each groundwater level observation. The weight of an observation in constraining parameters for a particular prediction is based on the distance between observation and prediction and also distance of the observation to the nearest blue line network (i.e. mapped river network).

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

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

2.6.2.8.2.9 Constraining parameters with groundwater level observations

Groundwater level observations are often the only data used to constrain the parameters and conceptualisation of a groundwater model. In the groundwater model for the Hunter subregion groundwater level observations are used to constrain the model parameters as well as streamflow observations.

In Section 2.6.2.7.1 the available groundwater observation data from the NSW Department of Primary Industries, Office of Water (DPI Water, Dataset 3) in the groundwater model domain are presented and discussed. A large number of these observations date back to the late 1970s or early 1980s and mostly correspond to single water level readings carried out directly after completing a groundwater bore. Some of these readings are likely to be spurious. The metadata associated with these measurements often indicate that the coordinates of the observation location are not surveyed, but estimated from a map. The elevation of ground level or the reference points for depth-to-watertable measurements is in most cases not surveyed either, but estimated from maps or digital elevation models.

High quality observation data are essential for building a conceptual understanding of groundwater flow in a region and identifying general trends in piezometric surface. However, uncertainties arising from poorly specified point (x,y,z) information and the representativeness of groundwater levels measured in bores shortly after their installation undermine the utility of an observation for constraining a groundwater model. Observations that had no surveyed coordinates or were not from groundwater observation bores were excluded from the dataset used to constrain the groundwater model. This greatly reduced the number of observation points to constrain the model.

Mining companies install and maintain groundwater monitoring networks in the vicinity of their developments. These data are not publically available and a licence to use this data requires individual negotiations with the mining companies. Even when a licence to use the groundwater level observations is granted, the data need to be subjected to a stringent quality assurance as well. The main concern here is not the spatial accuracy of the measurements, but the representativeness of the observation for regional groundwater flow conditions. Mine monitoring networks are usually designed to monitor groundwater level changes in the immediate vicinity of the mine or around areas of potential concern, such as close to a surface water feature. Such local detail is not captured in the regional model and using observations dominated by local hydrogeological conditions in constraining the model can introduce considerable bias in the regional parameter estimates.

Thus, in terms of data available to constrain the groundwater model, this is rated high. Data from a more extensive, quality-assured regional observation network will provide a stronger basis for constraining groundwater models in this subregion. This issue receives a medium score on the resources attribute. The quality control and assurance of the database entries, and their suitability to be included in the observation dataset to constrain the model, is based on a desktop study of the information provided in the database. Access to and more comprehensive analysis of the original records and/or a field campaign to identify and verify spatial coordinates of the database entries have the potential to reduce uncertainty in the observation record. There are no technical issues for collecting, verifying or using groundwater level observations, hence the low score for the technical attribute.

Despite the limited data availability and uncertainties in the observation record, the effect on predictions is rated medium. The assumption is important but not deemed to dominate the predictions. A larger observation database with less observation uncertainty has the potential to locally change the conceptual understanding of the system and change the final posterior parameter probability distributions. The sensitivity analysis (Section 2.6.2.7.3) indicated that groundwater levels are most sensitive to the drainage level of the river model nodes, while the change in groundwater level predictions are most sensitive to the hydraulic properties. A greater density of high-quality observations close to the river network will reduce the uncertainty in the drainage level, which in turn will allow for the groundwater level observation to better constrain the hydraulic properties of the system.

2.6.2.8.2.10 Constraining parameters with streamflow observations

Percentiles of the total observed historical streamflow are used to constrain the surface water – groundwater flux. By specifying that the average simulated historical surface water – groundwater flux needs to be between the negative of the 20th percentile of long-term total streamflow and the 70th percentile of long-term total streamflow, only the most extreme unrealistic simulations are excluded from the posterior parameter combinations.

If more robust, regional-scale estimates of surface water – groundwater fluxes are available, there is enormous potential to constrain this variable. Although some local-scale, detailed information is available (Lamontagne et al., 2003), long-term, regional-scale estimates are not available. The data attribute is therefore rated high.

Estimating surface water – groundwater fluxes at a regional scale is not trivial. The various methods available, such as baseflow separation with digital filters, salt balance or environmental tracers, each have their shortcomings. To obtain consistent, robust estimates of the surface water – groundwater flux, these methods need to be applied in combination. This analysis was deemed beyond the scope and operational constraints of the BAs.

The effect on predictions is deemed to be medium. The surface water – groundwater flux is most sensitive to the drainage level (*d_riv*) and, to a lesser extent, the hydraulic properties of the groundwater system, while drawdown predictions, however, are most sensitive to hydraulic properties, hydraulic enhancement after longwall mine collapse and mine pumping rates.

As with the groundwater level observation, narrowing the bounds on the surface water – groundwater flux can better constrain the river drainage level. When this parameter is better constrained, there is more potential for the groundwater level observations to constrain the hydraulic properties. This in turn will further constrain the predictions of drawdown due to the additional coal resource development (difference in drawdown between CRDP and baseline).

2.6.2.8.2.11 Zonal recharge from chloride mass balance

Groundwater recharge is implemented spatially using a spatially varying correction factor to the temporal recharge signal obtained from the surface water model output. The correction factor is based on measurements of chloride in groundwater and rainfall with the chloride mass balance method (see Section 2.1.3 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b)). The chloride deposition in rainfall was from a continental scale chloride deposition surface which used all available measured values within the subregion. The spatial coverage of bedrock groundwater chloride measurements in the Hunter subregion is variable. Other reliable and representative measurements of diffuse recharge are not available in the subregion either.

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

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

2.6.2.8.2.12 Lateral boundaries

The model’s north-eastern boundary has been assumed to be impermeable (coinciding with the extent of the geological basin), while general-head boundary conditions have been applied to its other lateral boundaries. The specified groundwater level is obtained from a quasi-steady-state pre-development simulation to ensure the groundwater level is consistent with the parameterisation.

The data attribute is rated high as there is very limited piezometric information available to independently specify the groundwater levels. The resources attribute is rated medium as it would require considerable additional resources in model development to expand the model to coincide with natural boundaries. The technical column is rated low as it is trivial to change the boundary condition in the model.

The effect on predictions is rated medium. Determining whether these boundary conditions are correct would help reduce boundary effects. Most of the mines are sufficiently far from the lateral boundary that the zone of hydrological change does not extend to the lateral boundary. Predictions around mines close to a general-head boundary, such as Ulan, Moolarben and Mount Owen, may be improved through reducing boundary effects.

2.6.2.8.2.13 Simulation period from 2012 to 2102

The simulation period for all BAs is 2012 to 2102 (see 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 *dmax* is not realised within the simulation period, as shown in Figure 40.

Extending the simulation period is not limited by data as it is about the future, hence the score is rated low. The resources attribute, however, is rated high. To ensure that the *dmax* is realised at all model nodes for all parameter combinations, it 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 rated medium. It is trivial to extend the length of the simulation in the groundwater model. The climate scaling factors used to specify future rainfall and therefore recharge are not available beyond 2100. It is therefore a technical issue in devising a justifiable future climate to assign to the modelling.

The effect on predictions, however, is rated low. The theoretical assessment of the relationship between *dmax* and *tmax,* presented in submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016), shows that any *dmax* realised after 2102 will always be smaller than the *dmax* realised before 2102. This is in line with the precautionary principle as it means that by limiting the simulation period, the hydrological change will not be underestimated.

2.6.2.8.2.14 Resolution and geometry of the mesh

The geometry of the mesh is taken from the geological model developed in Section 2.1.2 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b), although the horizontal resolution is variable, with high resolution close to rivers and mines.

The data and resources attribute are both scored medium, while the technical attribute is scored low. The latter reflects that it is straightforward to change the mesh resolution and geometry in the design of the model. For higher resolution meshes, with more elements, the computation time will increase. The resource attribute is thus scored medium to reflect that increased resolution requires an increase in computational load. The accuracy of the underlying geological model ultimately depends on the data availability and interpretation. This attribute is scored high. Note that model horizontal resolution is not constrained by data availability.

In the current parameterisation, the effect on predictions is low, as hydraulic properties do not vary with stratigraphy but with depth. Higher resolution geological models with improved representation of coal seams and local aquitards, however, may warrant revisiting this parameterisation scheme, which at least locally, may affect predictions. The overall score of this attribute is medium.

It is noted that NSW Geological Survey has developed a detailed three-dimensional geological model of part of the subregion. Project-timing issues prevented this recent geological model being integrated into the groundwater model.

2.6.2.8.2.15 Horizontal and vertical extent of alluvium

The horizontal and vertical extent of the alluvium is well defined and available from geological maps and shallow bores, especially compared to the understanding of the deeper sedimentary rocks. The data attribute is therefore scored low.

The variations in lateral extent and thickness of the alluvium are, however, often at a scale that is smaller than the model mesh resolution. A more accurate representation would therefore require a finer mesh, which in turn increases the computational load, hence a medium score for the resources attribute. There are no technical issues with implementing a finer mesh, so the technical score is low.

The overall impact on predictions is scored low. An improved accuracy in the representation of the alluvium may reduce the predictive uncertainty of additional drawdown locally in alluvial aquifers. The predicted change in surface water – groundwater exchange flux is deemed to be minimally affected by an increased resolution of the alluvium as this flux is mostly controlled by the river bed conductance and the river stage.

2.6.2.8.2.16 Evapotranspiration extinction depth

Potential evapotranspiration is obtained from AWRA-L and the evapotranspiration extinction depth is assumed to be proportional to vegetation height, and varies between 0 m to 10 m. These extinction depths are consistent with depths used in other groundwater modelling studies (Canadell et al., 1996; Doble et al., 2016).

The data attribute is scored high as there are very limited data available on rooting depth for different vegetation types in the Hunter subregion, let alone evapotranspiration rate as a function of groundwater level, rooting depth, vegetation, soil/rock type, etc. The resources and technical attributes are scored low as it is relatively straightforward to update the evapotranspiration extinction depth if new information is available.

Evaluating the impact on predictions of changing extinction depth is not straightforward and warrants a more formal evaluation. This was done using a local one-at-a-time sensitivity analysis in which each parameter is varied using a small increment, while keeping other parameters at their base value (Hill and Tiedeman, 2007). This analysis is the most frugal sensitivity analysis method because it requires only one or two model runs per parameter (Hill et al., 2015), but it can produce misleading results (Saltelli and Annoni, 2010). Four groundwater model parameter were used in the analysis: the extinction depth of evapotranspiration (*ET*) expressed as a fraction of the vegetation height, the effective porosity (*ne*), the horizontal hydraulic conductivity (*Kh*) and the hydraulic conductivity ramp function (*K_ramp*). The latter three were chosen as the reference parameters because the global sensitivity analysis showed that drawdown predictions were sensitive to them.

Results from the analysis indicated that the extinction depth does affect the predictions and the uncertainty in the predictions of *dmax*, but the effect is much smaller than for *ne* and *Kh.* While results from this local one-at-a-time sensitivity analysis should be viewed as indicative only (due to possibility of misleading results), they suggest that including extinction depth in the uncertainty analysis will only have a minimal effect on the posterior predictive distributions. The effect on predictions is therefore scored low.

2.6.2.8.2.17 Van Genuchten parameters

The Van Genuchten parameters control the hydraulic behaviour of the unsaturated zone in the groundwater model.

In the absence of local data, these parameters are based on literature values. The data attribute is thus scored high. Different values for the Van Genuchten parameters are easy to implement and will have a limited effect on the model runtime. Both the resource and technical attributes are scored low.

The effect on predictions is rated low. The unsaturated flow parameters control how much water is stored in regions above the watertable, which may affect the dynamics of the unsaturated region, in particular in the regions around rivers where baseflow and leakage occur.

2.6.2.8.2.18 No representation of faults

Faults are not incorporated in the geological model as insufficient information is available about their three-dimensional structure, dip, throw and displacement (see Section 2.1.2.2.4 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b)).

Faults are not included in the groundwater model either as there is insufficient information on the location and flow behaviour of faults and fractures in the subregion. The data attribute is therefore scored high. The resource attribute is scored medium as incorporating faults and fractures will require a refinement of the mesh and an update of the parameterisation. The technical attribute is scored low as there is no technical issue in implementing fault-related flow in the Multiphysics Object-Oriented Simulation Environment (MOOSE).

Effects on predictions is rated medium as faults and fractures can locally alter predictions.

2.6.2.8.2.19 No historical mines

Historical mines are those coal mining operations that had ceased operations prior to the end of 2012. These mines therefore were not included in the baseline, as outlined in the introduction.

Including such historical coal mining operations in the groundwater model requires extensive data on historical mine footprints and pumping rates. The data attribute is therefore scored high. Some of that information is available, especially for the more recent mines. It requires a considerable investment to collate that information, carry out a quality assurance and transform into a format suitable for incorporation in the groundwater model. The resources attribute is therefore scored high. The technical attribute is scored low as it is straightforward to add mines to the model if the information is available.

The effects on predictions is scored low, however. The effects of historical coal mining operations are the same between the baseline and CRDP and so cancel out in estimating the drawdown due to the additional coal resource development.

It is recognised that accurate representation of historical coal mining operations and their legacy effects may improve the representation of historical groundwater levels and surface water – groundwater flux, which in turn may reduce the uncertainty in the posterior parameter distributions.

2.6.2.8.2.20 Non-mining groundwater extraction rates

Groundwater extractions for non-mining uses across the subregion were based on licensed entitlements.

Historical data are generally not available on a bore-by-bore basis to define historical rates of extraction from licensed bores. The data attribute is rated low since actual extraction rates would only apply to the 1983 to 2012 reporting period and assumptions would still need to be made about rates of extraction into the future. The resources and technical attributes are rated low as it is trivial to model different extraction rates.

Effect on predictions is also low, as the same rates of extraction are used in both baseline and CRDP and their impacts largely cancel out in calculating the difference between the modelled results under baseline and CRDP. As previously stated, in relation to including more historical mines in the baseline, time series of actual water extraction rates would help to constrain the model parameters.

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2.6.2.9 Limitations and conclusions

Summary

The Hunter subregion groundwater model is developed with the finite element, multiphase groundwater flow simulator MOOSE (Multiphysics Object-Oriented Simulation Environment) to probabilistically assess the drawdown due to the additional coal resource development, and the year of maximum change, as well as to provide the change in surface water – groundwater flux as a boundary condition for the surface water modelling reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

Model results indicate a 100% probability of exceeding a 0.2 m drawdown within the mine footprint areas, but this reduces with increasing distance from the mines. The contour of 5% probability of exceeding 0.2 m drawdown is generally within 20 km of the mine footprint boundary.

The year of maximum change varies throughout the Hunter subregion. It is most likely to be during the decades after mining activity ceases, and it increases with increasing distance from mine tenements.

The Hunter subregion groundwater model is a stochastic regional-scale model: it has a large modelling domain and a relatively coarse model resolution. As such, it does not provide a deterministic result and it does not represent the level of lithological and hydrogeological information that is represented in local-scale groundwater models that have been built for small areas (i.e. individual coal mines) within the Hunter subregion.

Opportunities to improve the model can be directed to better constraining the assumptions that have the most influence on model results. Generally, the magnitude of drawdown due to the additional coal resource development, which is the difference in drawdown between CRDP and baseline, is most sensitive to the porosity and hydraulic conductivity; and somewhat sensitive to the mine pumping rates, the decay of hydraulic conductivity with depth, and the riverbed conductance. Generally, the change in surface water – groundwater flux is most sensitive to riverbed elevation (and thus river stage height), followed by the hydraulic conductivity, and the riverbed conductance. Neither is very sensitive to the recharge, the decay of porosity with depth, the ratio of vertical to horizontal conductivity, and the conductivity-enhancement ramp function.

2.6.2.9.1 Limitations

Quantification of the hydrogeological changes due to coal resource development in the Hunter subregion was undertaken using a regional-scale groundwater model. Having a large modelling domain and the requirement for computational efficiency to perform many simulations necessitated the implementation of a relatively coarse model resolution, albeit with areas of higher resolution around mines and along streams. Because the resolution of the model mesh (at best 500 m) defines the scale of information that can be represented in the model, local-scale information, even where it might have been available, was not incorporated into the parameterisation of the model. The probabilistic approach to quantifying the hydrological changes due to coal resource development in the bioregional assessments (BAs) was adopted to account for and be transparent about this uncertainty, but also to make best use of observation data to constrain model parameters.

A probabilistic framework, however, means there is not a single parameter combination that provides a 'best fit' to observations and a corresponding single set of predictions. In other words, the groundwater model is not a calibrated model designed to give a deterministic result to a model future. Any evaluation or further use of the parameter combinations used in the models or the predictions needs to take into account the full posterior distributions reported in Section 2.6.2.8. Input data, model files (including pre- and post-processing scripts and executables) and results are available at www.bioregionalassessments.gov.au.

The Hunter subregion groundwater model is a regional-scale model covering 34,000 km^2 at a resolution of more than 500 m. This means a decision was made to not try to capture information at the mine scale or less in developing the model, even though more detailed information may be available locally, particularly in the vicinity of coal mines. The implications of this are that local variations in geology and hydrogeology, which can significantly influence the local effects of coal mining activity, are not represented, and the regional model predictions may overestimate the likely hydrological changes. The reliability and accuracy of any predictions made by this regional model will be less than the reliability and accuracy of predictions made by a local mine-scale groundwater model that fully accounts for this level of detail, and direct comparisons between results from these local-scale models and results from this groundwater model should be viewed with caution.

The qualitative uncertainty analysis (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 groundwater-related receptors in the Hunter subregion. The BA groundwater modelling team (and authors of this report) deem these assumptions to be valid and acceptable for the purposes of the BA. These assumptions are not necessarily valid or acceptable for addressing other water resource management questions. Therefore, the authors recommend against using the Hunter subregion groundwater model for other purposes without assessing its suitability for the new purpose, having regard to its conceptualisation, parameterisation and implementation, and in line with the *Australian groundwater modelling guidelines* (Barnett et al., 2012).

Some limitations of the model relate to features or processes it does not represent. The groundwater model does not include faults or other geological structures across the modelling domain. Fracturing of rocks associated with folding and faulting creates pathways for water movement and, if well connected, can enhance hydraulic conductivities laterally and/or vertically. The model does, however, include hydraulic enhancement of the goaf above longwall mines as part of its representation of mine impacts, which conceptually includes hydraulic conductivity increases from fracturing of rock.

The model also does not include changes in recharge at the surface of subsidence zones. If fracturing of rock above longwall mines extends to the land surface, this would be expected to have some impact on recharge, particularly if the subsidence creates closed basins that intercept runoff, or leads to fracturing of a streambed and loss of streamflow, as has occurred in the Hunter subregion and Sydney Basin bioregion (NSW Scientific Committee, 2005; Krogh, 2015).

As implemented for the BA, the model assumes that the hydraulic enhancement from underground mining occurs on the first day of mining across the maximum footprint area of the mine. This assumption often causes a relatively short-lived surge (increase) in baseflow which gradually decays, but is largely a model artefact. Phasing in the area impacted by longwall mine collapse over the life of the mine has been shown to typically reduce this baseflow surge. The surface water – groundwater flux changes incorporated into the river model were modified to eliminate baseflow increases and ensure that hydrological changes to water-dependent assets is focused on the impacts of baseflow decreases.

2.6.2.9.2 Opportunities to reduce predictive uncertainty

An important outcome from the Assessment is identifying the main sources of uncertainty and the opportunities for improving regional-scale groundwater modelling in the Hunter subregion. The sources of uncertainty broadly relate to data, model implementation and representation of the baseline and coal resource development pathway (CRDP). These can be inter-related: for example, the quantity and quality of data available will influence decisions about the geometry of the model and representation of processes.

The sensitivity analysis in Section 2.6.2.7 identified the model parameters that had the largest influence on the groundwater model outputs of interest. Groundwater level predictions were found to be most sensitive to the drainage level of the river network (*d_riv*), hydraulic properties of the geological layers (*Kh*, *K_lambda, KvKh*) and the recharge multiplier (*RCH*). The drawdown, however, is most sensitive to the hydraulic properties (*Kh*, *K_lambda, KvKh*), porosity (*ne)* and variation in mine pumping rate (*Q_mine*). The drawdown predictions are much less sensitive to the drainage level or recharge. The predicted surface water – groundwater flux and change in this flux are most sensitive to riverbed conductance (*C_riv*) and hydraulic properties. Where feasible, opportunities to reduce predictive uncertainty of drawdowns are best directed to constraining the hydraulic properties.

Many of the assumptions and modelling choices, discussed in Section 2.6.2.8, were influenced by a lack of region-wide, good-quality data to better characterise the lithology and hydrogeology across the whole model domain and constrain model predictions: the available hydraulic conductivity data are not correlated with the geological layers and the lithology of the geological model; the drainage level (channel depth) along the stream network is generally poorly defined; acceptable historical groundwater level data to constrain the model are sparse; and the relative contribution of groundwater to streamflow is generally not known.

The hydraulic properties in the model do not vary with lithology (except that the alluvium has higher hydraulic conductivity and porosity than the underlying rock), therefore, there are no aquitards (at any scale) represented within the model layering. Hydraulic conductivities are assumed to decrease smoothly with depth (rate of decay is controlled by *K_lambda*). The model's predictive uncertainty would be reduced through a more accurate specification of the hydraulic properties of the groundwater system. This includes both the in situ hydraulic conductivity and porosity, and an improved characterisation of the hydraulic enhancement process caused by mining-induced strata deformation (see Section 2.6.2.7.2.2). More information about the hydraulic conductivity measurements (e.g. measurement method, lithology, depth, fracturing; presence of aquitards) would assist in classifying these data. Better resolution of the geological and lithological layers in the geological model might contribute to a better correlation of hydraulic conductivity measurements with lithology – that is, if better resolution permitted the observation data to be stratified more confidently by lithology.

Changes in the hydraulic properties used to represent the goaf in the model do not include changes to porosity (storage) and water head due to the volumetric expansion of the overburden. Inclusion of these changes will naturally decrease the initial slug of water (see Section 2.6.2.7.2.2), but will play no role in the long term behaviour of baseflow.

As discussed in Section 2.6.2.7, relatively few high-quality, long-term observations of groundwater levels are publically available. Many historical observations of groundwater level were not used for constraining the model as the observations did not have reliable coordinates, and/or the record was taken at the time of drilling and considered unlikely to represent the true groundwater level. A more detailed assessment of the quality of these data and field verification of bore locations are needed if more useful data are to be extracted from the existing dataset. Mining companies collect piezometer data, which could also help to constrain the groundwater levels locally.

The sensitivity analysis indicated that groundwater level and the surface water – groundwater flux are most sensitive to the riverbed elevation specified in the groundwater model through parameter *d_riv*. However, the predictions of drawdown (*dmax*) due to the additional coal resource development (i.e. maximum difference in drawdown between the coal resource development pathway (CRDP) and baseline) are not sensitive to this parameter. Unless the uncertainty in riverbed elevation is reduced independently – for instance, through surveyed river network information and higher spatial model resolution – additional or improved observation datasets will not greatly reduce the predictive uncertainty in *dmax*.

Selected percentiles of the total streamflow are used to constrain the surface water – groundwater flux in the model. There is a great opportunity to improve the regional-scale estimates of surface water – groundwater flux through a combination of baseflow separation, salt balance and environmental tracers.

Evapotranspiration in the groundwater model was represented by *PET* and an extinction depth which was assumed to be related to vegetation height. The extinction depth parameter was not included in the uncertainty analysis as it was deemed unlikely to affect *dmax* because it would have similar effects on the baseline and CRDP and therefore largely cancel out in estimation of *dmax*. The assumption was revisited using a one-at-a-time sensitivity analysis when model results showed differences in evapotranspiration between baseline and CRDP (see Section 2.6.2.8.2.16). This analysis supported the initial assessment that model predictions were not sensitive to the extinction depth parameter. Nonetheless, better representation of local-scale influences on evapotranspiration would improve local-scale predictions of groundwater levels, and potentially yield a more tightly constrained set of model parameters when compared with historical water-level data.

The predictive uncertainty would also be reduced by a more accurate representation of mining progression over time. This includes expanding the mine footprint area over time, rather than using the maximum footprint area from the first day of mining, and hence phasing in the hydraulic enhancement over the life of the mine also. Some of these improvements are relatively easy to implement, and were not undertaken due to operational constraints of the BA. During the period when the model was under construction, the coal resource development pathway changed numerous times due to, for example, mining companies lodging, modifying or withdrawing environmental impact statements.

2.6.2.9.3 Conclusions

The Hunter subregion groundwater model is developed with the finite element, multiphase groundwater flow simulator MOOSE (Multiphysics Object-Oriented Simulation Environment) to probabilistically assess the drawdown (*dmax)* due to the additional coal resource development, and year of maximum change (*tmax*), as well as provide the change in surface water – groundwater flux as a boundary condition for the surface water modelling reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

For more than three-quarters of the model output nodes, the median value of the simulated *dmax* is less than 0.2 m. The probability of exceeding this threshold is 100% within the immediate vicinity of the mine footprint area and decreases rapidly with increasing distance from the mine. The contour of 5% probability of exceeding 0.2 m drawdown is generally within 20 km of the mine footprint boundary. This also means that the zone of hydrological change of two mines only overlaps when they are within 20 km of each other.

Generally, the magnitude of drawdown due to the additional coal resource development, which is the difference in drawdown between CRDP and baseline, is most sensitive to the porosity and hydraulic conductivity; somewhat sensitive to the mine pumping rates, the decay of hydraulic conductivity with depth and the riverbed conductance; and much less sensitive to the river stage height, the rainfall recharge, the decay of porosity with depth, the ratio of vertical to horizontal conductivity, and the conductivity-enhancement ramp function.

The *tmax* varies between 2012 and 2102 and thus spans the entire simulation period. It indicates that while *dmax* can be achieved during mining operations, it is very likely that *dmax* is attained in the decades after mining ceases. The *tmax* increases with increasing distance from mine tenements. The largest drawdowns due to additional coal resource development occur in close vicinity of the mines, within or shortly after the peak mining period and within the simulation period. Further away from the mines, the drawdown due to additional coal resource development takes longer to reach a maximum, potentially beyond the simulation period, but as the drawdowns are not likely to be significant and are increasingly uncertain, there is little to be gained through extending the simulation period to provide a more precise estimate of *tmax*.

The simulated changes in surface water – groundwater flux are integrated into the surface water modelling, reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018). The additional coal resource development can sometimes lead to an increase in baseflow for some parameter combinations. The possibility of baseflow increases is consistent with the understanding of the dynamics of the groundwater system during and after mining as well as with the conceptualisation of the groundwater model, although observations of mine-induced baseflow increases have not been reported in the literature.

The probabilistic estimates of *dmax* are constrained by a distance-based weighting of groundwater level observations and by estimates of total streamflow. The groundwater level and streamflow observations mostly constrained the drainage level assigned to river nodes in the model and to a lesser extent the hydraulic properties of the groundwater model. The predictions of *dmax* were not sensitive to the drainage level, but to the hydraulic properties and, to a lesser extent, the mine pumping rates and the implementation of the hydraulic enhancement after longwall mine collapse. The latter two parameters are not strongly constrained by the observations.

The probabilistic hydrological changes presented in this product will form the basis of the further receptor impact modelling reported in companion product 2.7 for the Hunter subregion (as listed in Table 2) and the impact and risk analysis reported in companion product 3-4 for the Hunter subregion (as listed in Table 2). The significance of the groundwater changes due to additional coal resource development relative to groundwater changes under the baseline are also considered in the 3-4 product.

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

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Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

conceptual model: abstraction or simplification of reality

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

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

consequence: synonym of impact

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).

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

diversion: see extraction

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.

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).

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

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

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

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

groundwater system: see water system

hazard: an event, or chain of events, that might result in an effect (change in the quality or quantity of surface water or groundwater)

Hunter subregion: Along the coast, the Hunter subregion extends north from the northern edge of Broken Bay on the New South Wales Central Coast to just north of Newcastle. The subregion is bordered in the west and north–west by the Great Dividing Range and in the north by the towns of Scone and Muswellbrook. The Hunter River is the major river in the subregion, rising in the Barrington Tops and Liverpool Ranges and draining south-west to Lake Glenbawn before heading east where it enters the Tasman Sea at Newcastle. The subregion also includes smaller catchments along the central coast, including the Macquarie and Tuggerah lakes catchments.

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

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

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

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

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.

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.

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

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

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

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

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

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

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)

stratigraphy: stratified (layered) rocks

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

subsidence: localised lowering of the land surface. It occurs when underground voids or cavities collapse, or when soil or geological formations (including coal seams, sandstone and other sedimentary strata) compact due to reduction in moisture content and pressure within the ground.

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

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

unsaturated zone: the zone in soils and rocks occurring above the watertable, where there is some air within the pore spaces

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-dependent asset register: a simple and authoritative listing of the assets within the preliminary assessment extent (PAE) that are potentially subject to water-related impacts

water make: the groundwater extracted for dewatering mines

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

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

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

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