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

Groundwater numerical modelling for the Gloucester subregion

Product 2.6.2 for the Gloucester 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.

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http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.6.2.

Authorship is listed in relative order of contribution.

Cover photograph

View of the Gloucester valley NSW with the Barrington River and associated riparian vegetation in the foreground and the township Gloucester in the distance looking south from the Kia Ora Lookout, 2013

Credit: Heinz Buettikofer, CSIRO

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Executive summary

Coal and coal seam gas (CSG) development can potentially affect water-dependent assets (either negatively or positively) through a direct impact on groundwater hydrology. Presented in this product are the modelled hydrological changes in response to likely coal resource development in the Gloucester subregion after December 2012.

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

The groundwater numerical modelling in this product has a very specific objective; to probabilistically evaluate the impacts of a single development pathway at specified locations in the landscape to inform the impact and risk analysis (product 3-4). The modelling will therefore not produce a single best estimate of the impact, but will provide an ensemble of predictions.

Groundwater modelling for the Gloucester subregion follows the companion submethodology M07 (as listed in Table 1) for groundwater modelling. Numerical simulation of the impact of the coal resource development pathway (CRDP) on the identified receptors requires a model or model sequence that can simulate the impact on the regional groundwater system, the alluvial groundwater system and the stream network. In the bioregional assessment for the Gloucester subregion (the Assessment) this consists of a pragmatic coupling of three models. Firstly, an analytic element model (referred to as GW AEM) for regional groundwater. This model is designed to simulate the change in drawdown at the receptors associated with the groundwater bores in the Gloucester geological basin weathered zone, and to provide the change in groundwater level underneath the Avon and Karuah alluvium. Secondly, MODFLOW models (referred to as GW ALV) for both the Avon and Karuah alluvium, used to simulate the change in drawdown on receptors associated with the alluvium and the change in surface water – groundwater flux. Thirdly, the Australian Water Resources Assessment (AWRA) landscape (AWRA-L) surface water model to generate streamflow, taking into account surface water rainfall-runoff and surface water – groundwater flux.

Three existing groundwater models are identified that cover various parts of the Gloucester preliminary assessment extent (PAE). All three models are aimed at quantifying the impact of open-cut coal mines on groundwater systems and groundwater levels in alluvial aquifers. All three models are considered unsuitable for direct use in the Assessment, mainly because their spatial extent is too limited to simulate the cumulative hydrological change due the existing and proposed coal resource development.

The Gloucester Basin is considered to be a geologically closed basin with three main hydrogeological units:

- surface alluvium up to 15 m thick, a semi-confined to unconfined aquifer

- shallow weathered and fractured rocks up to 150 m thick, a confined to semi-confined aquifer
- interburden units alternating with coal seams to a maximum depth of about 2500 m, only considered to be water-bearing strata.

The shallow weathered and fractured rock layer underlies the alluvium entirely, and outcrops extensively across the rest of the surface of the Gloucester subregion. Both the Avon and Karuah rivers are unregulated streams, connected with local groundwater. The river system is mostly gaining, with baseflow estimated to be about one-tenth of total streamflow. The alluvial aquifer only receives water from the river system during high flow and flood events.

The CRDP for the Gloucester subregion includes the Duralie and Stratford mines and their expansions and the Rocky Hill Coal Project. AGL's proposed CSG development in the Gloucester Gas Project, stage 1 gas field development area is also included. The CRDP was confirmed in October 2015. There may be further stages (beyond Stage 1) of AGL's proposed CSG development in the Gloucester Gas Project but there is no publicly available documentation of these as at October 2015. In December 2015 AGL withdrew from its proposed Gloucester Gas Project and, according to the companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway, once the CRDP is finalised (October 2015) it is not revisited.

The regional GW AE model, the alluvial MODFLOW models and the AWRA-L model evaluated 10,000 parameter combinations, generated through a Latin Hypercube sampling to simulate the drawdown due to the additional coal resource development. These model results are used to train emulators, statistical models that replace the actual model chain in the uncertainty analysis.

Normal prior distributions are specified for most parameters, either in native or log space, with a mean equal to the centre of the range sampled in the design of experiment. The variance is chosen such that 99% of the probability mass is within the sampled range. A covariance is specified between the parameters controlling hydraulic conductivity and storage and between parameters controlling horizontal and vertical fault hydraulic properties. For the parameters controlling the decrease with depth of hydraulic properties and the fault hydraulic conductivity, the mean is not chosen to be equal to the centre of the sampled range to ensure the hydrologic change is over- rather than underestimated.

The prior parameter distributions of the analytic element model are constrained with the maximum CSG water production rate which resulted in posterior probability distributions for 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 (*dmax*) and year of maximum change (*tmax*) indicating that: (i) the effect on *dmax* is highly localized around the mine pits; (ii) it is unlikely to have drawdowns due to additional coal resource development in excess of 1 m, except in proximity of the mine pits; (iii) the largest *dmax* values are attained within or shortly after the production life of the coal mines and CSG field. Smaller drawdowns due to additional coal resource development, further away from the center of the development activity, are realized at later times, where the smallest noticeable drawdowns due to additional coal resource development are not fully realized within the simulation timeframe; and

(iv) in the modelled drawdowns, the effect of CSG production and the presence of faults and fractures cannot be distinguished from the effect of coal mining in the Gloucester subregion.

The prior parameter distributions for both alluvial MODFLOW models are constrained with historical estimates of the water balance. The resulting posterior ensembles of predictions indicate that (i) hydrological change is limited to the immediate vicinity of coal mines and (ii) it is very unlikely to have drawdown due to additional coal resource development in excess of 1 m in the alluvial aquifers and that (iii) it is very unlikely that the drawdown will cause the groundwater levels to drop below the drainage base of the stream network.

The qualitative uncertainty analysis lists the main model assumptions and choices and discusses their potential effect on the predictions. The model choices with the greatest perceived potential impact on the predictions are related to the implementation of the CRDP. Other model assumptions, such as the hybrid modelling approach, the choice for drainage boundary to represent the stream network and the length of the simulation period are shown to be conservative choices (i.e. the hydrological change is overestimated rather than underestimated).

The modelling framework is tailored to the specific CRDP and receptors and therefore should not be used for any other purpose without a rigorous reassessment of the validity of the model assumptions. The modelling did highlight that improved characterisation of hydraulic properties of the surface weathered and fractured rock layer and more detailed information of local geology around development have the most potential to reduce predictive uncertainty.

The results of this groundwater numerical modelling are used to inform the impact and risk analysis (product 3-4).

Contents

Figures

Tables

Contributors to the Technical Programme

The following individuals have contributed to the Technical Programme, the part of the Bioregional Assessment Programme that undertakes bioregional assessments.

Role or team	Contributor(s)
Assistant Secretary	Department of the Environment and Energy: Matthew Whitfort
Programme Director	Department of the Environment and Energy: Anthony Swirepik
Technical Programme Director	Bureau of Meteorology: Julie Burke
Projects Director	CSIRO: David Post
Principal Science Advisor	Department of the Environment and Energy: Peter Baker
Science Directors	CSIRO: Brent Henderson Geoscience Australia: Steven Lewis
Integration	Bureau of Meteorology: Richard Mount (Integration Leader) CSIRO: Becky Schmidt
Programme management	Bureau of Meteorology: Louise Minty CSIRO: Paul Hardisty, Warwick McDonald Geoscience Australia: Stuart Minchin
Project Leaders	CSIRO: Alexander Herr, Kate Holland, Tim McVicar, David Rassam Geoscience Australia: Tim Evans Bureau of Meteorology: Natasha Herron
Assets and receptors	Bureau of Meteorology: Richard Mount (Discipline Leader) Department of the Environment and Energy: Glenn Johnstone, Wasantha Perera, Jin Wang
Bioregional Assessment Information Platform	Bureau of Meteorology: Lakshmi Devanathan (Team Leader), Derek Chen, Trevor Christie-Taylor, Melita Dahl, Angus MacAulay, Christine Price, Paul Sheahan, Kellie Stuart, Carl Sudholz CSIRO: Peter Fitch, Ashley Sommer Geoscience Australia: Neal Evans
Communications	Bureau of Meteorology: Jessica York CSIRO: Clare Brandon Department of the Environment and Energy: John Higgins, Lea Locke, Miriam McMillan, Milica Milanja Geoscience Australia: Rachel Houlahan
Coordination	Bureau of Meteorology: Brendan Moran, Eliane Prideaux, Sarah van Rooyen CSIRO: Ruth Palmer Department of the Environment and Energy: Anisa Coric, Lucy Elliott, James Hill, Andrew Stacey, David Thomas, Emily Turner
Ecology	CSIRO: Anthony O'Grady (Discipline Leader), Caroline Bruce, Tanya Doody, Brendan Ebner, Craig MacFarlane, Patrick Mitchell, Justine Murray, Chris Pavey, Jodie Pritchard, Nat Raisbeck-Brown, Ashley Sparrow

Role or team	Contributor(s)
Geology	CSIRO: Deepak Adhikary, Emanuelle Frery, Mike Gresham, Jane Hodgkinson, Zhejun Pan, Matthias Raiber, Regina Sander, Paul Wilkes Geoscience Australia: Steven Lewis (Discipline Leader)
Geographic information systems	CSIRO: Jody Bruce, Debbie Crawford, Dennis Gonzalez, Mike Gresham, Steve Marvanek, Arthur Read Geoscience Australia: Adrian Dehelean, Joe Bell
Groundwater modelling	CSIRO: Russell Crosbie (Discipline Leader), Tao Cui, Warrick Dawes, Lei Gao, Sreekanth Janardhanan, Luk Peeters, Praveen Kumar Rachakonda, Wolfgang Schmid, Saeed Torkzaban, Chris Turnadge, Andy Wilkins, Binzhong Zhou
Hydrogeology	Geoscience Australia: Tim Ransley (Discipline Leader), Chris Harris-Pascal, Jessica Northey, Emily Slatter
Information management	Bureau of Meteorology: Brendan Moran (Team Leader), Christine Panton CSIRO: Qifeng Bai, Simon Cox, Phil Davies, Geoff Hodgson, Brad Lane, Ben Leighton, David Lemon, Trevor Pickett, Shane Seaton, Ramneek Singh, Matt Stenson Geoscience Australia: Matti Peljo
Products	CSIRO: Becky Schmidt (Products Manager), Maryam Ahmad, Helen Beringen, Clare Brandon, Heinz Buettikofer, Sonja Chandler, Karin Hosking, Allison Johnston, Maryanne McKay, Linda Merrin, Sally Tetreault-Campbell, Catherine Ticehurst Geoscience Australia: Penny Kilgour, Kathryn Owen
Risk and uncertainty	CSIRO: Simon Barry (Discipline Leader), Jeffrey Dambacher, Jess Ford, Keith Hayes, Geoff Hosack, Adrien Ickowicz, Warren Jin, Dan Pagendam
Surface water hydrology	CSIRO: Neil Viney (Discipline Leader), Santosh Aryal, Mat Gilfedder, Fazlul Karim, Lingtao Li, Dave McJannet, Jorge Luis Peña-Arancibia, Xiaogang Shi, Tom Van Niel, Jai Vaze, Bill Wang, Ang Yang, Yongqiang Zhang

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This technical product was reviewed by several groups:

- Senior Science Leaders: David Post (Projects Director), Steven Lewis (Science Director, Geoscience Australia), Brent Henderson (Science Director, CSIRO), Becky Schmidt (Products Manager)
- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment and Energy), this group comprises officials from the NSW, Queensland, South Australian and Victorian governments
- Independent reviewers: Dirk Mallants (CSIRO) Warwick McDonald (CSIRO).

Currency of scientific results

The modelling results contained in this product were completed in July 2015 using the best available data, models and approaches available at that time. The product content was completed in November 2016.

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.

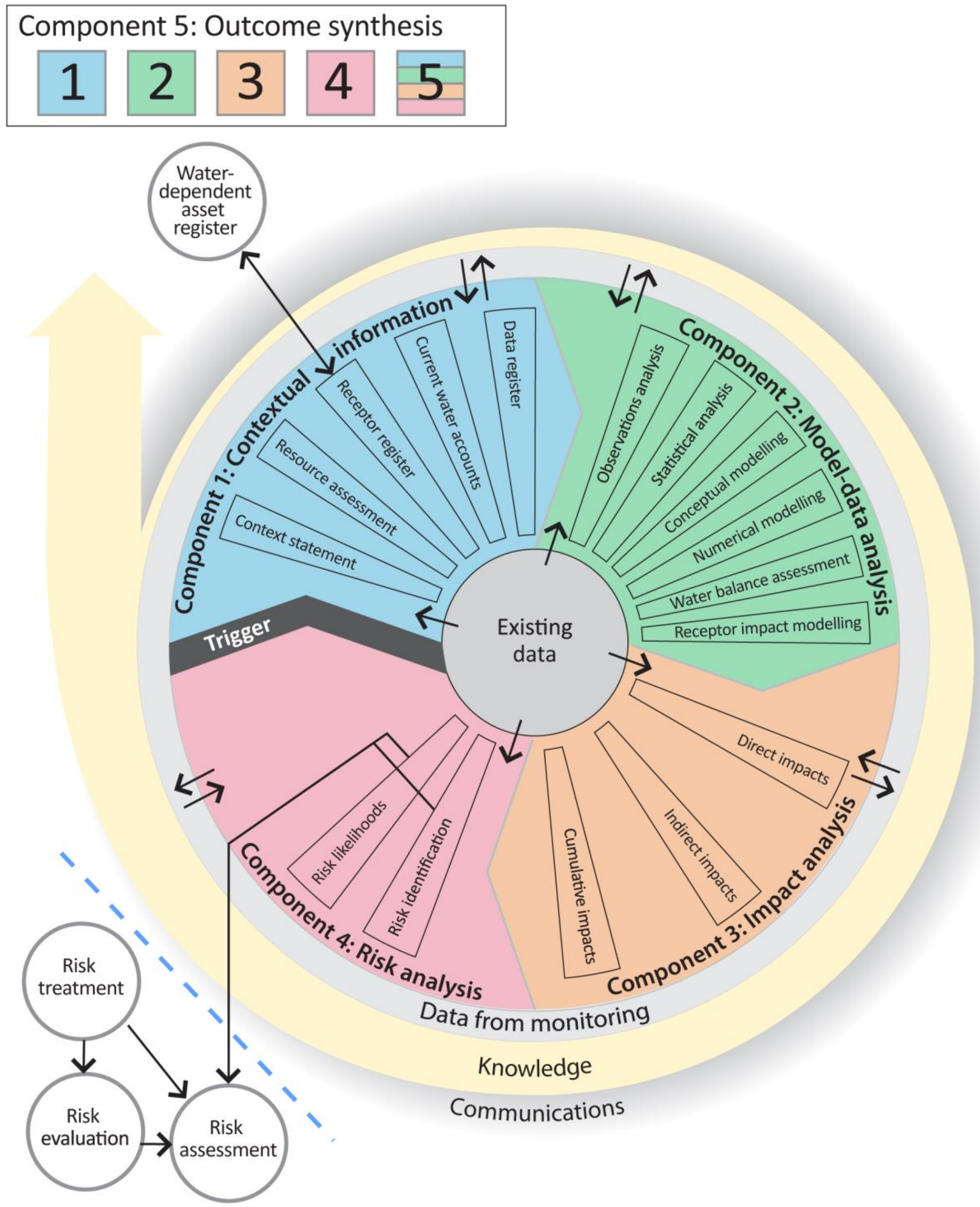

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

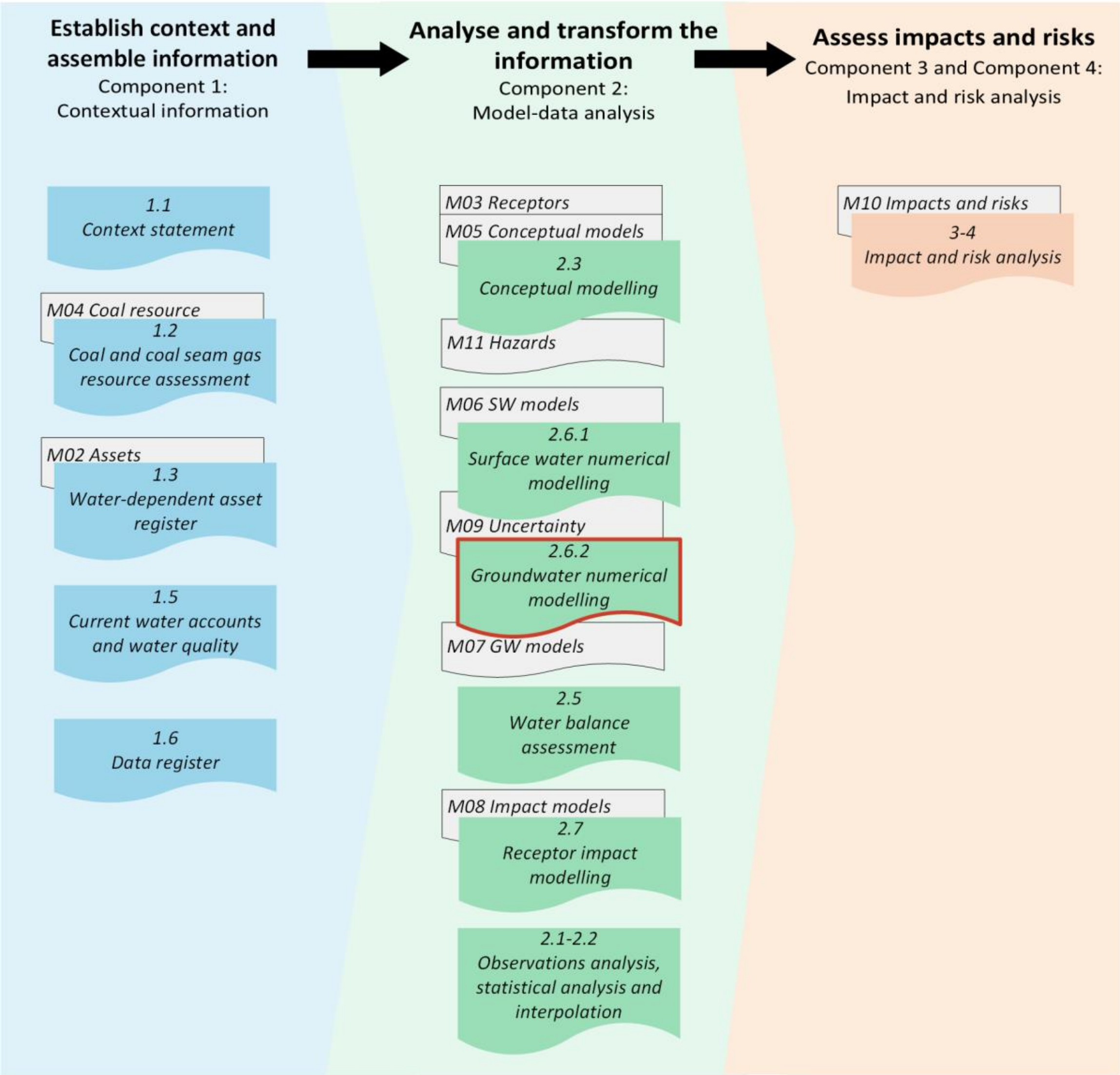

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Gloucester 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 Gloucester 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 Gloucester 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 Gloucester subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Gloucester 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°.
- Contact bioregionalassessments@bom.gov.au to access metadata (including copyright, attribution and licensing information) for all datasets cited or used to make figures in this product. At a later date, this information, as well as all unencumbered datasets, will be published online.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's created date. Where a created date is not available, the publication date or last updated date is used.

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 1 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 1 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 Gloucester subregion

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

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

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

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

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

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

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

2.6.2.1 Methods

Summary

The numerical modelling is designed to provide probabilistic estimates of the potential hydrological change due to coal resource development at receptors. Differences in spatial and temporal scale necessitated the development of a model chain of three models to assess the hydrological change in the surface weathered and fractured rock layer, the alluvial aquifer and in the stream network.

The model chain consists of a regional scale analytic element groundwater model to simulate the change in the surface weathered and fractured rock layer and provide a boundary condition for two local MODFLOW models that simulate groundwater flow in the alluvial aquifers. The change in surface water – groundwater interaction flux is propagated to the AWRA-L model that integrates this change with the interception of runoff by open pit mining to simulate the change in streamflow.

This section discusses the fitness for purpose of the model chain and modelling approach and provides an outline of the uncertainty analysis workflow.

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 product 3-4 (impact and risk analysis).

The modelling is focused on the change in hydrogeological stress and the hydraulic properties, rather than on reproducing historical conditions or predicting future-state variables of the system, such as groundwater levels 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.

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

The probabilistic aspect of the analysis implies that modelling does not provide a single best estimate of the change, but rather an ensemble of estimates based on user-defined probability distributions of input parameters. This ensemble enables statements such as:

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

To generate these ensembles of predictions, a large number of model parameter sets will be evaluated for the surface water and groundwater models. The range of parameters reflects both the natural variability of the system and the uncertainty in the understanding of the system as of 22 April 2016. During the uncertainty analysis, these parameter combinations are filtered in such a way that only those that are consistent with the available observations and the understanding of the system are used to generate the ensemble of predictions. When no relevant observations are available, the prior parameter combinations are not constrained. The details are documented in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016).

It is not possible to capture all uncertainty in the understanding of the system in the parameterisation of the numerical models. It is, therefore, inevitable that there will be a number of assumptions and model choices necessary to create the models. This is often referred to as structural or conceptual model uncertainty. These assumptions are introduced and briefly discussed in Section 2.6.2.3 about model development. The qualitative uncertainty analysis in Section 2.6.2.8.2 further provides a systematic and comprehensive discussion of these assumptions. This discussion focuses on the rationale behind the assumptions and the effect on the predictions.

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

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

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

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

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

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

2.6.2.1.2 Groundwater numerical modelling

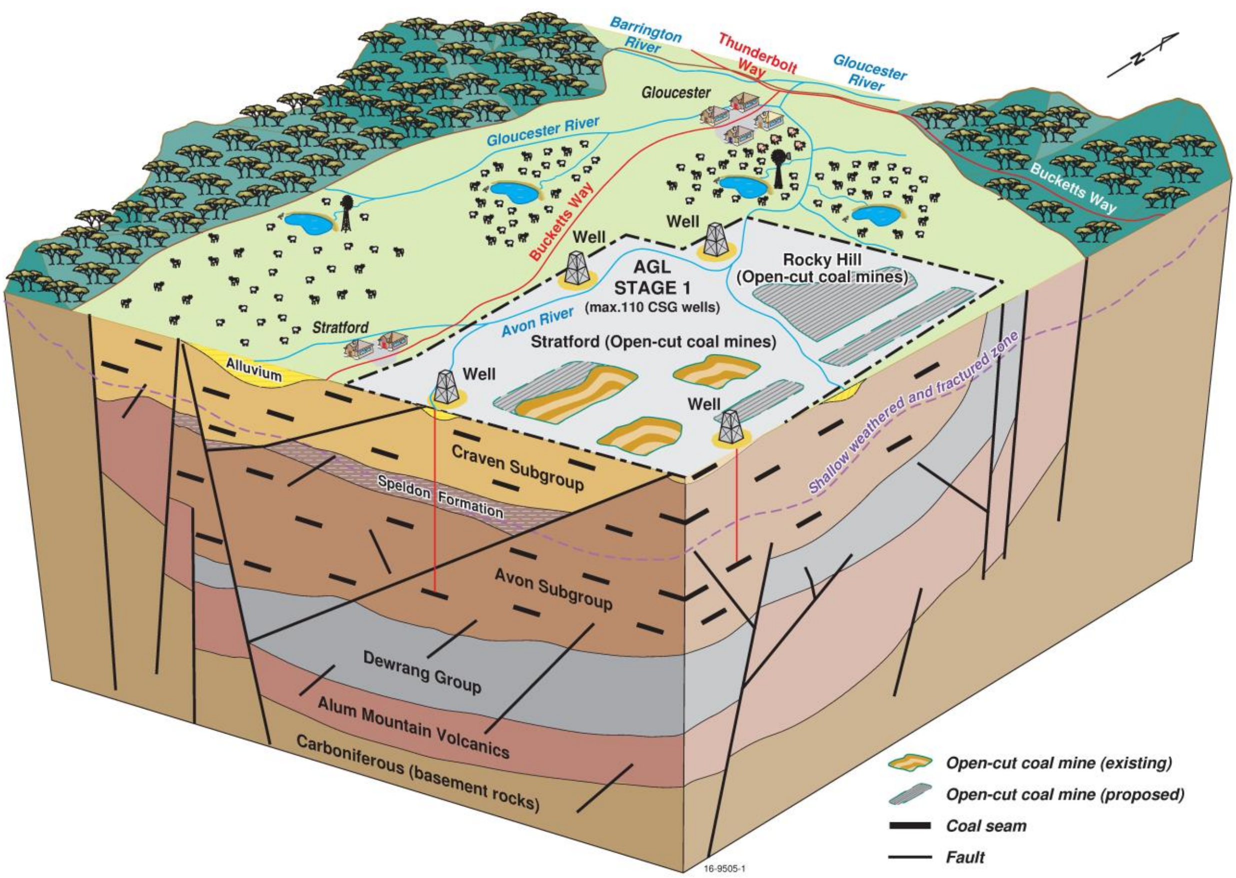

Figure 3 Conceptual block diagram of the Gloucester subregion

The conceptual understanding of the Gloucester subregion is summarised in Figure 3 and companion product 2.3 for the Gloucester subregion (Dawes et al., 2018). The Gloucester Basin is considered to be a geologically closed basin with three main hydrogeological units:

- surface alluvium up to 15 m thick, a semi-confined to unconfined aquifer
- shallow weathered and fractured rocks up to 150 m thick, a confined to semi-confined aquifer
- interburden units alternating with coal seams to a maximum depth of about 2500 m, only considered to be water-bearing strata.

The shallow weathered and fractured rock layer (SRL) underlies the alluvium entirely, and outcrops extensively across the rest of the surface of the Gloucester subregion. Both the Avon and Karuah rivers are unregulated streams (see Section 2.1.6 in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)), connected with local groundwater (McVicar et al., 2014, Section 1.1.6). The river system is mostly gaining, with baseflow estimated to be about one-tenth of total streamflow (Dawes et al., 2018, Section 2.3.2.4). The alluvial aquifer only receives water from the river system during high flow and flood events.

The main causal pathways inferred in Dawes et al. (2018), Section 2.3.5.3, for coal seam gas operations are aquifer depressurisation and inter-aquifer connectivity, while for open-cut mines the disruption of natural surface water drainage and inter-aquifer connectivity, including pumping to dewater mines by lowering the watertable, are listed as main causal pathways. Any water extraction in either the coal seams, interburden or the shallow weathered and fractured rocks has the potential to affect groundwater levels in the SRL and alluvium. A change in groundwater levels in the alluvium may affect the surface water – groundwater exchange flux and thus streamflow. Open-cut coal mines have a more direct impact on surface water flow as all rainfall within the mine footprint area is contained on site and no longer contributes to runoff. The role of faults and fractures to increase or decrease inter-aquifer connectivity is highlighted as an important knowledge gap.

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

Table 3 Assessment of groundwater numerical modelling approach in the Gloucester subregion

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

2.6.2.1.2.1 Prediction of hydrological response variables

The objective of the numerical modelling undertaken as part of a BA is to probabilistically assess hydrological changes arising from coal resource development at water-dependent assets and receptors (see companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2015)). The groundwater and surface water modelling predicts changes in hydrological response variables, the hydrological characteristics of the system or landscape class that potentially change due to coal resource development. These hydrological response variables are the input for receptor impact models that will evaluate how the change in hydrology and hydrogeology results in a change in the economic value or ecology of assets.

In order to probabilistically assess a change through the uncertainty analysis, the receptor locations and hydrological response variables need to be defined explicitly, both in their spatial and temporal support as in what state variable of the numerical model they relate to. The receptors directly linked to groundwater in the receptor register (see companion product 1.3 (McVicar et al., 2015) for the Gloucester subregion) are point locations associated with bores, basic water rights and groundwater (stock and domestic bores), water access rights and supply and monitoring infrastructure, were provided by the NSW Office of Water (2013). Groundwater-dependent ecosystems for which spatial coordinates are available and, at a minimum which aquifer or hydrogeological unit they are associated with, also were identified by the NSW Office of Water (Kuginis et al., *In prep.*). Table 4 summarises these groundwater receptors and their locations are shown in Figure 4.

Table 4 Summary of groundwater receptors in the Gloucester subregion

Zone	Basic water right (stock and domestic)	Water access right	Supply and monitoring infrastructure	Groundwater-dependent ecosystem	Total
Surface weathered and fractured rock layer	20	16	86	0	122
Alluvium	1	1	28	32	62
Outside model domain	1	1	14	39 (*)	55
Within mine lease	0	1	23	0	24
Total	22	19	151	71	263

(*) outside alluvium
Data: Bioregional Assessment Programme (Dataset 1)

The four types of receptors (basic water right, water access right, supply and monitoring, and groundwater-dependent ecosystem) are assigned to the zone they are located in. Bores are assigned to the surface weathered and fractured rock layer if they are outside the alluvium or, if they are in the alluvium, have a reported bore depth in excess of 15 m. Bores situated in the alluvium with no recorded bore depth or depth less than 15 m are assigned to the alluvium. 90 out of the 122 bores assigned to the surface weathered and fractured rock layer have recorded bore depths. Only 15 of these have depths in excess of 150 m, which are limited to supply and monitoring infrastructure bores. While it is very likely that these are bores associated with the exploration and monitoring of coal seam gas, the receptor database does however not record the owner of each bore. 24 groundwater receptors, 1 water access right and 23 supply and monitoring bores, appear to be located within a mine lease. These are excluded from the numerical modelling as they are beyond the resolution of the regional model and out of scope for the BAs.

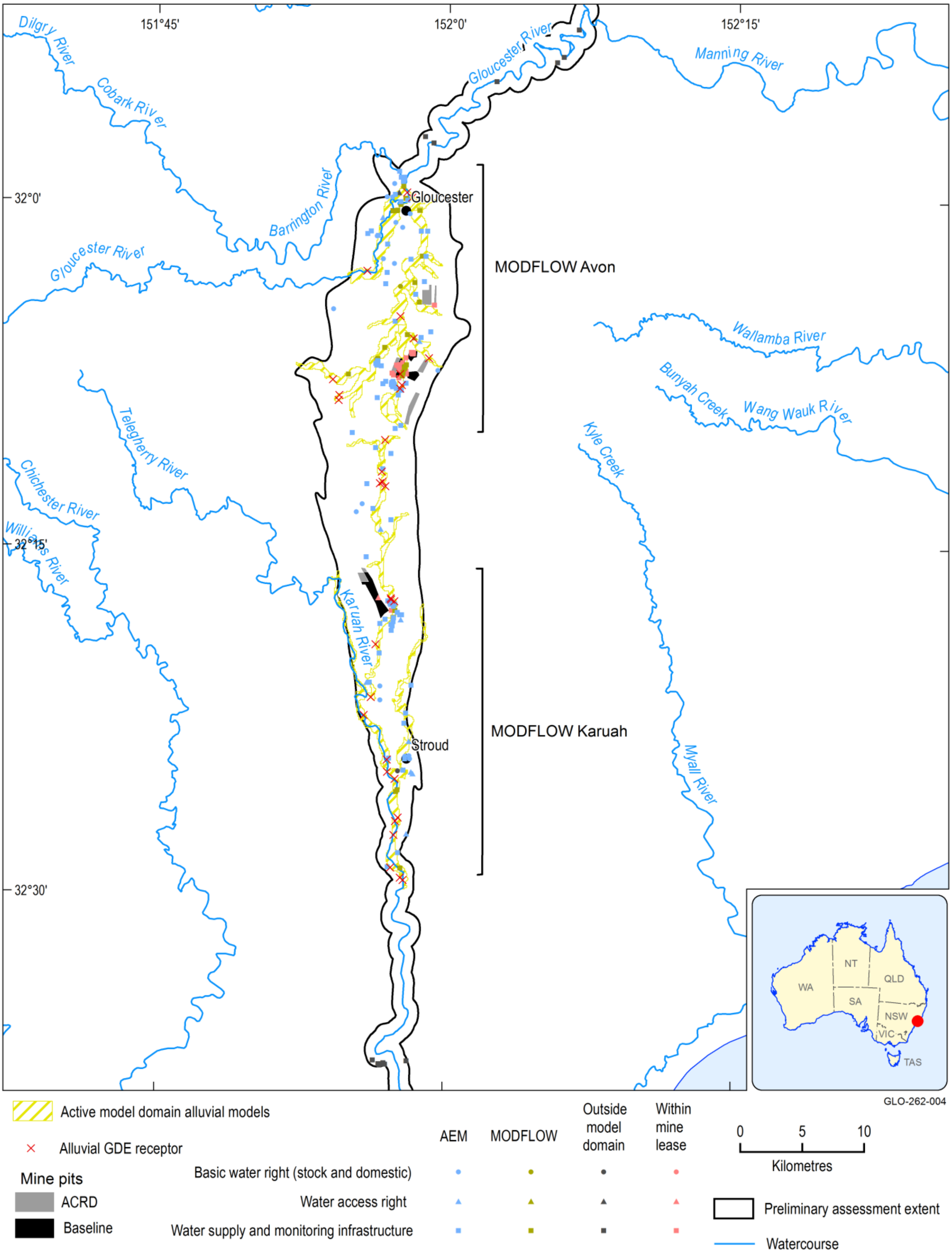

Figure 4 Groundwater receptor locations in the Gloucester subregion

ACRD = additional coal resource development

Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3)

Groundwater-dependent ecosystems are only included in the list of predictions of the numerical modelling if they are situated in the alluvium. The regional watertable outside the alluvium is hosted in the surface weathered and fractured rock layer and is mostly found at depths greater than 5 to 10 m (Parsons Brinckerhoff, 2015, Fig. 7.9). Groundwater-dependent ecosystems outside the alluvium are therefore likely to depend on local groundwater flow conditions beyond the resolution of the regional-scale groundwater modelling. For this reason, groundwater-dependent ecosystems outside the alluvium are not formally included as receptors in the numerical modelling. The regional-scale hydrological change resulting from the numerical modelling however, can be combined with local hydrogeological information to assess the change at the groundwater-dependent ecosystem location.

The components of the water balance are not specified as a hydrological response variable of relevance for a receptor impact model and are therefore not reported in this product. Companion product 2.5 for the Gloucester subregion (Herron et al., 2018) does summarise the water balance for the subregion and the change in these balances for selected periods in the future.

The hydrological response variables for groundwater are maximum difference in drawdown (*dmax*) for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures, and year of maximum change (*tmax*) at receptor locations, where drawdown is defined as the difference in groundwater level between the baseline and coal resource development. The difference in drawdown between CRDP and baseline is due to additional coal resource development.

For surface water, nine hydrological response variables are defined in submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) at 30 nodes along the stream network (companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018)).

Simulating the change in hydrological response variables at the various receptor locations necessitates the development of an integrated surface water – groundwater model. Groundwater and surface water, however, operate at very different spatial and temporal scales. The surface water obviously is bound to the river channel and floodplain. Streamflow is very responsive to individual rainfall events, requiring at least a daily temporal resolution. The groundwater in the alluvium is bound to the alluvial sedimentary deposits, which form a strip along the rivers of about 15 m thick. Groundwater levels in the alluvial respond to changes in rainfall and river stage, albeit at a longer timescale than surface water (see Section 2.1.5.2 in Frery et al. (2018)). Capturing this dynamic in a numerical model necessitates at minimum a monthly resolution. The deeper hydrogeological units, the SRL, interburden and coal seams are much more spatially extensive, both horizontally and vertically. The groundwater dynamics are very slow, with limited and delayed response to recharge events or flood events in the shallow weathered and fractured rock layer (Parsons Brinckerhoff, 2015, pp. 44–45). To simulate this part of the groundwater system, a high temporal resolution is not required.

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

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

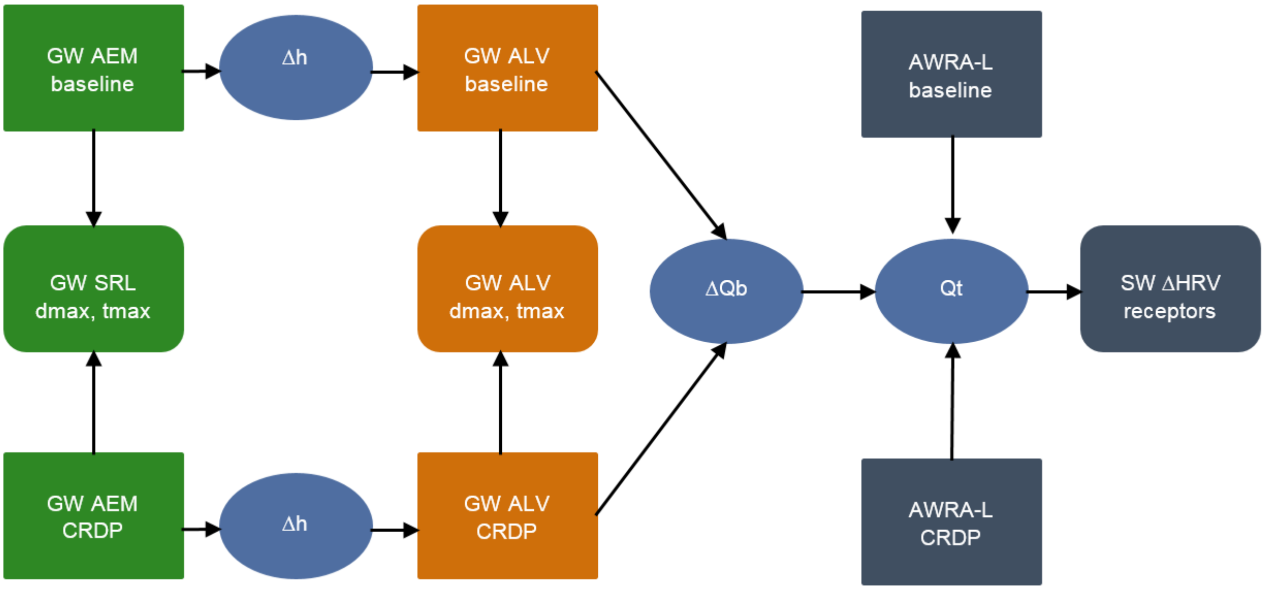

Figure 5 Model sequence for the Gloucester subregion

GW AEM: regional analytic element groundwater model; GW ALV: alluvial MODFLOW groundwater model; AWRA-L: rainfall-runoff model; SRL: surface weathered and fractured rock layer; 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; tmax: year of maximum change; Δh: change in groundwater level; ΔQb: change in surface water – groundwater interaction flux; Qt: total streamflow; ΔHRV: change in hydrological response variable; CRDP: coal resource development pathway; SW: surface water

The regional groundwater model is an analytic element model (referred to as GW AEM), designed to simulate the change in drawdown at the receptors associated with the groundwater bores in the Gloucester geological basin weathered zone, and to provide the change in groundwater level underneath the Avon and Karuah alluvium. The latter provides the lower boundary condition for the alluvial groundwater models. For both alluvial systems a MODFLOW model was developed (referred to as GW ALV) to simulate the change in drawdown on receptors associated with the alluvium and the change in surface water – groundwater flux. This flux is taken into account in the Australian Water Resources Assessment landscape (AWRA-L) surface water model generated streamflow. The change in a number of hydrological response variables is modelled at surface water receptor locations. The modelling of river management or routing of streamflow through the river network with a river model is not necessary as the salient features of streamflow can be simulated solely with a rainfall-runoff model (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

Figure 5 shows in more detail the sequencing of the different models. In the GW AE baseline coal resource development (baseline) model, the impact of historical coal mines and coal mines commercially producing coal as of December 2012 are simulated. The GW AE CRDP model simulates the impact of the CRDP, which is the impact of the baseline coal resource developments as well as those that are expected to begin commercial production after 2012. The difference in simulated drawdown of those two runs will be the simulated impact of the CRDP on the economic receptors in the shallow weathered and fractured rock layer of the Gloucester geological basin.

The GW AE baseline model and GW AE CRDP model simulated impacts underneath the alluvium feed into the alluvial groundwater models for the Avon and Karuah rivers. The difference in simulated drawdown of those two model runs is the simulated impact of the CRDP on the economic and ecological receptors in the Avon and Karuah alluvium. The GW ALV models for the Avon and Karuah rivers also simulate the time series of the change in surface water – groundwater exchange flux, $\Delta Qb(t)$, for the surface water catchments associated with receptor nodes in the AWRA-L model as:

$$\Delta Qb(t) = Qb_{baseline}(t) - Qb_{CRDP}(t) \tag{1}$$

The AWRA-L baseline run simulates streamflow at surface water receptors incorporating the effect of existing and approved open-cut coal mines. The AWRA-L CRDP run simulates streamflow at the surface water receptors incorporating the effect of existing and approved open-cut coal mines plus the additional coal resource development. The total streamflow difference, $\Delta Qt(t)$, is obtained as:

$$\Delta Qt(t) = Qt_{baseline}(t) - Qt_{CRDP}(t) - \Delta Qb(t) \tag{2}$$

The time series of $\Delta Qt(t)$ are summarised in the nine hydrological response variables to highlight different aspects of the hydrograph. These hydrological response variables will inform the receptor impact models for the surface water receptors.

2.6.2.1.2.2 Design and construction

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

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

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

As such, this concept can be implemented in any groundwater modelling code. The choice for analytic element modelling for this regional model is driven by the capability of this code to simulate flow through and the effect of linear features. This is essential to represent flow through faults and fractures. An example of using an analytic element model to represent flow through faults is presented in Department of the Environment (2014, p. 25, Figure 2.4). Simulating this behaviour in finite difference groundwater models, such as MODFLOW-2005, is more challenging. The current analytic element software is very flexible and makes stochastically varying crucial aspects of the conceptualisation, such as the number, position and nature of faults or the number and position of coal seams, relatively straightforward. This means that in the uncertainty analysis it becomes possible to explore more of the conceptual model uncertainty than would be practically feasible with finite difference model codes.

As the surface weathered and fractured rock layer in the Gloucester Basin can be considered as a largely confined flow system (McVicar et al., 2014, p. 56 in Section 1.1.4), the principle of superposition can be applied to directly estimate the change in groundwater levels and fluxes due to coal resource development with the analytic element model. This model approach is very similar to the approach used in Leake et al. (2008). The alluvial system is unconfined and the linearity assumption is likely to be violated. This warranted the design and construction of local MODFLOW models for the Avon and Karuah systems, with the change in boundary conditions due to coal resource development provided by the analytic element model. The MODFLOW models can be considered local refinements or child models of the analytic element model, similar to the approach taken in Abrams et al. (2016).

Further technical detail of the conceptualisation, parameterisation and implementation are documented in Section 2.6.1 of companion product for the Gloucester subregion (Zhang et al., 2018) for the AWRA-L model, and Section 2.6.2.3 for the GW AEM and alluvial MODFLOW models.

2.6.2.1.2.3 Integration with sensitivity and uncertainty analysis workflow

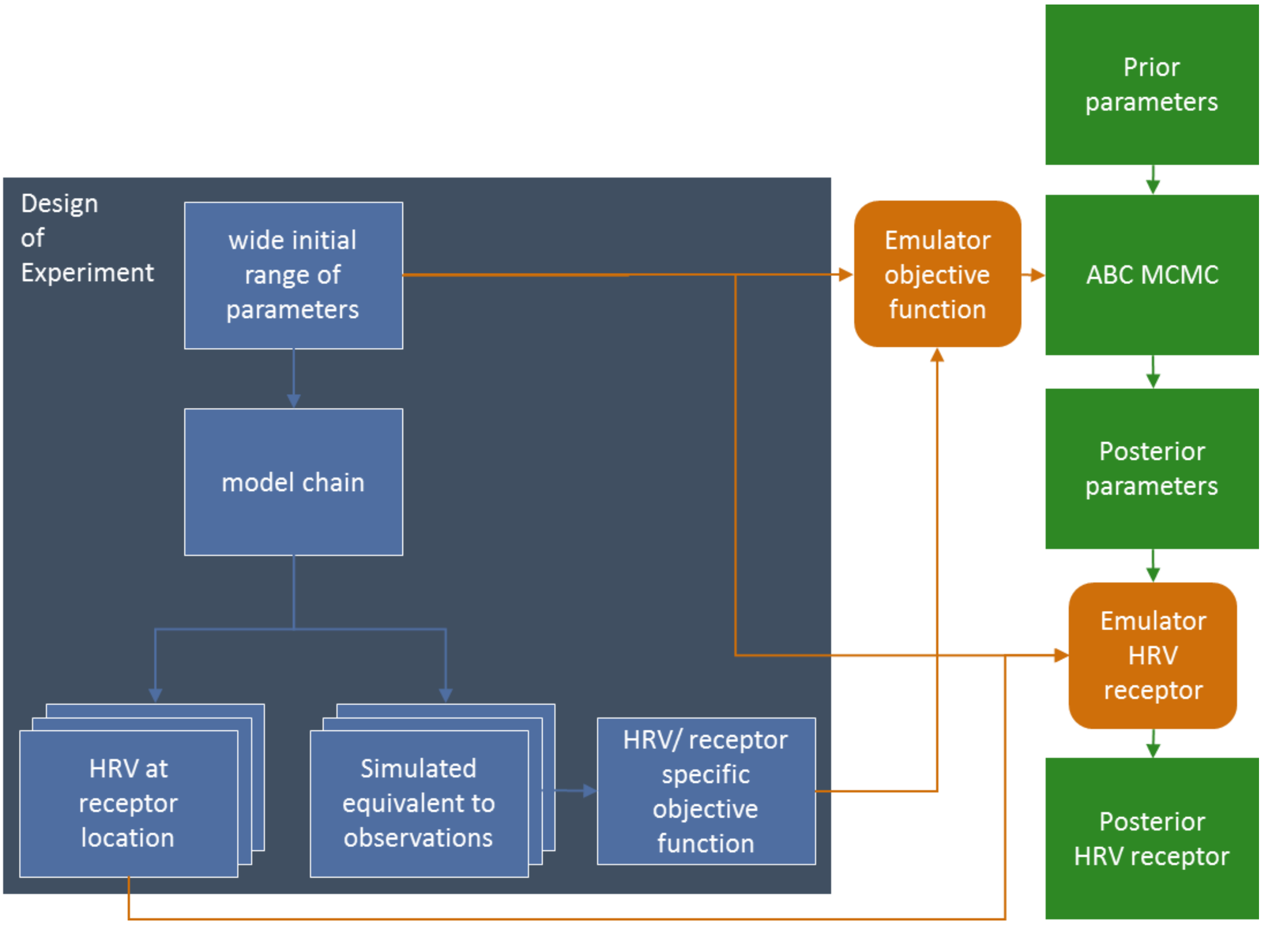

Figure 6 Uncertainty analysis workflow

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

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

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

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 is carried out, sampling extensively from this parameter range. For each evaluation the corresponding simulated change in hydrological response variables at the receptor locations is stored, together with the simulated equivalents to the observations. The latter are summarised into objective functions, tailored to each hydrological response variable.

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

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

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

The three models in the model chain for the Gloucester 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 provides the details of the implementation of this uncertainty propagation workflow for the GW AEM and alluvial MODFLOW models. The uncertainty analysis for the AWRA-L model is in sections 2.6.1.5-6 of companion product 2.6.1 for the Gloucester 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 Water balance components

A secondary objective of the numerical models is to inform the water balance assessment (companion product 2.5 for the Gloucester subregion (Herron et al., 2018)). The MODFLOW models and AWRA model produce estimates of the water balance under baseline and coal resource development futures and can therefore be used in that assessment. The analytic element model, however, only simulates the change in stress due to coal resource development. Its model output therefore has no information on other components of the regional water balance such as recharge or lateral exchange fluxes.

Notwithstanding this limitation, the simulated coal seam gas water production rates will be compared to the estimates of water production by the main coal seam gas proponent to formally constrain the parameter values of the analytic element model. Similarly, estimates of historical groundwater fluxes in the Avon and Karuah alluvial systems will be used to constrain the MODFLOW models.

2.6.2.1.2.5 Transparent and reproducible model outputs

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

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 these scripts and executables, provided the computational resources are available.

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2.6.2.2 Review of existing models

Summary

Three existing groundwater models have been identified that cover various parts of the Gloucester preliminary assessment extent (PAE). They are the Duralie Coal Mine model (developed using Groundwater Vistas software), the Stratford Mining Complex model (developed using Groundwater Vistas software) and the Rocky Hill Coal Project model (developed using the MODHMS modelling package). The Duralie Coal Mine model covers the south part of the Gloucester PAE, while the other two models cover the north parts of the Gloucester PAE. All three models were aimed at quantifying the impact of open-cut coal mines on groundwater systems, which also included a few water supply bores that are currently in use, and groundwater levels in alluvial aquifers.

As part of planning approval for the proposed coal seam gas (CSG) project in the Gloucester Basin, AGL Energy Limited (AGL) is developing a local-scale (cross-sectional model using FEFLOW), as well as a regional-scale, groundwater (using MODFLOW) numerical model (AGL Energy Limited, 2014). As these AGL models were still in development at the time of drafting this product, they were not included for review.

All three models are considered not suitable for direct usage in the bioregional assessment (BA) for the Gloucester subregion, mainly because their spatial extent is too limited to simulate the cumulative hydrological change due to the existing and proposed coal resource development.

This review focuses on both local and regional-scale groundwater models developed to simulate the groundwater impacts of coal seam gas (CSG) and coal mining development in the Gloucester subregion. The main goal of the review is to evaluate if any of the existing models can be used in their current form for the purpose of the bioregional assessment (BA) numerical modelling or if they can be modified to suit this purpose. The main criterion is if the spatial extent of the existing models, both horizontally and vertically, covers the preliminary assessment extent (PAE) or at least the entire geological Gloucester Basin.

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

Three local-scale groundwater flow models have been developed to support the environmental impact statements of the existing (Duralie Coal Mine and Stratford Mining Complex) and proposed coal resource (Rocky Hill Coal Project) developments. They are described in the following sections and Figure 7 shows the model domains of these models. From this map it becomes apparent that none of the existing models covers the entire PAE or geological basin. These models are therefore not suited for the numerical modelling in the Bioregional Assessment Programme.

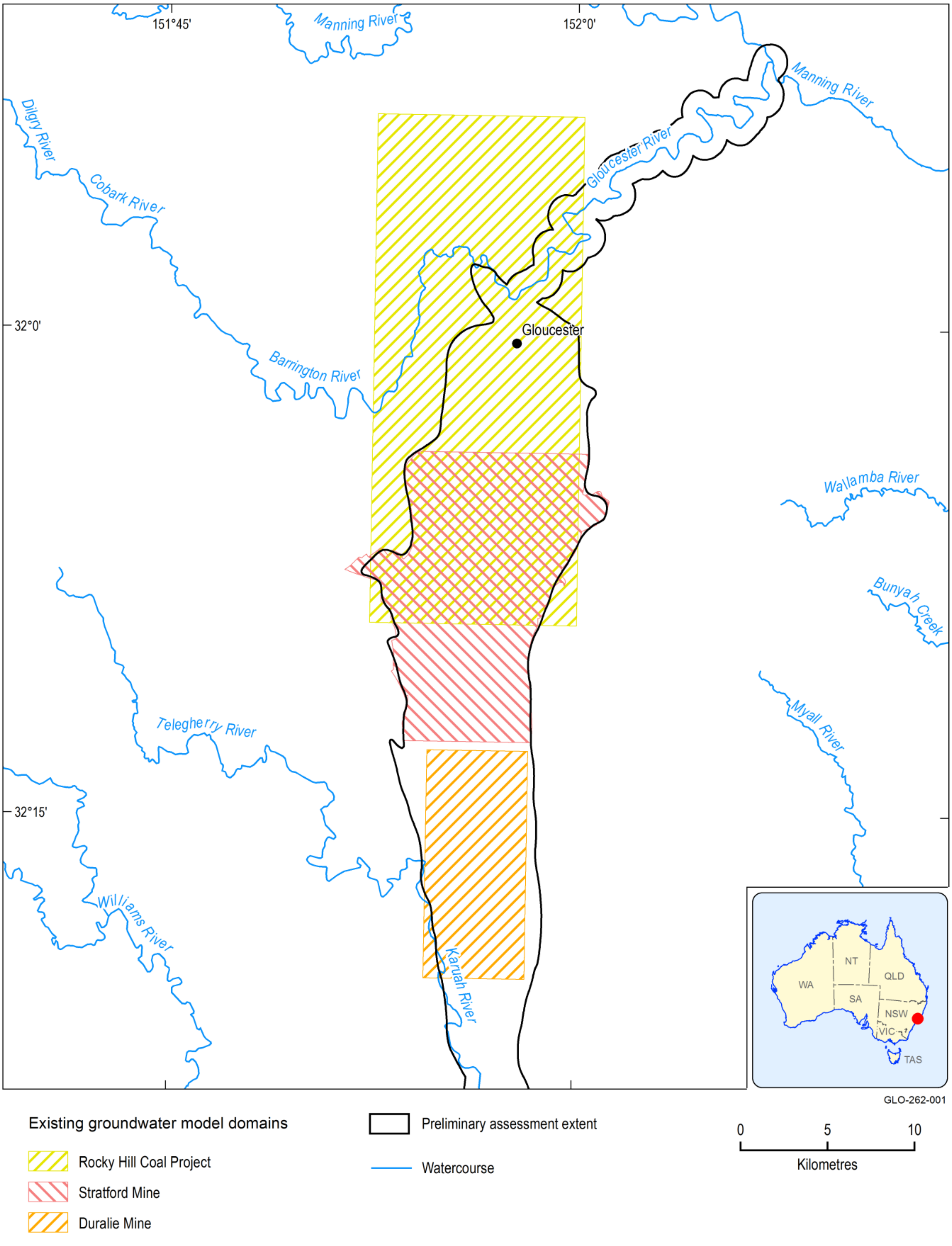

Figure 7 Model domains of existing groundwater models for the Gloucester subregion

Data: Bioregional Assessment Programme (Dataset 1)

As part of planning approval for the proposed CSG project in the Gloucester Basin, AGL Energy Limited (AGL) is developing a local-scale (cross-sectional model using FEFLOW), as well as a regional-scale, groundwater (using MODFLOW) numerical model (AGL Energy Limited, 2014). As these AGL models were still in development at the time of drafting this product, they were not included for review.

2.6.2.2.1 Review of groundwater assessment model for Stratford Mining Complex

Heritage Computing (2012) developed a groundwater model using Groundwater Vistas (a graphical user interface for MODFLOW and other models; Environmental Simulations Inc, 2011) in conjunction with solver MODFLOW-SURFACT (a groundwater modelling software package; HydroGeologic Inc, 2015) for the Stratford Mining Complex. The Stratford Mining Complex encompasses both the Stratford Coal Mine and Bowens Road North Open Cut. The objectives of the groundwater modelling were to assess the potential impacts of Stratford Coal Mine and Bowens Road North Open Cut mining (active and post) development on the groundwater as well as to assess cumulative impacts with the other proposed/approved surrounding mine (Rocky Hill Coal Project) and AGL CSG operations.

The model extent is 15 km × 17 km with an approximate depth of 0.6 km, of which about 70% is active in the simulation. The cells are uniform 50 m by 50 m comprising 340 rows by 306 columns, and about 930,000 active cells. The geometry of the model has four types of units divided into 13 layers. The eastern and western boundaries were chosen to coincide with topographic ridge lines and outcrops of the Alum Mountain Volcanics, and were considered as no-flow boundaries.

The northern and southern boundaries are chosen between 5 and 6 km from future mining areas, where groundwater contours suggest lateral flows are primarily in the east−west direction. These boundaries are simulated as no-flow boundaries accordingly. The model relies on ‘river’ cells in the top two layers to receive discharge near these two boundaries. The Avon River is represented by the MODFLOW river (RIV) package, with stage heights set to 0.5 m below ground surface, and bottom elevation varying from 0.5 m, at the river head, to 2.0 m, in lowland reaches, below ground surface. Dog Trap Creek and Avondale Creek both have river stage set to 2.0 m, and bottom elevation at 2.5 m, below ground level. Minor streams are represented as drains by the RIV package and assigned stage and bottom elevations of 0.1 m below the surface; all minor streams are considered solely as discharge features. Mining operations in the coal seam layers are represented by the MODFLOW drainage (DRN) package, with invert levels (i.e. floor level) set to 0.1 m above the base of the relevant layer. CSG activity in this model is implemented as a complete dewatering of the AGL zone 1 area in all coal seams of the geological model.

The hydraulic conductivity of materials was discretised into 17 zones in the horizontal plane and cut through the 13 layers. Zone 1 is the alluvium, zones 2 to 7 are for the weathered overburden and interburden units, and zones 8 to 17 are for coal seam layers. Calibrated horizontal hydraulic conductivity for alluvia varied from 0.2 to 10 m/day. Horizontal hydraulic conductivities in the coal seams and overburden are specified to decrease with depth according to:

$$Kh_{overburden} = 0.0057\exp(-0.025\ x\ depth) \qquad (3)$$

$$Kh_{coal\ seams} = 0.4211\exp(-0.014\ x\ depth) \qquad (4)$$

Vertical conductivity was initially set to one-tenth of horizontal conductivity, although calibration resulted in vertical conductivities of almost an order of magnitude higher than horizontal conductivity in some coal seams. Specific yield in the alluvium varied between 0.01 and 0.2, while this value is set to 5×10^{-3} for the other units. The storage coefficient for overburden and weathered rock is set to 1×10^{-4}, while for the coal seams this value is 1×10^{-3} for the 0 to 100 m range which decreases to 1×10^{-4} for the deeper coal seams. Riverbed conductances per grid cell varied from 25 to 100 m^2/day, but with no diagrams or indication of where the variations occur spatially. The drain conductance per grid cell was set to 1000 m^2/day to minimise any resistance to inflow.

Recharge from rainfall was imposed as a fixed percentage of rainfall in five distinct zones and varied from 0.25% (hills) to 8% (alluvium). Specific recharge rates were determined solely by calibration. Evaporation was applied uniformly across the model domain, with an extinction depth of 2.0 m below ground surface, and a rate of 0.4 mm/day equivalent to 146 mm/year. There is no discussion of the choice of either the evaporation depth or rate, although at the end of the calibration period it accounts for 7.6 ML/day, or 35% of total model discharge. Stock and domestic water bores were not represented in the model, as the amount of produced water was considered to be too small in volume and too irregularly taken. Large-scale pumping associated with future CSG was represented by 'drain' cells in the model set to an invert level appropriate for depressurisation of the target layer.

Steady-state calibration used 39 point targets, averaged at each site over the full monitoring record (from 1994 to 2010), near past and future mining developments. Automatic calibration using the Model-Independent Parameter Estimation and Uncertainty Analysis (PEST, Doherty, 2005) software was done iteratively during steady-state and transient calibration on hydraulic conductivity, water storage properties, and recharge rates as a percentage of rainfall. Transient calibration proceeded from the heads estimated by the steady-state model, using 90 monthly stress periods from January 2003 to July 2010. Sensitivity analysis was conducted for lateral and vertical hydraulic conductivities of coal seams and weathered rock interburden as well as recharge fraction in the hill zone.

The model predicted a complex pattern of stream loss and gain due to mining operations, but overall it is confined to the minor streams of Dog Trap and Avondale creeks. The patterns of loss and gain varied as pits begin mining or are decommissioned. Cumulative impacts were assessed for the Rocky Hill Coal Project and AGL's Gloucester Gas Project. Pits were represented by 'drain' cells 0.1 m above the bottom of the relevant layer, and CSG by drains with a groundwater level equal to a depressurisation target for gas production. Sensitivity was primarily assessed by pit inflow and CSG-produced water. These were most sensitive to lateral conductivity, but previous variations showed that increasing this led to a poorer fit to observed groundwater levels.

The main hydrological changes predicted by this modelling are:

- The impact on the water level in each privately owned bore is expected to be negligible.
- Drawdown of 1 m was predicted at end-of mining (December 2024) out to less than 1 km around all pits, except south of Roseville West Pit where it may extend to 1.6 km.
- The final voids from the mining pits would remain as permanent groundwater sinks, with increased recharge through the mine waste rock. Total inflow to three pits in the long term is modelled to be 0.9 ML/day.
- As mining progresses, it was anticipated there would be more leakage from the alluvium (in the near vicinity of the pits) to the weathered rocks. The direct water loss from alluvium is estimated as 0.08 ML/day, assuming 2 m of saturated thickness and 10% porosity. Water loss from the weathered rock (in the near vicinity of the pits) to pits is estimated as 1.1 ML/day over the life of mining, and may drop to 0.6 ML/day post mining.
- Cumulative effects are expected to be substantially greater than would be produced by the proposed mining operations. CSG activity would cause pronounced drawdown in the watertable between the Stratford Mining Complex and Stratford.

2.6.2.2.2 Review of groundwater model for Duralie Coal Mine

HydroSimulations (2014), using Groundwater Vistas in conjunction with MODFLOW-SURFACT, developed a groundwater model for the Duralie Coal Mine. The model was developed to define the impact of open-cut coal mines on groundwater systems, which also included a few water supply bores that are currently in use, and groundwater levels in the alluvial aquifer. No quantitative cumulative impact assessment was undertaken due to the large distance from the nearest coal mining and AGL CSG activity areas.

The model extent is 5.85 km × 13 km with an approximate depth of 500 m comprising 260 rows by 117 columns, and about 212,940 active cells. The hydrostratigraphy of the model has four types of units divided into seven layers. The eastern and western boundaries were chosen to coincide with topographic ridge lines and outcrops of the Alum Mountain Volcanics.

The Mammy Johnsons River and Wards River are established as river cells in model Layer 1 using the RIV package, thereby allowing water exchange in either direction between the stream and the aquifer. Minor drainage lines were established as drain cells in the model using the DRN package, allowing groundwater to discharge to the drainage lines as baseflow.

The median river conductance per grid cell is 150 m^2/day with a range from 10 to 450 m^2/day. River stage elevations on Mammy Johnsons River are based on observed stage data from government (NSW Office of Water) gauging stations. The drain conductances per grid cell were set at 50 m^2/day.

The model edges are considered as 'no-flow', with general head boundaries where Mammy Johnsons River enters and leaves the active model area in Layer 1. A wider general head boundary is applied across the alluvial extent of Wards River at the northern boundary. Equivalent general heads are applied through the stratigraphic section at the northern boundary. Drain cells are used to represent mining with a drain conductance per grid cell value of 0.2 m^2/day.

Rainfall recharge has been imposed as a percentage of actual rainfall (for transient calibration) or long-term mean rainfall (for steady-state calibration and prediction simulations) across five zones: regolith (2.6%), hills (10.8%), alluvium (0.9%), subcropping coal seams (0.36%) and spoil zones (0.36 to 2.7%).

Evapotranspiration is applied uniformly using MODFLOW's linear function, with a maximum rate of 3.7 mm/day and an extinction depth of 1.5 m. The recharge rates were determined during model calibration. Additional recharge zones were defined during predictive simulations for both the active mining area (zero recharge) and spoil infiltration (initially zero, then 5% after five years).

Local hydraulic conductivities are reported to range from 1 to 5 m/day for the alluvium and from 0.04 to 3 m/day for the coal seams in the 0 to 200 m depth interval.

Four separate model variants were presented: (i) steady-state calibration, (ii) transient calibration, (iii) transient prediction and (iv) post-mining recovery.

Steady-state calibration was performed against 167 head targets (observations) measured in various years, concentrated near current mining and the proposed Clareval North West open pit. Head targets were allocated to alluvium/regolith (10 points), coal measures/sandstones (15 points) and coal seams (142 points). Automatic calibration using PEST was done iteratively during steady-state and transient calibration on hydraulic conductivity, water storage properties, and recharge rates as a percentage of rainfall. Transient calibration proceeded from the heads estimated by the steady-state model, using 12 quarterly stress periods from January 2003 to December 2005. Sensitivity analysis was conducted for mine drain conductance, mine drain duration, river conductance and the vertical hydraulic conductivity of alluvium on predicted fluxes.

After calibration, the hydraulic conductivities for the coal seams vary between 0.01 and 0.15 m/day and between 1×10^{-6} and 0.5 m/day for the other stratigraphic layers, including the regolith. The ratio of horizontal to vertical conductivity ranges from 0.1 to 5×10^4. Specific yield varies between 0.005 and 0.08 and specific storage is 2×10^{-5} m^{-1} for the alluvium and regolith and 1×10^{-6} m^{-1} elsewhere. The drain conductance for drain cells representing mine dewatering was reduced to 0.2 m^2/day.

The main hydrological changes predicted by this modelling are:

- There is no significant reduction in groundwater levels simulated in the alluvium.
- There is negligible impact on access to water in known registered production bores licensed to external parties.
- There is negligible loss of groundwater yield to surface stream systems (i.e. Mammy Johnsons River).

- Drawdowns are limited to the east, west and south by outcropping volcanics, propagate to the north, and are in the order of 1 to 2 m in the coal seams at the model boundary.
- There is substantial reduction in potentiometric head in the aquifers of the deeper groundwater system due east and to the north of the Duralie Coal Mine area.

2.6.2.2.3 Review of groundwater model for Rocky Hill Coal Project

Australian Groundwater and Environmental Consultants Pty Ltd (2013) developed a groundwater model using MODHMS modelling package (HydroGeologic Inc, 2001). The model was developed to define the impact of open-cut coal mining on groundwater systems, which also included a few water supply bores that are currently in use, and groundwater levels in alluvial aquifers. It also was used for cumulative impact analysis, when in addition to the proposed Rocky Hill Coal Project, the model accounted for AGL CSG activities and the Stratford Coal Mine extension.

The model extent is 6 km × 14.5 km comprising 188 rows by 95 columns, and about 178,600 rectilinear cells. The model has ten layers: alluvial (one layer), colluvium/weathered Permian (one layer), Permian interburden and minor coal seams (four layers), and major coal seams and minor interburden (four layers). However, there is no information on spatial distribution of these layers or their thickness. Only hydraulic properties of individual layers are presented. The majority of the model boundaries were set as no-flow boundaries with limited cells in Layer 1, as constant head boundaries, to represent inflow and outflow from the alluvium. In the model, ephemeral creeks were represented as drains with bed elevation of 4 m below the topographic surface elevation.

The hydraulic conductivity of materials was discretised into six zones along the horizontal plane. Hydraulic conductivity varied from 0.002 to 150 m/day. Recharge from rainfall was imposed as a fixed percentage of rainfall in three zones. Evapotranspiration was applied to the entire model domain as the mean annual rate of 1059 mm/year, with an extinction depth of 2 m below ground surface using the evapotranspiration package. Irrigation wells were not represented in the model, as the amount of produced water was considered to be too small in volume. The modelling was undertaken in three steps:

1. The steady-state model was designed within MODFLOW, and was used to define initial groundwater level conditions for the second step.
2. Transient calibration was undertaken using MODHMS's full capacity (overland flow, channel flow, unsaturated zone modules were included) using a daily stress period from March 2011 to February 2012.
3. The transient predictive model was undertaken using MODHMS's full capacity (overland flow, channel flow, unsaturated zone modules were included) using a quarterly stress period.

The calibration of the steady-state model resulted in hydraulic conductivities of 0.5 m/day for the alluvium, 5×10^{-3} m/day for the weathered zone, 2.64×10^{-2} m/day for the coal seams, 4×10^{-3} m/day for the interburden and 1×10^{-6} m/day for the Alum Mountain Volcanics. Vertical hydraulic conductivity is a factor 10 less than horizontal. For the transient calibration, a daily time step was used for rainfall, and the transient prediction model adopted a quarterly time step over a 14-year modelling period. The water balance was not given either for transient calibration or prediction models and comparison between the two calibration models was not proposed.

Model verification was done using the groundwater level/hydraulic heads monitoring data, which was collected for 12 monitoring bores. Sensitivity analysis was undertaken for the steady-state calibration model, when the sensitivity of simulated heads to a series of model parameters was based on the relative composite sensitivity (RCS) approach as defined in PEST. Two parameters were identified: hydraulic conductivity of overburden and the interburden layers, to which model calibration was most sensitive. Uncertainty analysis was undertaken for one water balance component: water inflow to the pits. The model parameters were assigned the range ±50% and the resulting inflow to the pit ranged from 9% reduction to a 2% increase of the base case model. The parameters which the inflow to the pit was most sensitive to were: specific yield in Layer 1 (alluvial sediments, colluvium and regolith) and hydraulic conductivity of interburden layers and minor coal seams.

The groundwater model was used to project mining impact on groundwater users and impact on the alluvial aquifer:

- *groundwater users*: zero drawdown was identified for the privately owned bores, which are located within the boundary of the model domain
- *alluvial aquifer***:** the cumulative impacts were estimated as (i) from the surrounding operations (AGL CSG and Stratford Coal Mine) (i.e. without Rocky Hill Coal Project); and (ii) Rocky Hill Coal Project and the surrounding operations (AGL CSG and Stratford Mining Complex). The impact was presented as the changes in inflow from the Permian units to the alluvial aquifer. The inflow is 0.4 to 0.6 ML/day (without the Rocky Hill Coal Project). The Rocky Hill Coal Project operation projected to reduce this inflow from the Permian units to the alluvial aquifer to 0.1 to 0.4 ML/day.

2.6.2.2.4 Review of groundwater model for AGL Waukivory Pilot Project

Parsons Brinckerhoff developed a numerical cross-sectional model using FEFLOW, as part of AGL's approval for Waukivory Pilot Project in the Stage 1 gas field development area (AGL Energy Limited, 2014). The model objective was to assess the depressurisation of the alluvium, shallow rock and upper coal measures, due to proposed fracture stimulation and flow testing of four existing pilot exploration wells: Waukivory 11 to Waukivory 14 (AGL Energy Limited, 2014, see Figure 1, p. 91). AGL has proposed to develop a regional-scale model for the Gloucester Basin.

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2.6.2.3 Model development

Summary

The regional analytic element groundwater model (GW AEM) is developed to simulate the drawdown under the coal resource development pathway (CRDP) and under the baseline coal resource development (baseline), at the groundwater receptors in the weathered zone. The difference in drawdown between CRDP and baseline is due to the additional coal resource development. The GW AEM also provides the change in groundwater level in the weathered zone underneath the Avon River and Karuah River alluvium. This will provide the boundary condition for the alluvial groundwater models of the Avon River and Karuah River.

The conceptualisation of the regional model allows the hydraulic properties of the interburden and coal seams to decrease exponentially with depth and to stochastically vary the number and position of coal seams, the presence of seismic faults and the position of subseismic faults.

To assess the impact of coal resource development on groundwater receptors situated in the alluvium of the Avon and Karuah systems and on the surface water – groundwater flux for these river systems, two MODFLOW groundwater models are developed.

They are both two-layer models in which the upper layer represents the alluvial aquifer and the lower layer serves to interact with the regional groundwater model that predicts the change in groundwater level in the underlying weathered zone due to coal resource development.

2.6.2.3.1 Objectives

As stated in Section 2.6.2.1, the objective of the numerical modelling undertaken as part of a bioregional assessment (BA) is to probabilistically assess hydrological changes arising from coal resource development at water-related assets and receptors. The main objectives of the regional analytic element groundwater model (GW AEM) therefore are (i) to provide the drawdown due to additional coal resource development at the receptors located in the surface weathered and fractured rock layer (Section 2.6.2.1, Figure 3 and Table 4) and (ii) provide the change in groundwater levels underneath the Avon and Karuah alluvium for the baseline coal resource development (baseline) and coal resource development pathway (CRDP). These changes are used as the lower boundary condition for the Avon and Karuah alluvial MODFLOW models.

The MODFLOW models will simulate changes in groundwater level at receptor locations associated with the Avon and Karuah alluvium. The MODFLOW models will also estimate the change in surface water – groundwater flux to propagate to the surface water models (companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018)).

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

There is no receptor for which changes in water balance are considered to be the hydrological response variable. While changes in water balance therefore are not an objective of the modelling, probabilistic estimates of coal seam gas (CSG) water production rates will be provided by the analytic element model while changes in the exchange flux between the surface weathered and fractured rock layer and the alluvium are discussed in relation to the MODFLOW models. A more comprehensive discussion on the water balance of the Gloucester subregion is presented in companion product 2.5 (Herron et al., 2018).

2.6.2.3.2 Hydrogeological conceptual model

The conceptual understanding of the Gloucester subregion is defined in companion product 2.3 (Dawes et al., 2018) and summarised in Section 2.6.2.1 and Figure 3. This section pertains to the conceptualisation of groundwater flow in the deeper sedimentary layers and the surface weathered and fractured rock layer, in function of the earlier defined objectives for the analytic element model. The section also describes the conceptualisation of flow in the alluvium and the interaction with the surface weathered and fractured rock layer for the alluvial groundwater models of the Avon and Karuah.

2.6.2.3.2.1 Analytic element model

The bedrock underneath the alluvium and outcropping outside the alluvial extent in the Gloucester Basin cannot be considered as an aquifer system in the traditional sense. This is due to the overall low permeability of the sedimentary rocks and the absence of clearly defined hydrostratigraphic units that can be considered as aquifers. Flow in this sedimentary sequence is dominated by secondary permeability generated through faults and fractures (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). Particularly in the weathered zone at the top of the sedimentary sequence, this secondary permeability is locally high enough to allow water to be produced from bores for stock and domestic water use.

A common conceptualisation of groundwater flow through faults and fractures is that faults act as barriers to flow perpendicular to the fault plane, while in the plane parallel to the fault they can act as conduits (Fachri et al., 2013; Bense et al., 2013). The resistance to flow in the plane perpendicular to the fault, often in the horizontal direction, can arise from the juxtaposition of permeable and less permeable units and from the occurrence of a clay-rich fault gauge in the core of the fault zone (Loveless et al., 2011). The fracturation and brecciation of the fault zone, however, can provide enhanced hydraulic conductivity in the plane parallel to the fault plane, often in the vertical direction (Loveless et al., 2011). Recent investigations of local hydrogeological behaviour of fault zones in the Gloucester subregion (Parsons Brinckerhoff, 2015) indicate that the juxtaposition of coal seams to interburden units by faulting leads to compartmentalisation of coal seams. This points to faults acting as barriers to flow in the horizontal direction. A 29-day pump test in the Waukivory fault zone did not provide any indication that faults act as conduits vertically in the Gloucester subregion. Despite the results of this pumping test, the conceptualisation of faults as horizontal barriers to flow and vertical conduits is adopted. This choice is mostly driven by the adoption of the precautionary principle; faults acting as vertical conduits provide a pathway for depressurisation at depth to migrate rapidly to the shallower stratigraphic units. Not representing this feature could lead to underestimating drawdown in the surface weathered and fractured rock layer. The probabilistic parameterisation of the vertical and horizontal hydraulic conductivities of the fault features (Section 2.6.2.6), however, allows for faults to range from conduits in the vertical to features with hydraulic properties indistinguishable from the interburden.

Hydraulic conductivity has been observed to decrease with depth in this basin (see Parsons Brinckerhoff, 2015, Figures 7.1, 7.2 and 7.3). While there are insufficient observations of the storage coefficient to empirically deduce a similar relationship for storage, it assumed storage also decreases with depth. This is discussed in greater detail in Section 2.6.2.6.

The groundwater system is therefore conceptualised as a sedimentary basin with hydraulic properties that vary as a function of depth rather than as a function of stratigraphy. The top of the sequence is the surface weathered and fractured rock layer with a higher hydraulic conductivity and storage than the unweathered rock. The sedimentary rocks, in this context referred to as interburden, are interspersed with horizontal, thin coal seams with higher hydraulic conductivity and storage than the interburden (Figure 8).

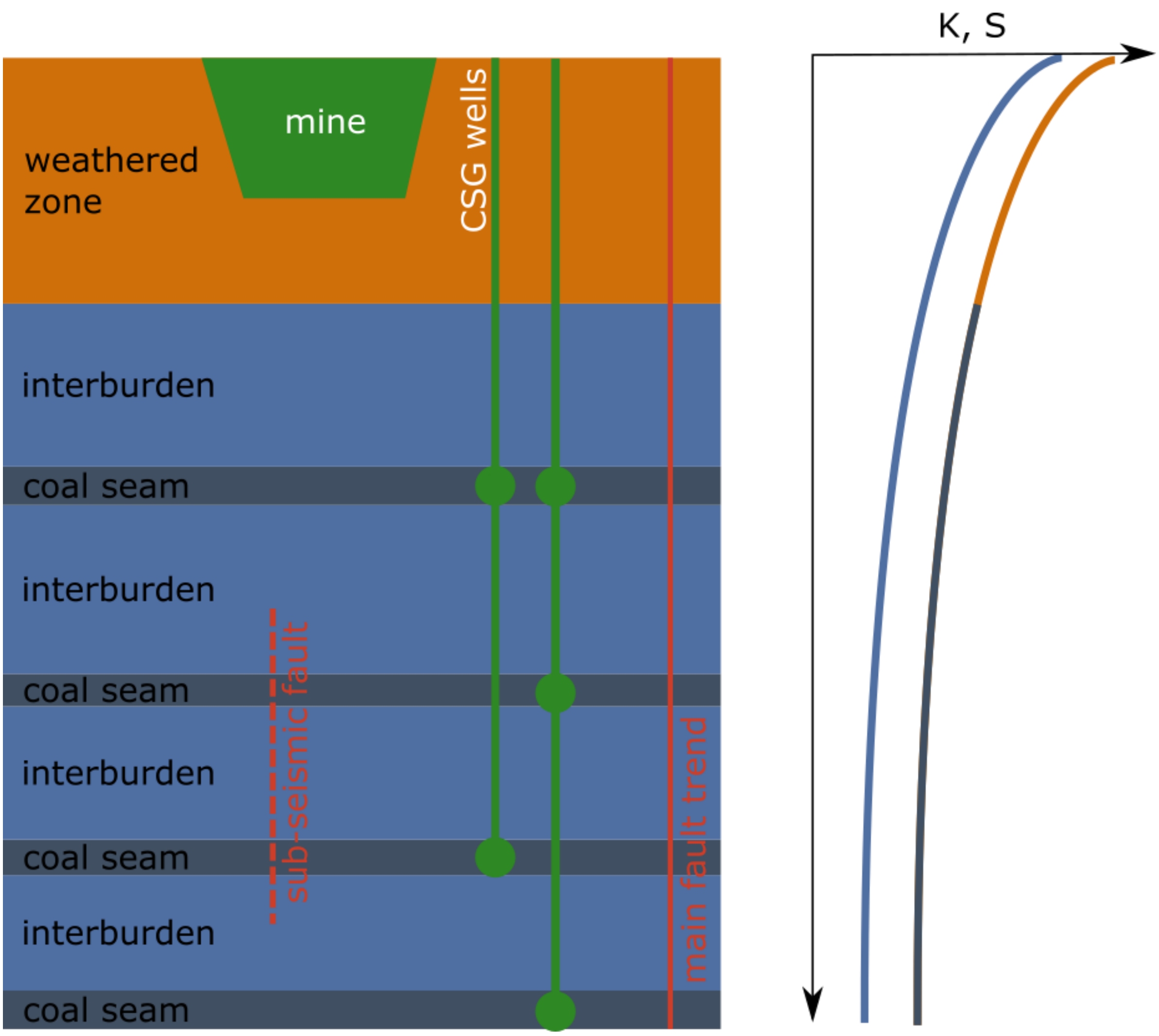

Figure 8 Hydrogeological conceptual model of the regional analytic element groundwater model for the Gloucester subregion

K = hydraulic conductivity; *S* = storage; CSG = coal seam gas
Graph illustrates the decrease of *K* and *S* with depth where colours in the graph correspond to the colour of hydrostratigraphic unit in the diagram on the left.

Throughout the interburden and the coal seams, major faults and subseismic faults are present. Major faults are defined as faults that can be identified on seismic sections, while subseismic faults are smaller faults beyond the resolution of the seismic section. Major faults are considered to affect the entire sedimentary sequence, while the vertical extent of the subseismic faults is limited. Both types of faults are conceptualized as horizontal barriers to flow while being potential vertical conduits. The major faults form the lateral boundaries of the modelled system.

In reality the coal seams are not horizontal or continuous. The sparsity of data and highly heterogeneous nature of the coal seams do not allow representation of the individual coal seams exactly in the model. Although this conceptualisation does not fully represent the geometrical complexity of the coal seams, the implementation of major and subseismic faults allows for depressurisation from CSG production to be propagated not only horizontally through the coal seam and vertically through the sedimentary column, but it also allows propagation throughout the entire sedimentary column rapidly via the faults. Through the same mechanism, the horizontal propagation is hindered by faults, representing compartmentalisation of the coal seams.

The aim of this model is to simulate a change in groundwater levels due to coal resource development rather than reproduce historical observations. In this predominantly confined system, the principle of superposition is valid and therefore initial conditions in groundwater level are assumed to be equal to the top of the model, throughout the model. Recharge is not accounted for in this model. Any recharge to the groundwater system will mitigate the drawdown caused by coal resource development. Not accounting for recharge will therefore only over estimate, not under estimate, the drawdown.

2.6.2.3.2.2 Alluvial MODFLOW models

The mapped alluvium in the Gloucester subregion forms two contiguous units: a northern unit for the Gloucester and Avon rivers (referred to as the Avon model), and a southern unit for the Karuah and Mammy Johnsons rivers (referred to as the Karuah model). The conceptualisation of the groundwater flow in function of the objectives is the same for both units and is illustrated in Figure 9.

In both cases, the alluvial unit is very thin (circa 7 to 15 m) compared to the vertical extent of the sedimentary basin (circa 250 to 1000 m). The alluvial unit is not completely uniform, consisting of a series of layers and lenses of grades of material from sand to clay. At the regional scale, however, there is no consistent set of measurements or descriptions of the alluvial material that allow imposition of any specific spatial pattern or structure on the MODFLOW parameters. For this reason, both the thickness and physical properties of the alluvium are considered uniform across the model domain.

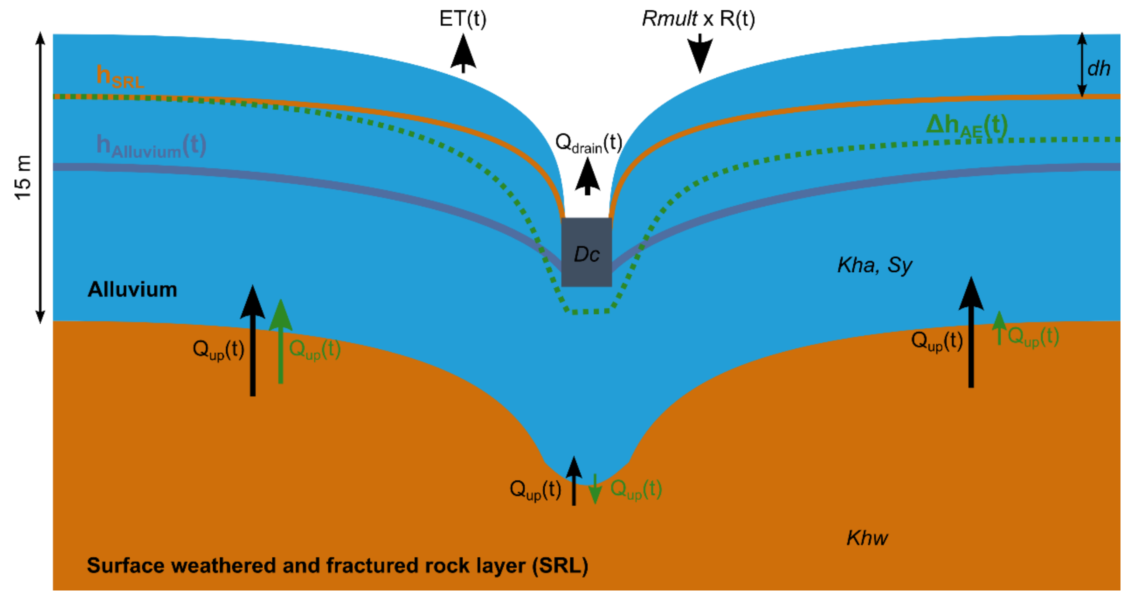

Figure 9 Hydrogeological conceptual model of the alluvial groundwater models for the Avon and Karuah alluvium for the Gloucester subregion

$h_{Alluvium}(t)$ = spatio-temporal groundwater level in alluvial aquifer; h_{SRL} = specified head boundary, constant in time, in the surface weathered and fractured rock layer; $\Delta h_{AE}(t)$ = spatio-temporal change in groundwater level in the surface weathered and fractured rock layer, simulated by the analytic element model; $Q_{up}(t)$ = spatio-temporal exchange flux between alluvium and surface weathered and fractured rock layer; $Q_{drain}(t)$ = spatio-temporal drainage flux; R(t) = spatio-temporal recharge flux; ET(t) = spatio-temporal evapotranspiration flux; *Khw* = hydraulic conductivity of surface weathered and fractured rock layer; *Kha* = hydraulic conductivity of alluvium; *Sy* = specific yield of the alluvium; *Rmult* = recharge multiplier; *Dc* = hydraulic drainbed conductance; *dh* = depth to the specified groundwater level in the surface weathered and fractured rock layer.

Within the MODFLOW alluvial models, only two numerical layers are considered (Figure 9): the alluvium and the surface weathered and fractured rock layer. In the alluvial layer groundwater levels and fluxes are simulated. The top of the layer follows the topography from a 90 m digital elevation model (DEM) (Farr et al., 2007) and the layer is assigned a constant thickness of 15 m. The surface weathered and fractured rock layer provides a time-varying specified head lower boundary that interacts with the alluvial layer. The head difference between the specified head in the surface weathered and fractured rock layer and the head in the alluvial layer results in a spatio-temporal exchange flux between the alluvium and the weathered zone. The drawdown simulated in the surface weathered and fractured rock layer by the analytic element model underneath the alluvium is subtracted from this specified head. This results in a specified head boundary that varies in space and time. This change in groundwater level integrates the change in flow conditions caused by coal resource development as none of the coal resource developments extract water from the alluvium directly.

The main recharge mechanism is diffuse recharge while evapotranspiration occurs where the watertable is sufficiently close to the surface. The main discharge mechanism is through the river network. The river system is predominantly gaining, that is, the rivers drain the groundwater system.

2.6.2.3.3 Design and implementation

2.6.2.3.3.1 Analytic element model

Analytic element models are grid-independent (Bakker, 2013). Their resolution is determined by the discretisation of the internal boundary elements, the points, lines and polygons representing head or flux boundaries. In the temporal domain it is necessary to define stress periods (i.e. periods in which the stresses and boundary conditions are constant), but it is not necessary to temporally discretise into time steps. This means the solution to groundwater flow equations can be evaluated at arbitrary points and times. Yearly stress-periods are chosen as this corresponds to the temporal resolution of the available mine pumping rates. As the analytic element model is only simulating the change due to coal resource development, the simulation period starts in 1995, the earliest date mine pumping rates are available, and ends in 2102, as specified in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016).

In view of the uncertainty analysis, certain aspects of the model are simulated as a stochastic process. Throughout the product, the model design or the model results will be illustrated using data of a single realisation. These single realisations are typical examples of the stochastic process, but should by no means be regarded as an ‘optimal’ realisation or representing the mean or median of the range.

2.6.2.3.3.2 Alluvial MODFLOW models

The extent of the alluvial models is based on the mapped alluvium in the geological map 1:100,000 (McVicar et al., 2014, Figure 22). The model domain is discretised in 90 m grid cells with all grid cells outside the alluvium extent marked inactive (Figure 10).

The simulation period starts in 1983, ends in 2102 and has 1440 monthly stress periods (period of time in which all model stresses, such as pumping and recharge, remain constant) with one time step per stress period, in line with companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016).

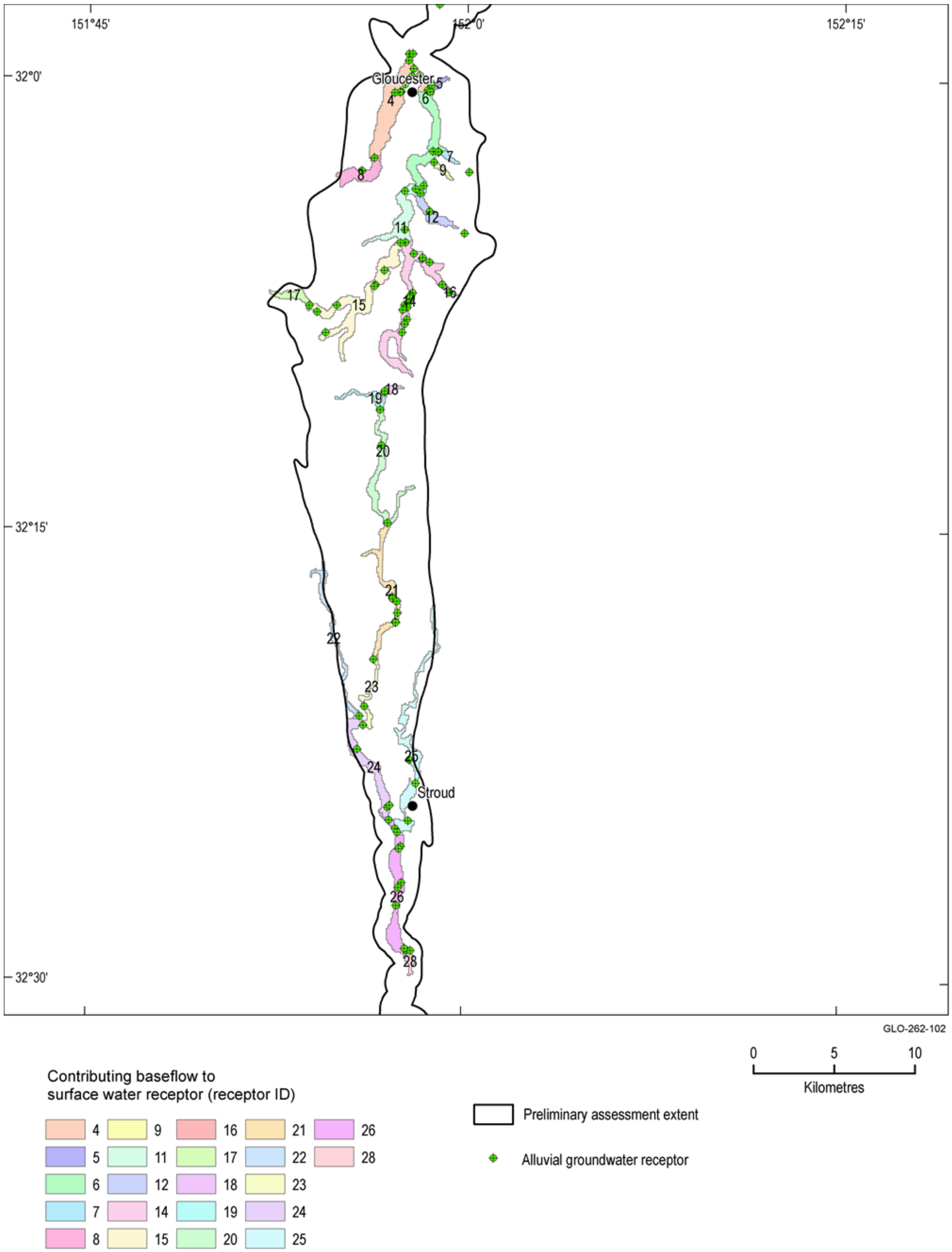

Figure 10 Alluvial MODFLOW model domain for the Avon (north) and Karuah models (south) for the Gloucester subregion

The indicated zones correspond to surface water receptor catchments (see Section 2.6.1.3.2).
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2)

2.6.2.3.4 Model code and solver

2.6.2.3.4.1 Analytic element model

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

The groundwater model was created as a Python script and solved using a 64-bit Python installation and the 64-bit distribution of the TTim package. The script, together with the input files and documentation, are available at http://www.bioregionalassessments.gov.au.

2.6.2.3.4.2 Alluvial MODFLOW models

For this groundwater model the industry standard MODFLOW model is used (Harbaugh et al., 2000), MF2000 1.18 version (USGS, 2014). The groundwater flow equations are solved based on a finite-difference solution of the three-dimensional groundwater flow equation, in a time-stepping manner where the previous solutions for groundwater heads and fluxes are used as the initial conditions for the next time period.

The time requirement for a solution of the equations is most often driven by the number of grid cells and layers. The fact that the alluvium is relatively sparse (see Figure 10, only about 10% of the model area is active alluvium cells) makes the computational effort small, requiring about 30 seconds for 100 years of simulated heads. The main driver of actual run time, however, is the amount of time spent reading and writing data to disk storage, sometimes over a network. For this reason, the fewest possible number of files are written and stored, fast temporary storage is used where available, and larger files required for water balance summary and head observation are deleted after analysis of each run. The model files and executables, including the technical information about running the model, are available at http://www.bioregionalassessments.gov.au.

2.6.2.3.5 Geometry and hydrostratigraphy

2.6.2.3.5.1 Analytic element model

The model layers are horizontal, of constant thickness and infinite in extent. The top of the model is set at an arbitrary level of zero metres and the total thickness of the simulated sedimentary column is less than 1000 m.

The groundwater system is implemented as an alternating sequence of aquifers and aquitards (Figure 8). Groundwater level and flow are only simulated for the aquifers. The flow between two successive aquifers is controlled by the hydraulic gradient between them and the hydraulic properties assigned to the aquitard separating both aquifers. In this model, the starting aquifer is the weathered zone with a nominal thickness of 75 m (McVicar et al., 2014). Deeper down in the basin, only the coal seams are considered to act as aquifers. The interburden is simulated as aquitards. This implies that no groundwater levels in the aquitards are calculated.

The coal seams are assigned a nominal thickness of 3 m each, in accordance with the coal seam thickness reported in companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, Figure 24). The number and position of the coal seams are generated stochastically, allowing for the density of coal seams to vary with depth, according to stratigraphy (see McVicar et al., 2014, Figure 24). Coal seams are considered to be between 250 and 1000 m in depth. In reality, coal seams are present outside this range, but CSG exploitation will only occur within this depth range (see companion product 1.2 for the Gloucester subregion (Hodgkinson et al., 2014, Section 1.2.3.2, p. 26)). An example of a single stochastic realisation of the distribution of coal seams is shown in Figure 11.

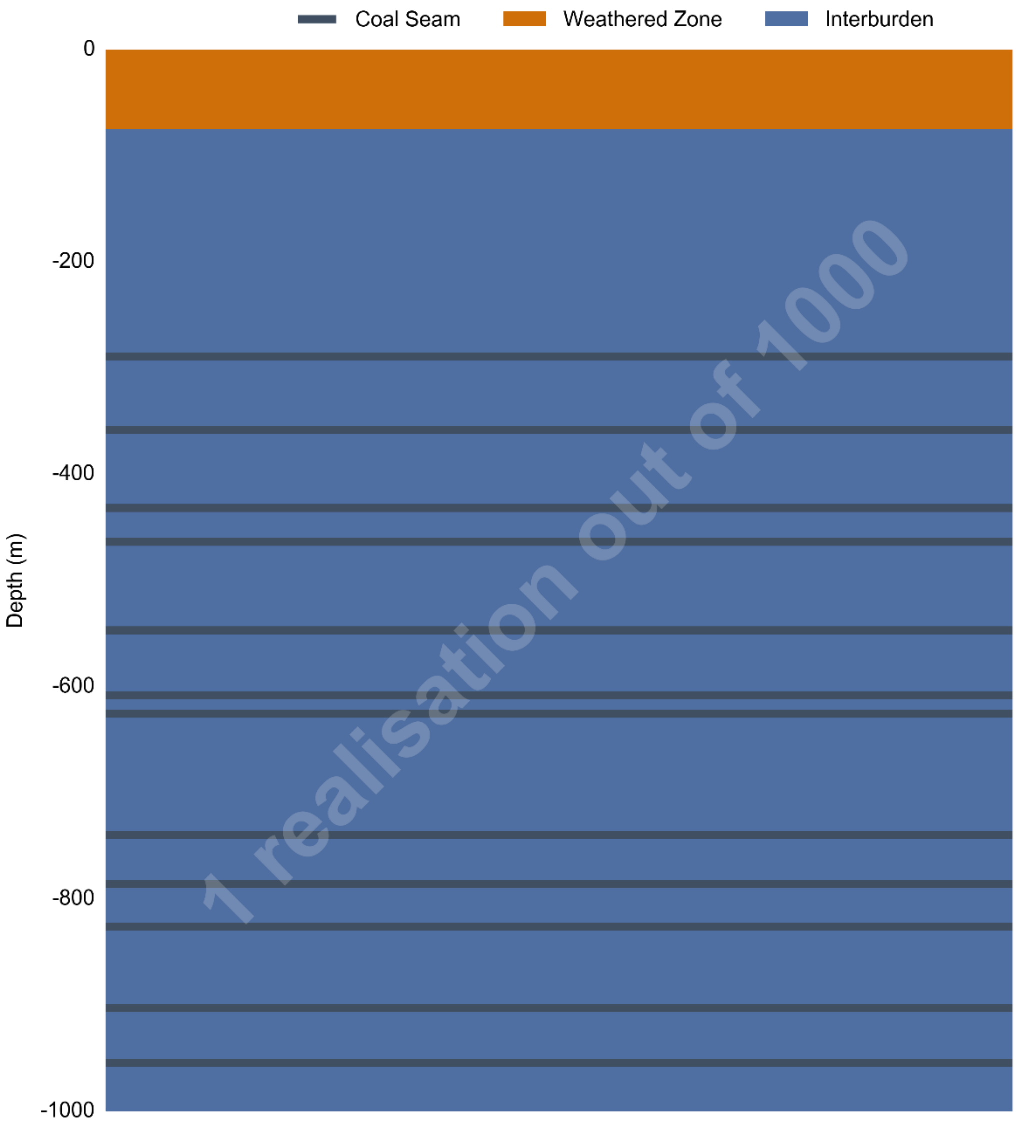

Figure 11 Single realisation of coal seam distribution for the Gloucester subregion

Data: Bioregional Assessment Programme (Dataset 3)

As stated in companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, Section 1.1.3.1.1), throughout all of the Permian strata, normal, strike-slip and reverse faults occur. The fault density is higher near the flanks and faults orientations are generally northerly striking with dips toward the central axis of the geological basin. Major fault trends are implemented as linear features that provide a vertical connection between all layers and a horizontal impedance to flow. The flow rate through the major faults is controlled by the fault hydraulic conductivity. The position of the major fault trends is inferred from geological maps and geological modelling from companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018). Note that in this interpretation of the structural features of the Gloucester Basin, fewer faults are identified compared to those identified on the geological map of the region (Roberts et al., 1991). Figure 12 shows the position and probability of the major fault trends. The geographic location of the potential major faults is considered known and kept fixed for all realisations, whereas their probability of occurrence at those locations is treated as a stochastic process. In other words, every realisation can be different in terms of presence or absence of major faults.

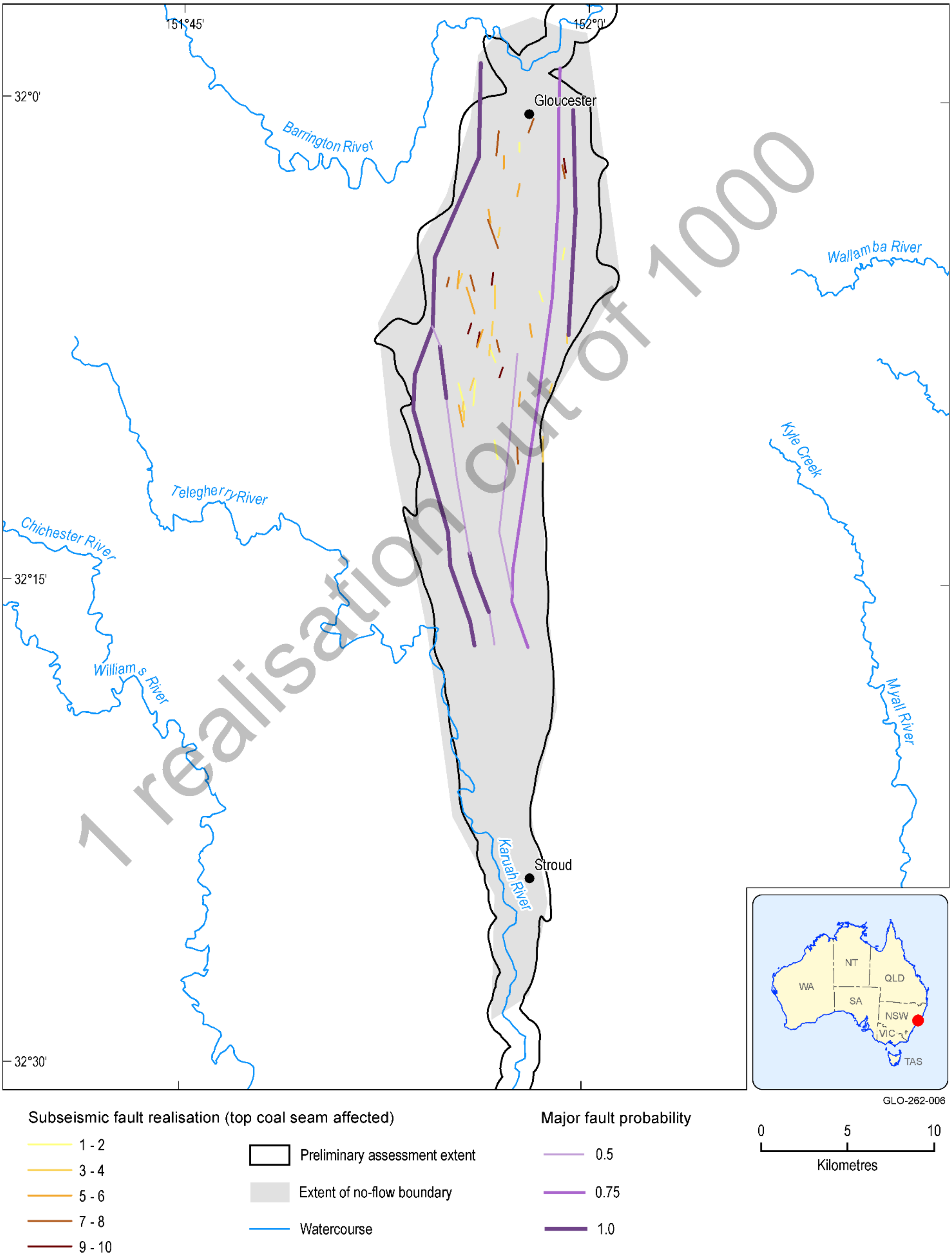

Figure 12 Major fault trend probability, single subseismic fault distribution realisation and no-flow boundary for the Gloucester subregion regional analytic element groundwater model

Data: Bioregional Assessment Programme (Dataset 3)

Subseismic faults, which are faults with a displacement too small to be identified from a seismic section, less than 100 m, are generated stochastically in the vicinity of the planned coal resource development. For the GW AEM, the subseismic faults of interest are those with a fault height between 200 and 1000 m, where the fault height is the vertical extent of the fault zone. Larger faults can be identified on seismic sections and are assumed to be mapped at the regional scale as part of the major fault network. Faults with heights less than 200 m are not considered to be important for the regional groundwater model as it is unlikely that these faults are large enough to alter regional groundwater flow.

Fault heights are, however, very hard to measure. A more common and less ambiguous measure to characterise faults is the fault displacement. Figure 13 in Section 2.1.2.2 in companion product 2.1-2.2 (Frery et al., 2018) shows a number of type curves for the Gloucester subregion to relate fault displacement and cumulative number of faults. These type curves can be used to estimate the number of faults with a given displacement. The displacement range that corresponds to the fault height range of interest (between 200 and 1000 m) is based on a number of global datasets. Nicol et al. (1996) estimated the average ratio between fault height (*H*) and fault length (*L*) (the length of a fault along strike) to be equal to 2.15. The fault height range of 200 to 1000 m corresponds to approximate fault lengths of 400 to 2000 m. On a similar dataset, Kim and Sanderson (2005) empirically established a ratio of 0.01 between maximal displacement or throw and fault length. Faults between 400 and 2000 m then correspond to a throw range between 4 and 20 m. For that throw range, in a 10 x 10 km area (the scale that corresponds most closely to the size of the Gloucester Basin), the fault length distribution (*X*) in the Gloucester subregion can be approximated by taking 40 samples from a beta distribution (Bailey et al., 2005; Frery et al., 2018):

$$X \sim 500 + 1500\beta(1,3) \quad (5)$$

The strike of the faults is chosen to align with the major tectonic axis of the basin and to vary between 338° and 022°.

One thousand stochastic realisations of the subseismic fault network are generated, each comprising 40 faults that connect three model aquifers (coal seams or surface weathered and fractured rock layer) with each other. Determining which model aquifers are connected is also part of the stochastic process. Figure 12 shows a single realisation of a subseismic fault network. The number of realisations proved to be sufficient to ensure that the entire region was represented as faulted.

The generation of subseismic faults is limited in extent. The north and south limits were chosen at a distance beyond the proposed CSG development area. Any subseismic faults outside this domain are considered to have a negligible effect on the predictions.

The generation of a stochastic network was done in the following steps:

1. Take 40 samples from the beta distribution to get the fault lengths.
2. Take 40 random uniform samples of an angle between 338° and 022°.

3. In a 'for' loop:
   a. generate a random point within the extent of the subseismic fault domain as the starting point for a fault
   b. calculate the endpoint of the fault from the fault length vector and angle vector
   c. accept the fault if it is fully contained within the domain, otherwise reject it and go back to step a.
4. Assign random upper coal seam a number between one and ten, add two to obtain lower coal seam.

The watertable is situated in the surface weathered and fractured rock layer (Figure 8). To represent the phreatic part of this weathered zone, a leaky layer is simulated on top of the sequence of aquitards and aquifers, in line with the recommendation in Hemker (1985). Groundwater levels are not computed in this layer, but it allows the simulation of the release of water from storage due to dewatering of the phreatic part of the weathered zone.

2.6.2.3.5.2 Alluvial MODFLOW models

The geometry of the active area is controlled by the mapped extent of alluvium and the DEM (Farr et al., 2007). The alluvial layer is fixed to be 15 m thick and exactly follows the topography, while the second layer extends down to an arbitrary datum.

No aquitards exist in the vertical model domain, only a vertical hydraulic conductivity between the two layers to control flow between them based on head difference.

The fault network in the analytic element model is not propagated in the alluvium as there is no indication to date that hydraulic properties in the alluvium are affected by fault activity. It is trivial, however, to change the hydraulic properties of the alluvial models locally should future observations indicate fault activity has altered hydraulic conductivity in the alluvium.

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2.6.2.4 Boundary and initial conditions

Summary

The lateral boundaries of the regional analytic element groundwater model (GW AEM) coincide with the geological basin and are implemented as no-flow boundaries. As the model directly simulates the change to the groundwater system rather than the state of the system, recharge and surface water – groundwater interactions are not included in the regional groundwater model.

The lateral boundaries of the Avon and Karuah models are considered no-flow boundaries.

The spatio-temporal pattern of historical recharge is computed with Australian Water Resources Assessment Landscape model (AWRA-L). This pattern is scaled to match estimates of recharge to the alluvium. For the baseline coal resource development (baseline) and coal resource development pathway (CRDP) runs the recharge pattern is further scaled seasonally to account for climate change.

Potential evaporation is set equal to half of the historical pan evaporation with an extinction depth of 2 m. Water extraction for irrigation, stock and domestic use is not included.

2.6.2.4.1 Lateral

2.6.2.4.1.1 Analytic element model

Analytic element modelling is grid independent and by default assumes aquifers are of infinite extent. The geological Gloucester Basin boundaries were therefore explicitly implemented as no-flow boundaries (Section 2.6.2.3.5).

2.6.2.4.1.2 Alluvial MODFLOW models

The Gloucester subregion is a closed geological basin. The alluvial aquifer is a relatively thin skin on a much thicker geological sequence. The saturated thickness of the lateral boundaries is very small compared to the thickness of the aquifer, and thus there are zero-flow boundaries along all edges.

2.6.2.4.2 Recharge

2.6.2.4.2.1 Analytic element model

Recharge was not included in the regional analytic element groundwater model (GW AEM). Recharge in no development, baseline coal resource development (baseline) and coal resource development pathway (CRDP) is the same. In this modelling approach, only the change in the system due to coal resource development is simulated. The change in recharge due to coal development is zero and therefore recharge is not included. A more detailed discussion on this rationale and the effect on predictions is provided in the qualitative uncertainty analysis in Section 2.6.2.8.

2.6.2.4.2.2 Alluvial MODFLOW models

Recharge to the alluvium is determined in two stages. Firstly, the target amount is determined from the observed salinity of the alluvium and stream and set as a fraction of monthly rainfall. After the Australian Water Resources Assessment Landscape model (AWRA-L) was fitted to the streamflow of the subcatchments, a monthly recharge distribution is extracted and scaled to the target values already used in fitting the MODFLOW model. The initial estimate was 20% of monthly rainfall applied to each stress period as recharge to alluvium. During the uncertainty analysis, this percentage is allowed to vary between 2% and 40% (see Section 2.6.2.8).

The fitting period was a 30-year interval from 1982 to 2011. The same 30-year interval was used for future climate runs, but recharge values were modified by seasonal scaling factors derived from global climate models (GCMs) as outlined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

2.6.2.4.3 Surface water

2.6.2.4.3.1 Analytic element model

Surface water features were not included in the GW AEM; these are accounted for in the MODFLOW models that represent the alluvial system. A more detailed discussion on this rationale and the effect on predictions is provided in the qualitative uncertainty analysis in Section 2.6.2.8.

2.6.2.4.3.2 Alluvial MODFLOW models

As discussed in Section 2.1.5.1.2 in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018) and in Section 7.4 in Parsons Brinckerhoff (2015), the Avon and Karuah river systems are considered to be gaining systems (i.e. the alluvial groundwater discharges water into the river system). Only during short periods of very high stream levels does the river provide water to the alluvial aquifer. This is illustrated in Figure 13.

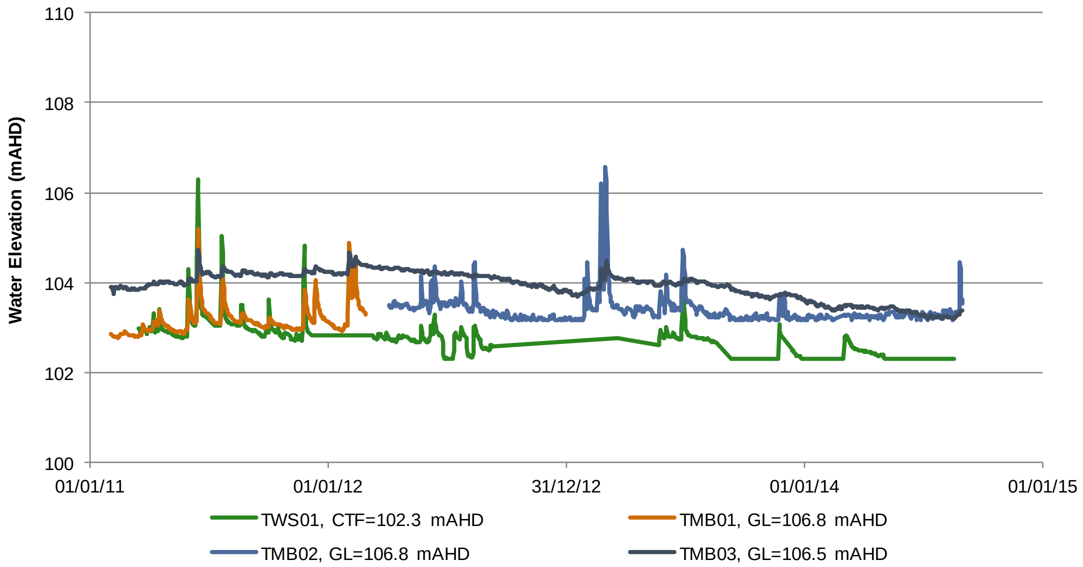

Figure 13 A Gloucester River stream hydrograph and nearby bore hydrograph records for the Gloucester subregion

Bore TMB01 is 2 m from the stream gauge TWS01, TMB02 is 328 m away and TMB03 is 662 m away; CTF = cease to flow; GL = ground level.
Data: AGL (Dataset 1)

Two of the commonly used implementations of the Cauchy boundary condition, or head-dependent flux boundary, to represent surface water – groundwater interaction available in MODFLOW are the DRAIN package and the RIVER package (Brunner et al., 2010).

In the DRAIN package an invert level or drain elevation is specified together with a drainbed conductance. Drainage, water leaving the groundwater system through that boundary, only occurs if the simulated groundwater level in the grid cell specified as a DRAIN cell exceeds the invert level. The drainage flux is calculated based on the head gradient between the invert level and the groundwater level and the drainbed conductance. This boundary condition therefore only allows water to leave the system, no water enters the groundwater system if the groundwater level is below the invert level.

In the RIVER package, on the contrary, this two-way interaction is possible. In a RIVER grid cell, the river stage and the river bed elevation is specified as well as the riverbed conductance. The flux through the boundary condition is calculated based on the head difference between the simulated groundwater level and the river stage. If the groundwater level is above the river stage, this boundary acts very similar to the DRAIN package, and flow leaves the groundwater system. When groundwater levels are simulated that are lower than the river stage, water will flow from the river into the groundwater system.

In the Avon and Karuah MODFLOW models, rivers are represented through the DRAIN package, with the drainbed elevation set to 4 m below the land surface.

The obvious drawback of choosing the DRAIN boundary condition is that losing river conditions cannot be accurately modelled. The rationale behind this choice, however, is driven by the precautionary principle. Under gaining conditions, a DRAIN boundary will over estimate the gradient compared to a RIVER boundary, as the river stage elevation will always be higher than the drainbed elevation. The change in flux due to coal resource development will therefore always be over estimated and therefore the change in groundwater level will also be over estimated. Even under losing conditions, the change in flux due to coal resource development will not be underestimated, unless the change due to coal resource development results in simulated groundwater levels below the drainbed elevation. A RIVER boundary condition would be able to estimate the change in flux even under these conditions. The main drawback of the RIVER package, however, is that under losing conditions it will result in an underestimate of the drawdown caused by coal resource development. The induced groundwater flow through the river bed under losing conditions will compensate drawdown, especially close to the river boundary. Choosing a DRAIN boundary condition to represent rivers ensures the modelling will always over estimate drawdown and only under estimate fluxes when simulated groundwater levels are below drainbed elevation. In the discussion of the results it will be verified if and to what extent groundwater levels are predicted below the drainbed elevation. A more detailed discussion on the concepts outlined above is provided in the qualitative uncertainty analysis section (see Section 2.6.2.8).

2.6.2.4.4 Evaporation

2.6.2.4.4.1 Analytic element model

Direct evaporation is not incorporated in the analytic element model. Direct evaporation occurs where the watertable is in proximity to the surface. This is not likely in the surface weathered and fractured rock layer where the regional watertable is generally several metres below the surface (Parsons Brinckerhoff, 2015).

Not incorporating evaporation is again in line with the precautionary principle. An evaporation top boundary de facto provides an upper limit to the simulated groundwater levels. By not incorporating this top boundary, the drawdown can only be over estimated.

2.6.2.4.4.2 Alluvial MODFLOW models

Within the alluvium watertables are shallower and direct evaporation is more likely. For past and future 30-year blocks, a value of half the measured pan evaporation was imposed as potential evaporation at the ground surface, with a linear extinction depth set to 2 m constant across the domain, that is, any groundwater at 2 m depth or deeper is not subject to evaporation.

2.6.2.4.5 Pumping

Most of the registered bores in the Gloucester subregion are in the alluvium, and while the amount of pumping over time is unknown, the licensed extraction volumes are small (Frery et al., 2018, Table 11). The total licensed extraction rate in the Gloucester subregion is currently 1.8 GL/year, assigned to 107 bores in the alluvium and 53 in the surface weathered and fractured rock layer.

There is no pumping specified in the analytic element model or the MODFLOW models that is not related to coal resource development. Pumping rates are not affected by coal resource development and therefore identical between the baseline and coal resource development future. Non-coal related pumping will thus not affect the predicted change in groundwater levels or fluxes.

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2.6.2.5 Implementation of coal resource development pathway

Summary

The coal resource development pathway (CRDP) for the Gloucester subregion includes extensions to two existing coal mines – Stratford Mining Complex and Duralie Coal Pty Ltd – and one new mine – the Rocky Hill Coal Project. AGL's proposed CSG development in the Gloucester Gas Project, stage 1 gas field development area is also included.

For numerical modelling purposes the CRDP was finalised in October 2015, and while AGL withdrew from its proposed Gloucester Gas Project in December 2015, as described in the companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), the CRDP was not revisited.

The coal resource development pathway (CRDP) is defined in companion product 2.3 for the Gloucester subregion (Dawes et al., 2018). This section details the numerical implementation of the coal mines and coal seam gas (CSG) extraction in the analytic element model. There are no coal resource developments that extract water directly from the alluvium.

2.6.2.5.1 Open-cut mines

Several open-cut coal mines are active or planned in the Gloucester subregion (Figure 14). For each, mine-pit footprints are digitised of the historical position of the main excavation, the approved extensions and the proposed new developments. Figure 15 summarises the water extraction for each pit from a mixture of measured rates (for the historical pumping rates), and modelled, expected pumping rates (baseline coal resource development (baseline) and CRDP), based on environmental impact assessment reports (see companion product 1.2 for the Gloucester subregion (Hodgkinson et al., 2014)). Note that the mine footprints are entirely contained within the surface weathered and fractured rock layer, that is, none of the mine footprints extends into the alluvium.

The pumping rate time series is assigned to the mine footprint polygon in the regional analytic element groundwater model (GW AEM) in the surface weathered and fractured rock layer as a Neumann boundary condition, that is, a specified flux boundary condition that varies in time (Franke et al., 1987). The historical pumping rates are identical in both the baseline and CRDP runs. The future (i.e. post 2012) pumping rates in the CRDP run are the pumping rates for the new-to-be-developed mines (Rocky Hill Coal Project, Avon North Open Cut and Stratford East Open Cut) or mines that are planned to be extended (Duralie Coal Mine, Stratford Roseville West Pit Extension). The mines that will be extended have the CRDP pumping rate assigned to the combined baseline and CRDP polygon (Figure 14). Only the combined pumping rate of the existing and extension of the mine are available. The combined pumping rate is assigned to the mine polygon in the CRDP. The pumping rate for the baseline run is the combined pumping rate multiplied by the ratio of area of the existing mine over the area of the extended mine.

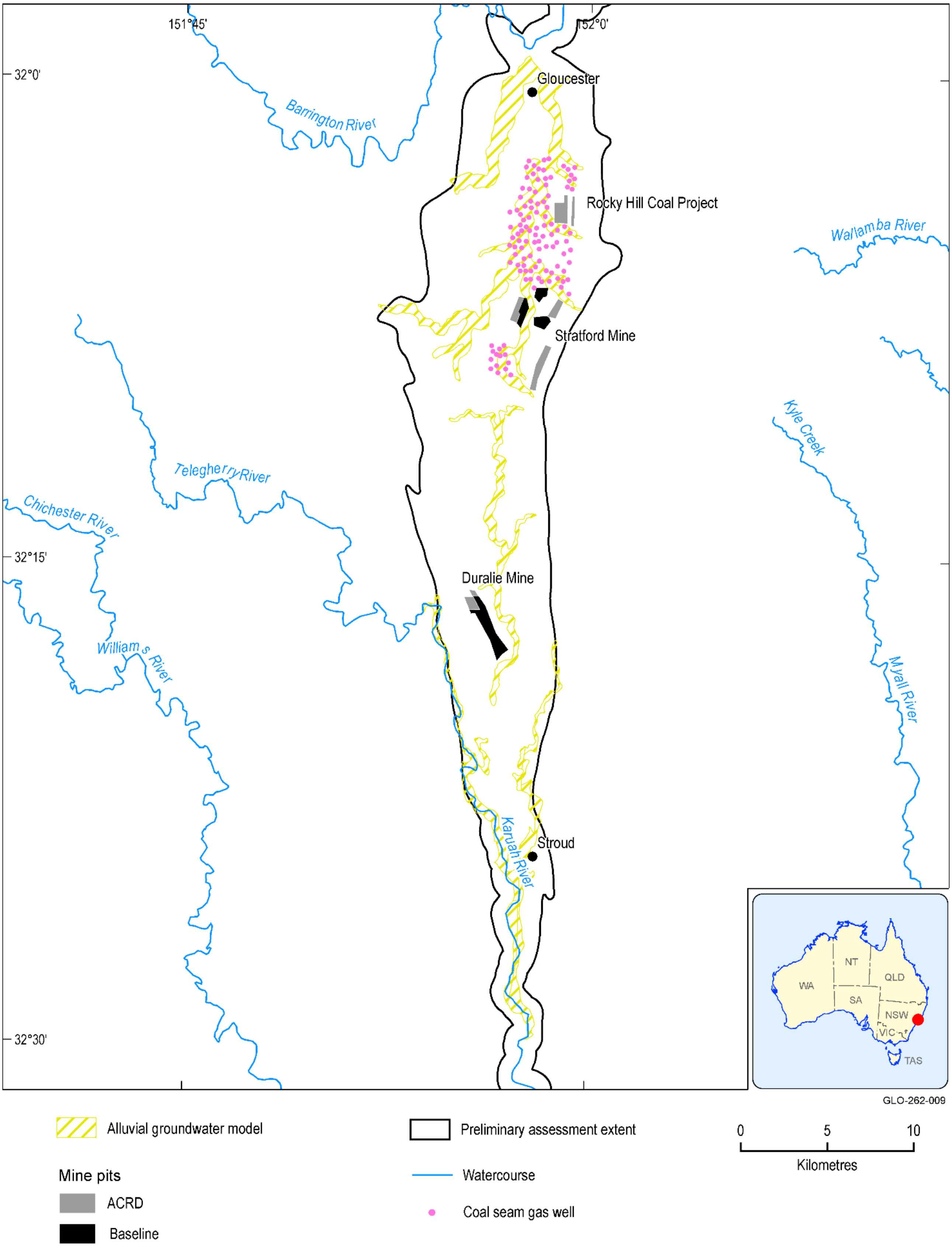

Figure 14 Locations of baseline coal resource development and coal resource development pathway (CRDP) open-cut mines and the locations of the 110 randomly generated coal seam gas wells in the Gloucester subregion

ACRD = additional coal resource development
Data: Bioregional Assessment Programme (Dataset 1)

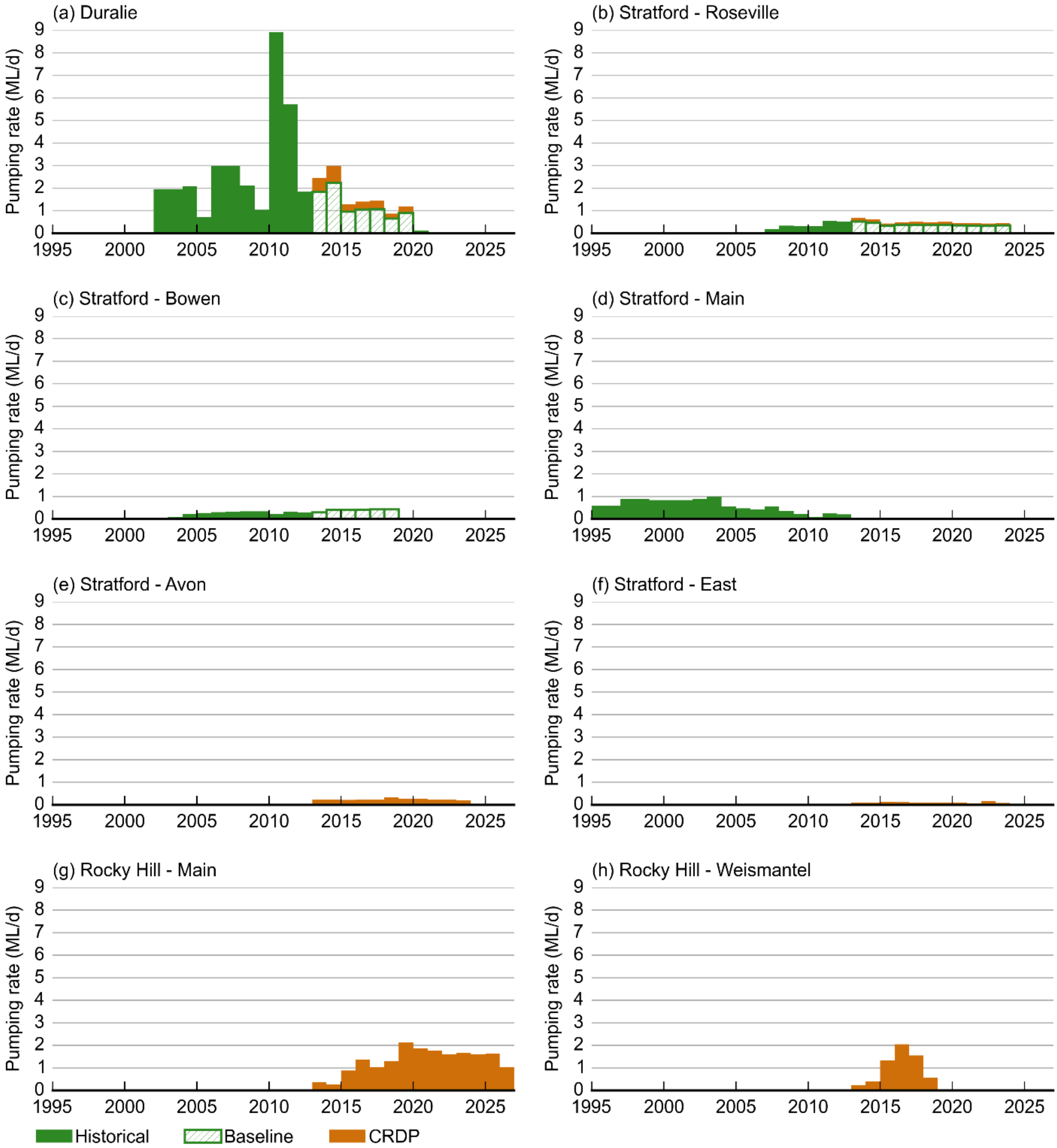

Figure 15 Time series of historical, baseline coal resource development and coal resource development pathway (CRDP) pumping rates in ML/day for all open-cut mines in the Gloucester subregion

Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.5.2 Coal seam gas wells

For numerical modelling purposes the CRDP was finalised in October 2015, and while AGL withdrew from its proposed Gloucester Gas Project in December 2015, as described in the companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), the CRDP was not revisited.

While the CRDP includes both Stage 1 and Stage 2 of the AGL gas field development area, only Stage 1 is modelled due to the availability of information (see companion product 1.2 for the Gloucester subregion (Hodgkinson et al., 2014)). In Stage 1, 110 wells are planned. For the purposes of the modelling, it is assumed that the wells are drilled in a four-year period between 2013 and 2017. Each well will be actively exploited in the model for a 20-year period. As the exact location of these wells is not known at this stage, 110 wells are randomly distributed within the AGL Stage 1 gas field development area (Figure 14) subject to the following rules, in line with the locational principles outlined in Parsons Brinckerhoff (2015):

- It is ensured no wells are positioned within a 200 m buffer of a major fault, as it assumed that faulted coal seams are not favourable for CSG production. Likewise, none of the 110 wells are placed in current or planned open-pit mines.
- None of the 110 wells are placed within the 2 km exclusion zones around residential areas in NSW.
- Each CSG well is assigned well screens in randomly selected coal seams, varying between 6 and 12 coal seams. Each well screen is simulated as an individual well in which the head is set equal to the top of the lowermost coal seam at that location, plus 25 m.

The locational principles in Parsons Brinckerhoff (2015) are more detailed and include rules with regards to distance to existing residences (minimum 200 m) and watercourses (minimum 40 m for major watercourses, 20 m for minor watercourses) as well as rules to avoid significant vegetation and riparian areas and heritage sites. As these detailed rules are not incorporated in the random placement of coal seam gas wells in the GW AEM due to operational constraints, it is unlikely that the CSG wells will eventuate in the locations indicated in Figure 14. Note that in this figure a number of CSG wells are located within the Avon alluvium MODFLOW model domain. This merely indicates that some wells will depressurise coal seams directly underneath the alluvium, it does not indicate water being extracted from the alluvium.

In the analytic element modelling code Ttim (Bakker, 2015), it is not possible to switch off a head-dependent well during a transient run. In order to simulate recovery, a two-stage process is adopted. In the first stage, water production for each individual well screen is computed with a transient run that covers the exploitation period, with the CSG wells implemented as head-dependent wells with a well diameter and entry resistance nominally set to 0.25 m and 100 days for all wells. In the subsequent run, that covers the entire simulation period, the CSG wells are implemented as flux-specified wells, with a flux during production from the previous simulation and zero flux after exploitation has stopped. For each parameter combination, the pumping rate will vary and is therefore recorded as a yearly time series as part of the model output. The volume of water required to depressurise the targeted model coal seams to the specified groundwater head will be simulated by the numerical model.

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2.6.2.6 Parameterisation

Summary

The regional analytic element groundwater model (GW AEM) has 15 parameters that are included in the sensitivity and uncertainty analysis. The parameters govern the stochastic elements of the conceptual model, such as the coal seams and faults and the hydraulic properties of the coal seams, interburden and faults.

In the alluvial Avon and Karuah MODFLOW models, six parameters are allowed to vary. These include the hydraulic properties of the alluvium and the weathered zone, the riverbed conductance, recharge and a constant head offset that represents the interaction with the deeper basin. Hydraulic properties are assumed to be spatially uniform.

2.6.2.6.1 Analytic element model

Table 5 lists the parameters of the regional analytic element groundwater model (GW AEM) included in the sensitivity and uncertainty analysis together with a short description, a starting value and the range within which the parameter is expected to vary. The parameters are organised in three groups. The 'stochastic' group parameters are integer values that refer to a stochastic realisation of the coal seams, major or subseismic faults. The 1000 realisations of the number and position of the coal seams, major fault probability and subseismic fault distribution are randomly combined with the other parameters. The 'hydraulic properties: sedimentary rocks' group consists of all parameters that control the hydraulic properties, such as hydraulic conductivity and storage for the interburden and the coal seams. The 'hydraulic properties: faults' group has the parameters that govern the hydraulic behaviour of the faults in the model. The permeability of the coal seams in the Gloucester subregion has been observed to decrease with depth (Figure 16; Parsons Brinckerhoff, 2015).

Table 5 Parameters for the regional analytic element groundwater model for the Gloucester subregion

Group	Parameter name	Value	Description	Unit	Minimum	Maximum
Stochastic	*CoalSeamID*	0	Stochastic realisation number of coal seam distribution	na	0	999
	MajorFaultID	0	Stochastic realisation number of major fault distribution	na	0	999
	SubseismicFaultID	0	Stochastic realisation number of subseismic fault distribution	na	0	999
Hydraulic properties: sedimentary rocks	*K_IB_intercept*	0.03	a1 in eq 6 for Kh interburden	m/d	0.3×10^{-3}	0.3
	K_CS_intercept	0.3	a1 in eq 6 for Kh coal seam	m/d	0.03	3
	K_IB_slope	1.3×10^{-3}	a2 in eq 6 for Kh interburden	m^{-1}	6.5×10^{-3}	2.6×10^{-2}
	K_CS_slope	1.3×10^{-3}	a2 in eq 6 for Kh coal seam	m^{-1}	6.5×10^{-3}	2.6×10^{-2}
	S_IB_intercept	2.3×10^{-4}	a1 in eq 6 for storage interburden	m^{-1}	2.3×10^{-5}	2.3×10^{-3}
	S_CS_intercept	2.3×10^{-3}	a1 in eq 6 for storage coal seam	m^{-1}	2.3×10^{-4}	2.3×10^{-2}
	S_IB_slope	5.42×10^{-3}	a2 in eq 6 for storage interburden	m^{-1}	2.71×10^{-3}	1.08×10^{-2}
	S_CS_slope	5.42×10^{-3}	a2 in eq 6 for storage coal seam	d^{-1}	2.71×10^{-3}	1.08×10^{-2}
	KvKh	0.1	*Kv* over *Kh* for interburden	na	0.01	1
	ne	0.1	Specific yield of weathered zone leaky layer on top of model	na	0.001	0.3
Hydraulic properties: faults	*Kfh*	1×10^{-3}	Fault horizontal hydraulic conductivity	m/d	1×10^{-5}	1×10^{-1}
	Kfv	1×10^{-3}	Fault vertical hydraulic conductivity	m/d	1×10^{-5}	1×10^{-1}

The ‘value’ column is an initial value, while the ‘minimum’ and ‘maximum’ columns span the range sampled in the design of experiment. na = not applicable; eq = equation; *Kv* = vertical hydraulic conductivity; *Kh* = horizontal hydraulic conductivity
Data: Bioregional Assessment Programme (Dataset 1)

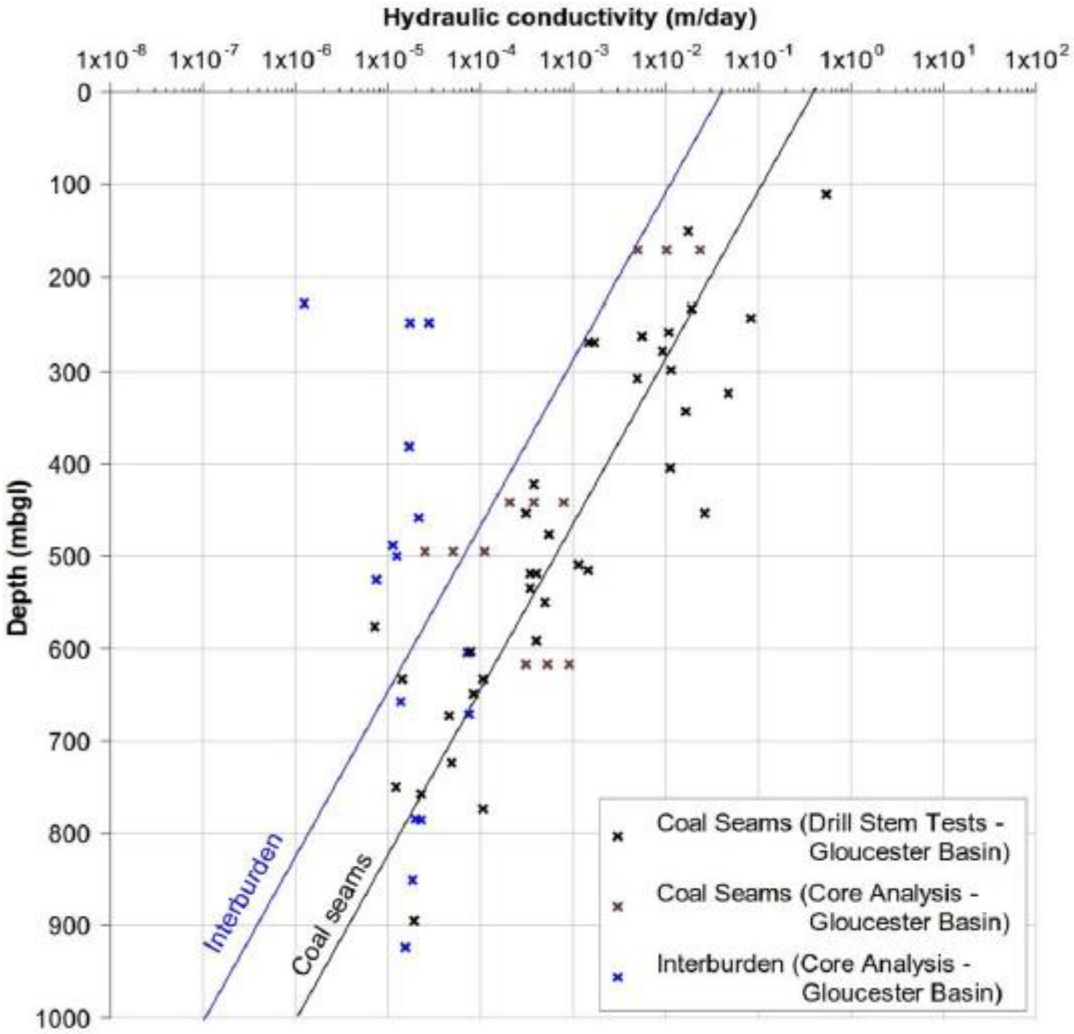

Figure 16 Observed decrease in permeability with depth in coal seams and interburden in the Gloucester subregion

Source: Parsons Brinckerhoff (2015), Figure 7.2, p. 41

It is assumed that the processes driving this decrease in permeability in the coal seams also affect the interburden, and hydraulic parameters that are a function of permeability, such as horizontal and vertical hydraulic conductivity, also decrease with depth. In a strict sense, the storage of a hydrostratigraphic unit is a function of the compressibility of the lithology and not of the permeability. However, in the GW AEM storage is also considered to decrease with depth, under the assumption that compressibility also decreases with depth.

The variation with depth of the hydraulic parameters is described with an exponential function of the form:

$$P = a_1 \exp(-a_2 d) \quad (6)$$

with *P* the hydraulic parameter, a_1 and a_2 coefficients that control the exponential decrease, and *d* the depth in metres below the surface. Four such relationships are defined; the hydraulic conductivity (*K*) and storage (*S*) for the coal seams (*CS*) and for the interburden (*IB*). The a_1 parameter is the intercept (*intercept*) of the relation with the x-axis (i.e. the value of the parameter at zero metres depth). The a_2 coefficient is the slope of the decrease of the parameter with depth. Larger values indicate a stronger decrease with depth of the parameter. In the Stratford Mining Complex groundwater model (Heritage Computing, 2012), similar equations are used for the initial values of hydraulic conductivity in the coal seams and the interburden:

$$K_{interburden} = 0.0057 \exp(-0.025d) \quad (7)$$

$$K_{coal\ seams} = 0.4211 \exp(-0.014d) \quad (8)$$

The ranges for the coefficients for hydraulic conductivity and storage for the interburden and for the coal seams used in the design of experiment are listed in Table 5. The range of hydraulic conductivity and storage those values correspond to are shown as a function of depth in Figure 17. Details on how this range is sampled is provided in Section 2.6.2.7.3 for the design of experiment and Section 2.6.2.8 for the uncertainty analysis.

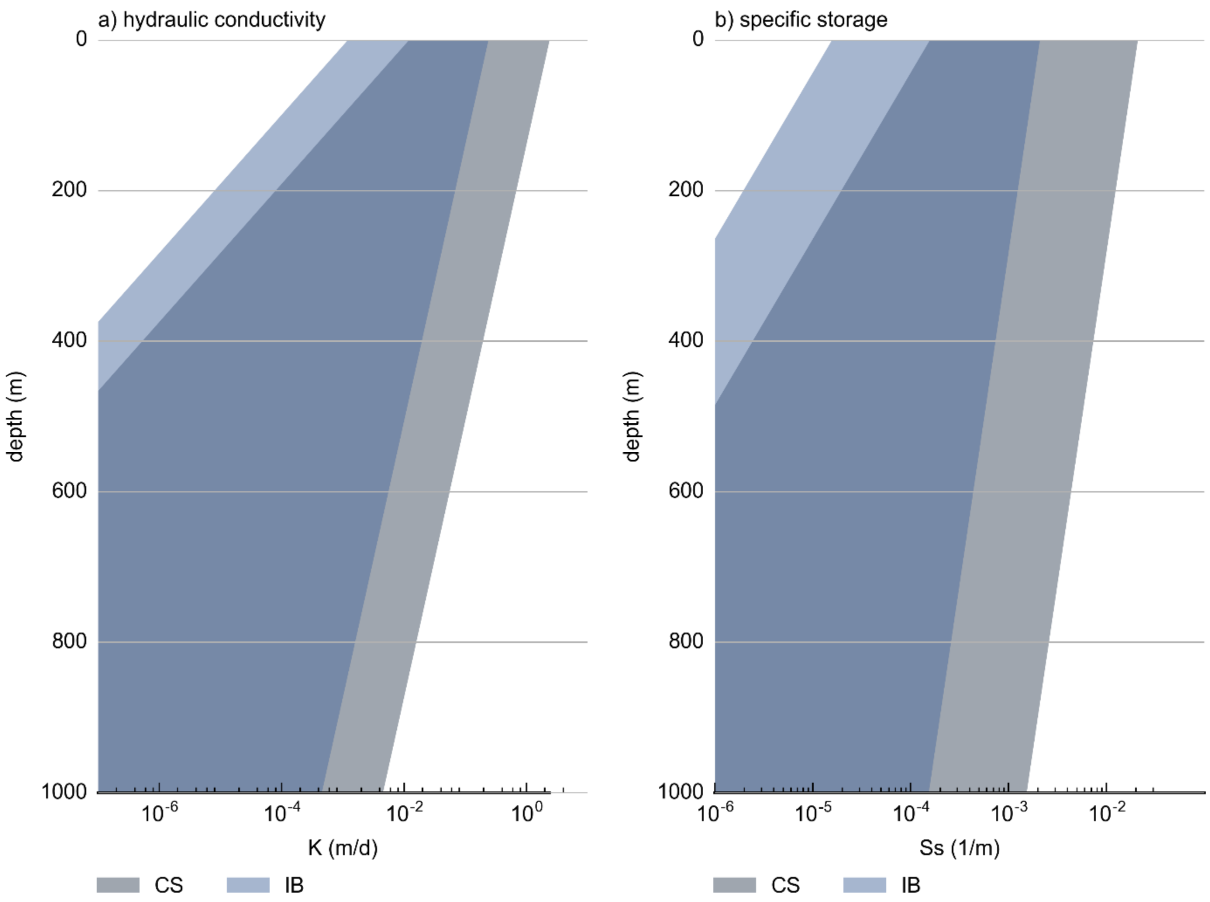

Figure 17 Range of hydraulic conductivity (a) and storage (b) for the coal seams and interburden as a function of depth that is sampled in the design of experiment

Note the dark blue color is the result of the overlapping range for coal seam and interburden
Data: Bioregional Assessment Programme (Dataset 1)

The hydraulic properties are calculated for the centre of each layer, interburden or coal seam. Any hydraulic conductivities below 1×10^{-7} m/day or storage values below 1×10^{-6} are replaced with 1×10^{-7} m/day and 1×10^{-6} respectively. These thresholds ensure numerical stability and avoid physically unrealistic parameter values.

K_CS_intercept is the hydraulic conductivity of the coal seams at zero metres depth, which in the GW AEM corresponds to the surface weathered and fractured rock layer, and varies between 0.03 and 3 m/day. This range encompasses the values of hydraulic conductivity for the coal seams and fractured rock reported in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018) and the review of existing models (see Section 2.6.2.2). For *K_IB_intercept*, the hydraulic conductivity of the interburden at zero metres depth, the range of *K_CS_intercept* is lowered by an order of magnitude and varies between 3×10^{-3} to 0.3 m/day. This is in accordance with the values reported for the deep water-bearing layers in Table 8 in Section 2.1.3.1.2 of companion product 2.1-2.2 (Frery et al., 2018).

The only available information to infer the slope of the exponential decrease function is the dataset of permeability measurements of coal seams (Figure 16). The range chosen in the design of experiment for the interburden and coal seams is the same and varies from 6.5×10^{-3} to 2.6×10^{-2} m^{-1}. This range, in combination with the intercept values, ensures that hydraulic conductivity in both the coal seams and the interburden in the depth interval targeted for CSG extraction (between 200 m and 1000 m) ranges over at least four orders of magnitude. This very wide range is a reflection of the uncertainty associated with these properties.

Measured values of storage are not available to inform the ranges for the design of experiment. The intercept and slope values for coal seams and interburden are chosen such that the range spans at least two orders of magnitude, that interburden storage is less than the storage in the coal seams and that the 200 m to 1000 m depth range encompasses 1×10^{-5} m^{-1}, the value most commonly assigned to storage at depth in the existing groundwater models in the region (see Section 2.6.2.2).

The interburden layers are simulated as leaky layers for which head and flux are not computed. These layers are represented through a vertical flow resistance term, *c* [T], which is computed as:

$$c = \frac{\tau}{K_h(d_{mid})\ x\ KvKh} \tag{9}$$

with τ the thickness of the layer, $K_h(d_{mid})$ the hydraulic conductivity evaluated at a depth corresponding to the middle of the layer, and *KvKh* the ratio between vertical and horizontal hydraulic conductivity. The range of *KvKh* is chosen to vary between 0.01 and 1, which means vertical hydraulic conductivity ranges from being equal to horizontal conductivity to being two orders of magnitude lower than horizontal conductivity. There are no direct measurements of vertical conductivity available to validate or constrain this range. The range represents the uncertainty in the conceptual understanding of the hydraulic properties in this region, from strongly anisotropic to isotropic. Due to predominantly horizontal sedimentological features in most sedimentary basins, it is considered very unlikely for vertical hydraulic conductivity to be greater than horizontal hydraulic conductivity.

The specific yield of the weathered zone leaky layer on top of the model is chosen to vary from 0.001 to 0.3, which represents a specific yield corresponding to a very low effective porosity (such as in a system where porosity only comprises the voids created by fractures) at the low end and a specific yield corresponding to a high porosity (such as in very coarse, unconsolidated material) at the high end.

The hydraulic properties of the faults are controlled by f_{hres}, the resistance flow encounters entering the fault (flow normal to the fault plane) and f_{vres}, the flow resistance within the fault (vertical flow along the fault plane). The flow entry resistance is computed as:

$$f_{hres} = \frac{f_w}{K_{fh}} \quad (10)$$

with f_w the width of the fault (m) and K_{fh} the horizontal hydraulic conductivity of the fault (m/day). The flow entry resistance is chosen to be equal for both major and subseismic faults and a nominal fault width of 1 m is adopted in this study. The range of the horizontal fault conductivity is chosen to vary from 1×10^{-5} m/day to 0.1 m/day. This range reflects the current uncertainty in the conceptual understanding of the hydraulic behaviour of faults as it allows the fault hydraulic behaviour to vary from barriers to horizontal flow at the low end of the range to almost no impedance to horizontal flow at the high end of the range. It is very unlikely for the fault width to vary over more than an order of magnitude. Stochastically varying the fault width parameter would therefore have limited effect on the range of the flow entry resistance term as the fault hydraulic conductivity varies over four orders of magnitude.

The flow resistance within the fault is computed with a similar equation as the one for flow entry resistance. The fault width, however, is replaced with the fault height, the vertical extent of the fault plane. In line with the discussion of the stochastic fault generation (Section 2.6.2.3.5), these are nominally set to 100 m for subseismic faults and 1000 m for major faults. The range of vertical hydraulic conductivity is the same as for horizontal hydraulic conductivity. Stochastically varying the fault height parameter would again have limited effect on the range of the flow resistance term as the fault hydraulic conductivity varies over four orders of magnitude. The wide range of conductivity allows the faults to act as conduits of flow vertically or as barriers, again reflecting the current limited understanding of fault hydraulic behaviour in this region.

2.6.2.6.2 Alluvial MODFLOW models

Table 6 lists the parameters that are included in the sensitivity and uncertainty analysis, their initial values, and the minimum and maximum of the range sampled in the design of experiment.

Table 6 Parameters of the Avon and Karuah models for the Gloucester subregion

Parameter name	Value	Description	Unit	Minimum	Maximum
Kha	1.0	Saturated hydraulic conductivity of top alluvial layer	m/d	0.1	10.0
Khw	0.003	Saturated hydraulic conductivity of lower weathered layer	m/d	0.0001	0.01
Sy	0.15	Specific yield of the top alluvial layer	na	0.25	0.05
Dc	100.0	Hydraulic conductance of lower boundary of drain bed	m^2/d	10.0	1000.0
Rmult	1.0	Multiplier for monthly recharge	na	0.1	2.0
dh	2.0	Depth to water in the lower weathered layer	m	0.0	5.0

The 'value' column lists the initial parameter value simulation, while the 'minimum' and 'maximum' columns show the range sampled for the design of experiment. The last two lines list non-variable parameters used in the simulations.
Na = not applicable.
Data: Bioregional Assessment Programme (Dataset 2)

The *Kha* parameter is the hydraulic conductivity of the alluvial model layer. The range chosen covers two orders of magnitude and is in accordance with hydraulic conductivity values observed in this region (see companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018, Section 2.1.3.1.2, Table 8)). Hydraulic conductivity is assumed to be uniform within the alluvium.

Khw is the hydraulic conductivity of the weathered zone model layer. In the model, the conductivity is considered to be isotropic (i.e. equal in all directions). With a specified head boundary condition in all active model cells, this parameter effectively controls the vertical flux into alluvium from the weathered zone and should in fact be considered as a vertical hydraulic conductivity. The range in Table 6 for this parameter therefore reflects the observed range of vertical hydraulic conductivity in the surface weathered and fractured rock layer (Frery et al., 2018).

Sy is the specific yield of the unconfined alluvial layer and *Dc* is the hydraulic conductance of the drainage cells. Observations of these parameters are not available in the Gloucester region and their ranges are based on literature values (Fetter, 2001).

Rmult is a multiplier to scale the recharge time series and ranges from 0.1 to 2. This means that recharge is varied in a range between 2% and 40% of recharge. This is in line with the variations in recharge estimates for the alluvium from previous studies (Section 2.6.2.2).

The last parameter, *dh*, is the offset in the weathered zone specified head and varies between 0 and 5 m. This wide range allows for the exchange flux between the weathered zone and the alluvium to vary from predominantly upwards to predominantly downwards.

The initial values are determined through a trial-and-error process in which the overall model behaviour was evaluated (see Table 6, 'value' column). This evaluation included visual inspection of three hydrographs in the lower, middle and upper parts of the catchment. If any of the simulated alluvial hydrographs exhibits artesian behaviour, then this would imply direct groundwater discharge to the land surface and was not considered a good fit.

Likewise, components of the water balance were inspected to ensure upward flux from the weathered zone into the alluvium is positive and the discharge to the model drain cells is consistent with the baseflow estimates (see Section 2.6.2.7 and companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)).

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Datasets

Dataset 1 Bioregional Assessment Programme (2016) GLO MF Model v02. Bioregional Assessment Derived Dataset. Viewed 4 May 2016, http://data.bioregionalassessments.gov.au/dataset/9d732408-003e-4901-86a7-cea95b585640.

Dataset 2 Bioregional Assessment Programme (2016) GLO AEM dmax v01. Bioregional Assessment Derived Dataset. Viewed 4 May 2016, http://data.bioregionalassessments.gov.au/dataset/c54640db-ca88-4ed2-8e58-6b1a198293c5.

2.6.2.7 Observations and predictions

Summary

The regional analytic element groundwater model (GW AEM) and the Avon and Karuah MODFLOW models are designed to predict the maximum difference in drawdown (*dmax*) for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures, and time to this maximum change (*tmax*) at the groundwater receptors in the surface weathered and fractured rock layer and the alluvial aquifers respectively.

In the design of experiment, ten thousand parameter combinations, generated through a Latin Hypercube sampling, are evaluated to provide a training set for the emulators that are used in the uncertainty analysis.

The sensitivity analysis based on these runs indicate that *dmax* and *tmax* for both the analytic element and the alluvial models are most sensitive to the hydraulic properties of the weathered zone. In addition to that, the drainage flux in the Avon MODFLOW model is most sensitive to the hydraulic conductivity of the alluvium and the riverbed conductance, while in the Karuah MODFLOW model the drainage flux is most sensitive to the recharge multiplier.

The exchange flux with the deeper sedimentary basin is for both the Avon and Karuah MODFLOW models most sensitive to the hydraulic conductivity of the weathered zone and the constant head offset.

2.6.2.7.1 Observations

2.6.2.7.1.1 Analytic element model

The regional analytic element groundwater model (GW AEM) is designed to simulate the change in head due to coal resource development, not to simulate historical, pre-development groundwater flow dynamics. From companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018) it is apparent that there is very limited historical groundwater flow or head data available that are suited to constrain the groundwater model predictions at a regional scale, outside the alluvium. Therefore, in this model the prior distributions of the parameters will not be constrained by observations of the state variables (see Section 2.6.2.8).

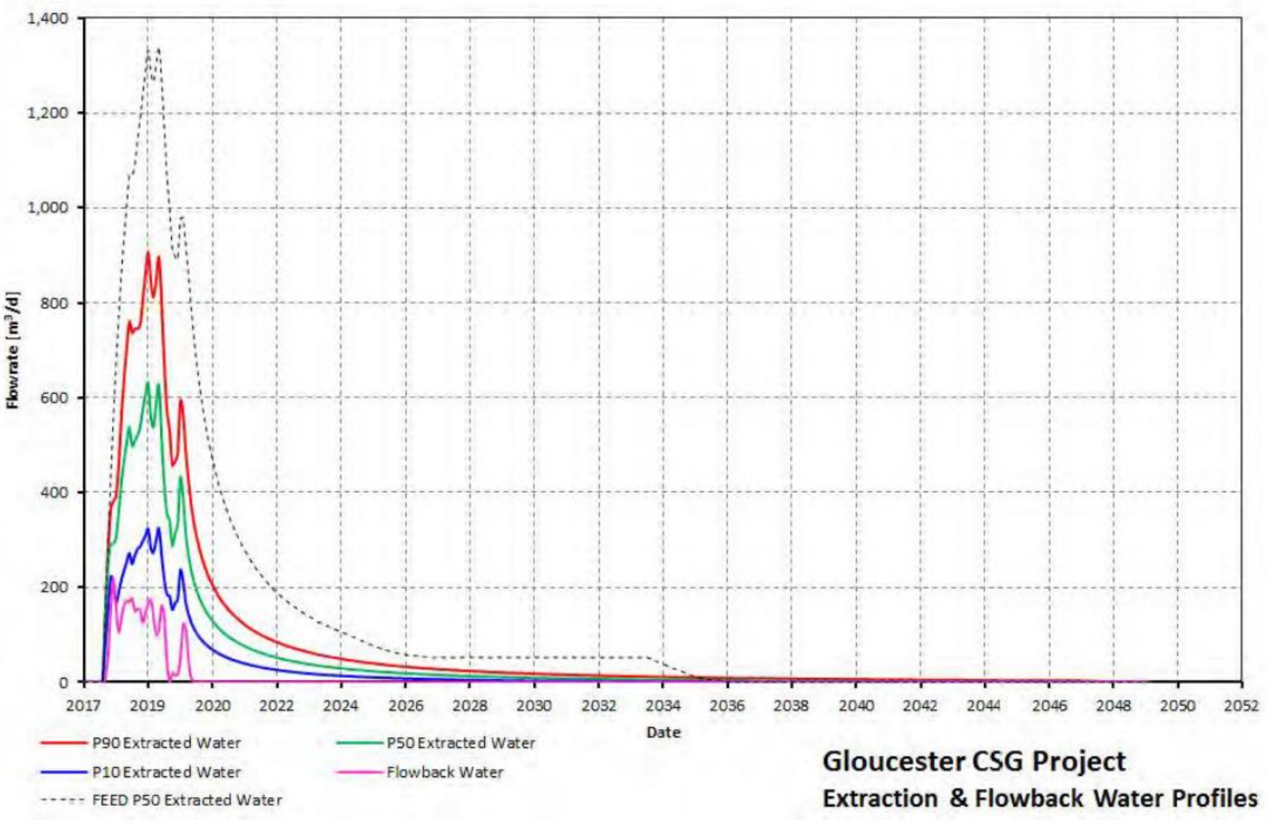

Figure 18 Predicted extracted water flow profile over life of Gloucester Gas Project

Source: AGL Energy Limited (2015). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of AGL Energy Limited.

AGL Energy Limited (AGL) has provided estimates of the expected water production for its Stage 1 gas field development area (Figure 18; see also Section 2.1.6.4 in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)). Figure 18 shows the 10th, 50th and 90th percentiles of predicted water extraction rates. These estimates are based on detailed reservoir modelling incorporating local information on the hydrogeology and coal seam gas (CSG) exploitation that is beyond the resolution of the regional-scale GW AEM. The water production rate increases rapidly in the early stage of CSG development and decreases slowly after this peak. The maximum predicted water extraction rate is approximately 0.32 ML/day, 0.6 ML/day and 0.9 ML/day for the 10th, 50th and 90th percentiles, respectively.

The CSG wells are implemented as a head-dependent boundary in the model and the simulated water production rates are stored for each simulation. While the water production cannot be considered as hard data to constrain the model, it provides a reality check of the model as it allows verification as to whether the simulated stress to the system is of the same order of magnitude. Based on Figure 18, any parameter combination that results in a maximum water extraction rate in excess of 1.1 ML/day is deemed to be unrealistic. This value is well above the 90th percentile predicted by AGL Energy Limited. Section 2.6.2.8 details how this information is integrated in the uncertainty analysis.

2.6.2.7.1.2 Alluvial MODFLOW models

Groundwater levels in the alluvium are highly influenced by local conditions, such as local heterogeneity in aquifer properties and temporal dynamics of surface water – groundwater interaction as illustrated in Figure 13. From Section 2.1.3.1.1 in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018) it is apparent that the groundwater level monitoring data density, both spatially and temporally, is very low. There is a high risk that by constraining regional-scale parameters with head observations that are dominated by local factors, parameters will be biased and not representative (Doherty and Welter, 2010).

The choice is therefore made to constrain the model with estimates of the water balance, more specifically the upward influx into the alluvium from the weathered zone and the discharge to the river system. These estimates of the water balance integrate spatial heterogeneity and temporal fluctuations in boundary conditions and are therefore more representative to constrain regional-scale parameters.

The observed values are determined on a long-term basis, assuming that measured salinity values in aquifers and streams were a good indicator of water mixing ratios (see companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)). For the Avon model, the long-term estimate over the 1982 to 2011 period of discharge to the river system is 7 GL/year ± 2.0 GL/year. The estimated upward flux over the same period is assumed to be 0.5 GL/year ± 0.5 GL/year. For the Karuah model the estimates are 6.5 GL/year ± 2.5 GL/year and 0.9 GL/year ± 0.9 GL/year for drainage flux and upward flux, respectively (Table 7). The ranges in these fluxes reflect the natural variability and observation uncertainty in the water balance estimates.

These estimates are comparable to the water balance estimates for the entire Gloucester Basin by Parsons Brinckerhoff (2015) of 9.3 GL/year baseflow and 1.5 GL/year upward flow.

Table 7 Estimated mean and standard deviation of the long-term groundwater fluxes used to constrain the Avon and Karuah models for the Gloucester subregion

Model	Observation data	Target (GL/y)	Tolerance (GL/y)
Gloucester-Avon	Discharge to drain	7.0	±2.5
	Upward flow	0.5	±0.5
Karuah-Mammy Johnson	Discharge to drain	6.5	±2.5
	Upward flow	0.9	±0.9

2.6.2.7.2 Predictions

2.6.2.7.2.1 Analytic element model

As stated in Section 2.6.2.1 and Section 2.6.2.3, the regional GW AEM is designed to probabilistically estimate the hydrological change due to coal resource development on the groundwater bores screened in the surface weathered and fractured rock layer (Figure 2, Figure 19).

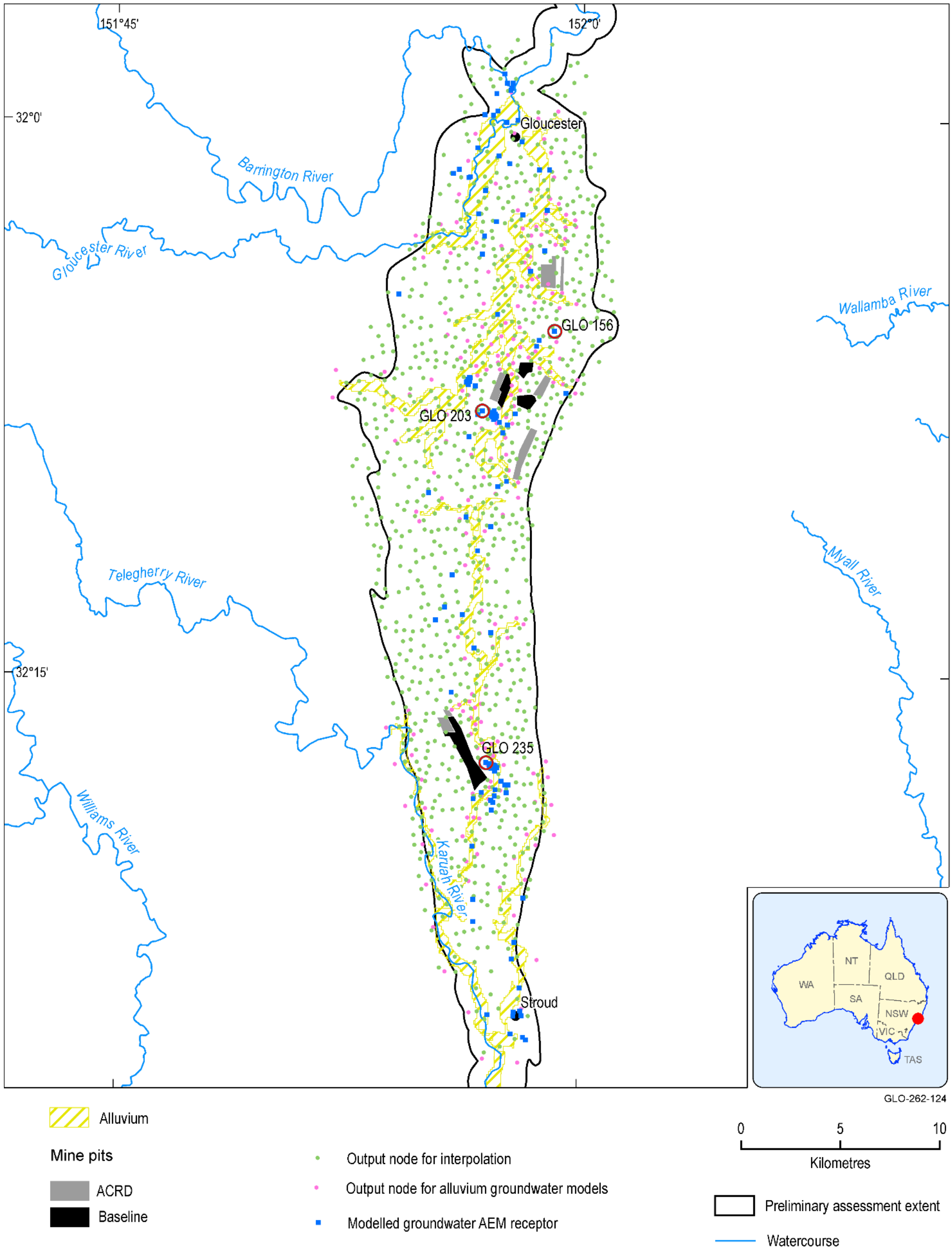

Figure 19 Regional analytic element groundwater model output locations

ACRD = additional coal resource development, AEM = analytic element model
Data: Bioregional Assessment Programme (Dataset 2, Dataset 3, Dataset 4)

The GW AEM also provides the time series of change in the lower boundary condition for the Avon and Karuah alluvial MODFLOW models. As drawdowns vary smoothly in space and time and to avoid the numerical burden of computing drawdown time series at every 90 m grid cell with a monthly time step, outputs were generated only for the surface weathered and fractured rock layer at a selection of 108 points (Figure 19) every ten years of simulation between 0 and 100 years. This selection of output locations and times is the result of a trial-and-error procedure to ensure information loss is minimal. The spatial density of points was controlled by the position of the Avon River and Karuah River alluvium model grid and the proposed coal seam gas (CSG) development area. For communication with the alluvial groundwater models, this model output was resampled and interpolated to the desired spatial and temporal resolution.

To produce the probabilistic maps of the maximum difference in drawdown (*dmax*) under the baseline coal resource development (baseline), under the coal resource development pathway (CRDP) and due to the additional coal resource development (obtained as the difference in drawdown between CRDP and baseline), an interpolation is carried out on the model results evaluated at the 1000 locations shown in Figure 19. To rationalise the computational resource requirements, the evaluation of the analytic element model at the 1000 locations is only done with a sample of 200 parameter combinations from the final posterior parameter distributions.

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

This is illustrated in Figure 20, for receptors GLO_156, GLO_203 and GLO_235. The location of these receptors is indicated in Figure 19. GLO_156 is situated between the Rocky Hill Coal Project and Stratford Mining Complex developments, about 2 km from both. GLO_203 is within 500 m of the western boundary of the Stratford Mining Complex and GLO_235 is less than 500 m from the Duralie Coal Mine. Figure 20 shows the simulated drawdown at these locations for both baseline and CRDP for the realisation that is closest to the median predicted impact (see Section 2.6.2.1). The bottom set of plots in Figure 20 shows the difference between the baseline and CRDP runs and illustrates the computation of *dmax* and *tmax*.

For receptor GLO_156, the maximum drawdown under the CRDP is realised within the simulation period. The timing of the maximum difference in drawdown (*dmax*) coincides with the maximum drawdown under the CRDP. At receptor GLO_203, the maximum drawdown under both baseline and CRDP is not achieved before the end of the simulation period. The maximum difference in drawdown (*dmax*), however, occurs around 2060. This indicates that in that period, the drawdown during CRDP is simulated to happen at a faster rate than in the baseline.

Receptor GLO_235 shows a negative drawdown due to additional coal resource development (additional drawdown), that is, less drawdown under CRDP than for under the baseline. In this particular case this is due to the fact that the increase in pumping rate from Duralie Coal Mine under the CRDP is not proportional to its increase in area. This causes the centre of the cone of depression under the CRDP to move north, locally resulting in less drawdown. Towards the end of the simulation period, the increased pumping rate does manifest itself as an increased drawdown (Figure 20(f)).

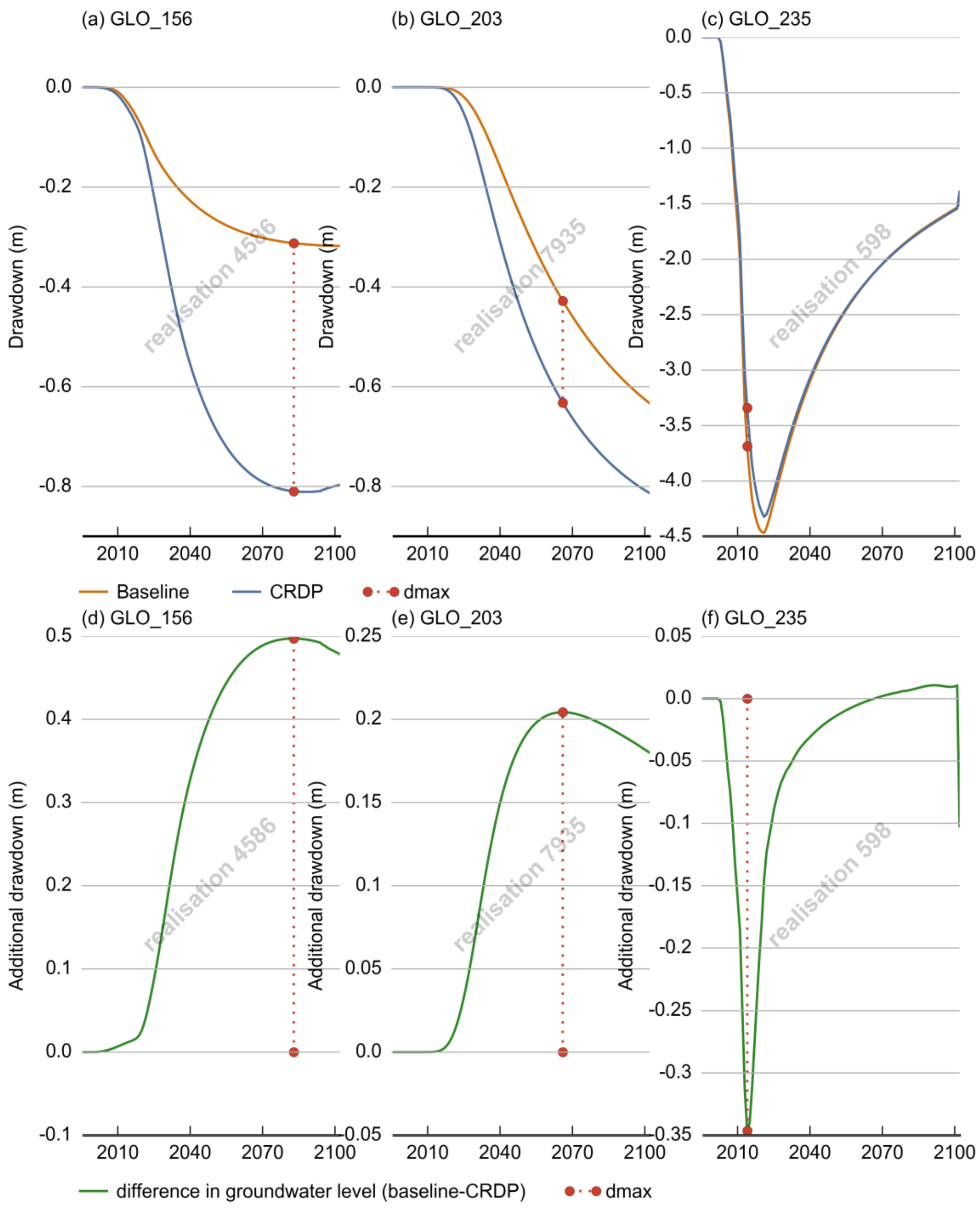

Figure 20 Example of regional analytic element groundwater model output time series of receptors GLO_156, GLO_203 and GLO_235 for the Gloucester subregion

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

2.6.2.7.2.2 Alluvial MODFLOW models

As outlined in Section 2.6.2.1, the alluvial MODFLOW models are designed to predict the drawdown due to additional coal resource development and year of maximum change at those receptors located within the alluvial model domain (Figure 10).

The alluvial MODFLOW models also provide time series of change in drainage flux. This change in flux is combined with the Australian Water Resources Assessment landscape model (AWRA-L) streamflow predictions to simulate the change in total streamflow (see companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018)). The MODFLOW drainage flux is aggregated for each monthly stress period for each of the catchments defined in AWRA-L, the area upstream of each surface water receptor (Figure 10).

The components of the water balance are not specified as a hydrological response variable of relevance for a receptor impact model and are therefore not reported in this product. Companion product 2.5 for the Gloucester subregion (Herron et al., 2018) does summarise the water balance for the alluvial MODFLOW models and the change in these balances for selected periods in the future.

2.6.2.7.3 Sensitivity analysis

In the design of experiment phase of the uncertainty analysis workflow (Figure 6, Section 2.6.2.1) a set of parameter combinations and corresponding model outputs is generated by evaluating the GW AEM and the alluvial MODFLOW models a large number of times, to train the emulators that replace the model chain in the uncertainty analysis. This training dataset is also used for the formal sensitivity analysis. Ten thousand different combinations are generated of the parameters of the GW AEM (listed in Table 5 of Section 2.6.2.6.1), the alluvial MODFLOW models (listed in Table 6 of Section 2.6.2.6.2) and the AWRA-L model (listed in Table 7 of Section 2.6.1.5.1 in companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018)).

The number of samples is considered sufficient if, emulators trained with that number of samples are able to accurately predict the model response for unsampled parameter combinations (Sacks et al., 1989). Due to the large number of predictions that are required from the model chain, it is not possible to guarantee that the sampling scheme is sufficient for each and every individual prediction. The accuracy of the emulators is, however, individually evaluated and emulators that do not satisfy the accuracy criteria are omitted from the uncertainty analysis (see Section 2.6.2.7.4).

A pragmatic choice is made to generate 10,000 parameter combinations of the entire model chain in the design of experiment. The size of the training set, 10,000 samples, is a trade-off between the sampling density of parameter space and computational resources available (both in run-time and storage space). The bioregional assessment (BA) modelling team used the Pearcey and Bragg clusters, which are part of the High Performance Computing facilities of CSIRO (CSIRO, 2016) to evaluate the model runs for the design of experiment and the subsequent training and running of the emulators for the uncertainty analysis.

The design of experiment set of parameter combinations is generated using a maximin Latin Hypercube design (see Santner et al., 2003, p. 138). Latin Hypercube sampling is a stratified random sampling of a multivariate parameter space designed to provide an even coverage of parameter space (Iman, 2008). The maximin Latin Hypercube design is generated like a standard Latin Hypercube design, one design point at a time, but with each new point selected to maximise the minimum Euclidean distance between design points in the parameter space. Points in the design span the full range of parameter values in each dimension of the parameter space, but also avoid redundancy among points by ensuring that no two samples are too close together (since nearby points are likely to have similar model output).

Figure 21 shows histograms of the 10,000 parameter combinations. The parameters are sampled uniformly on a log10 scale (*K_IB_intercept*, *K_CS _intercept*, *S_IB_intercept*, *S_CS_intercept*, *KvKh*, *Kfh*, *Kfv*, *ne*) or on a natural scale (*K_IB_slope*, *K_CS_slope*, *S_IB_slope*, *S_CS_slope*). In the design of experiment, no correlation between parameters is specified.

2.6.2.7.3.1 Analytic element model

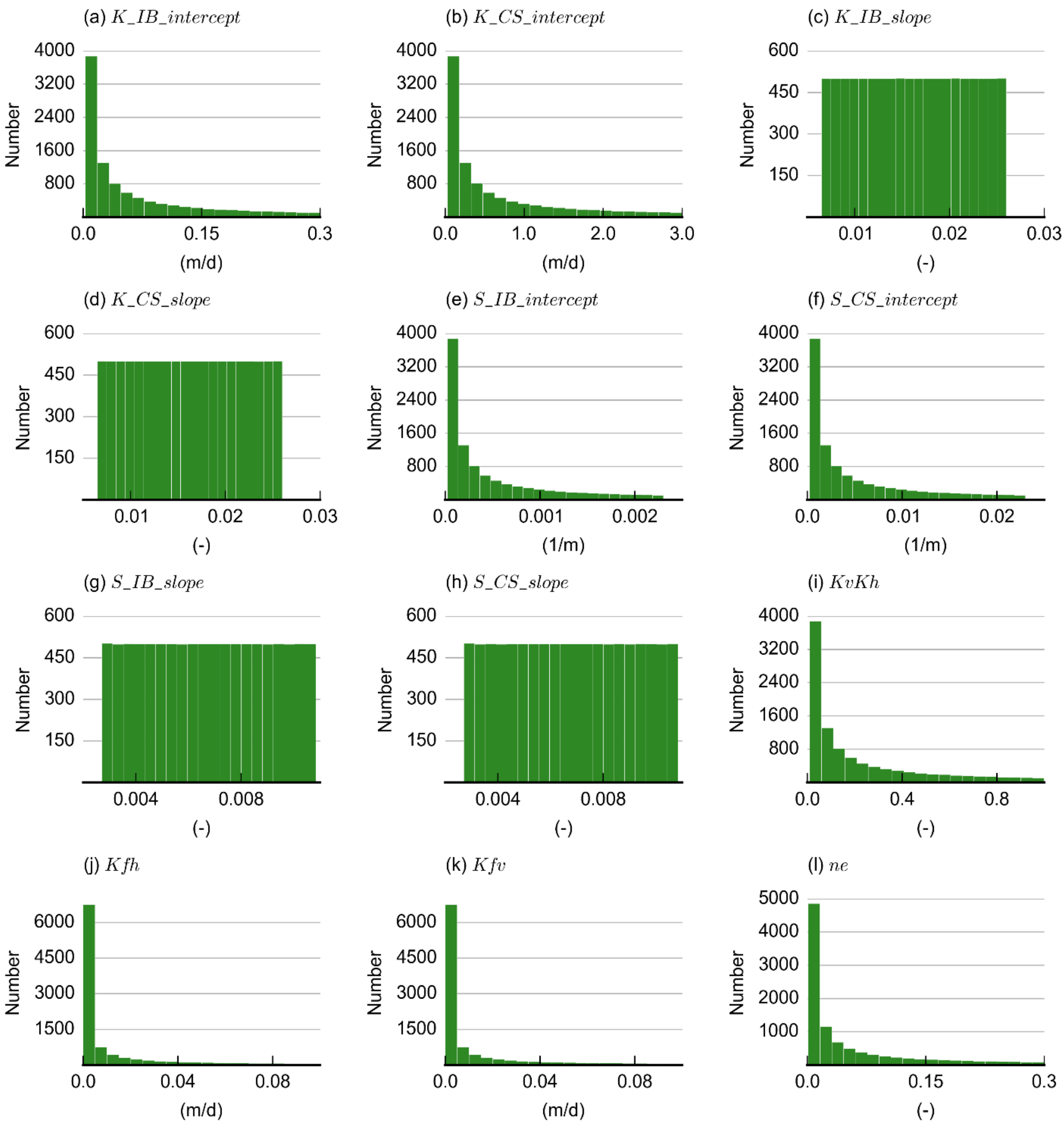

Figure 21 Histograms of the Latin Hypercube sampling of the parameter space of the regional analytic element groundwater model for the sensitivity analysis for the Gloucester subregion

Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 1)

Figure 22 shows the actual hydraulic conductivities and storage assigned to the model based on this Latin Hypercube sampling for two nominal depths: 250 m and 1000 m. As mentioned in Section 2.6.2.6, the numerical model implements lower threshold values to ensure numerical stability. These are also incorporated in Figure 22.

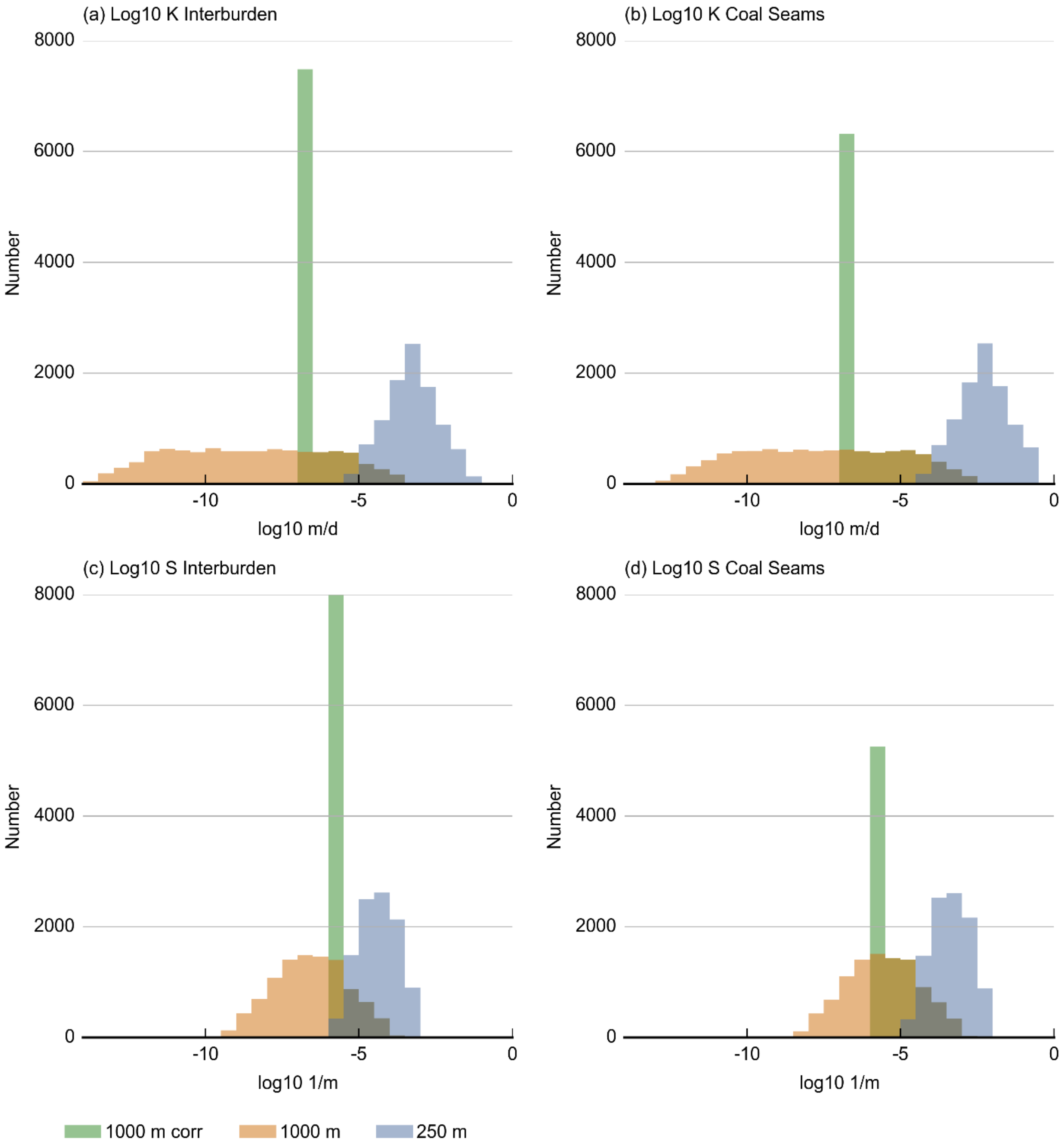

Figure 22 Range of hydraulic conductivity (*K*) and storage (*S*) for interburden and coal seams at 250 m and 1000 m for the Gloucester subregion

1000 m corr incorporates the lower threshold of 1 x 10^{-7} m/day for hydraulic conductivity and 1 x 10^{-6} for storage
Data: Bioregional Assessment Programme (Dataset 1)

Ten thousand parameter combinations are evaluated, 7819 of these simulations produced *dmax* and *tmax* values; 2181 returned a 'Not a Number' value for at least one receptor. These failed runs represent parameter combinations for which the GW AEM could not arrive at a converging solution. Figure 23 shows box and whisker plots of the parameter ranges that gave rise to successful and failed model runs. In these plots, the box represents the interquartile range (25th to 75th percentile) and the whiskers extend from the 5th to the 95th percentile. The median is indicated by a horizontal line through the interquartile box. Outliers, points below the 5th percentile or above the 95th percentile, are depicted as black points.

Failed model runs appear to be limited for parameter combinations that lead to low vertical conductivity of the interburden (low *K_IB_intercept*, *high K_IB_slope* and low *KvKh*) and high interburden storage (high *S_IB_intercept*) in combination with elevated hydraulic conductivity/low storage of the coal seams (high *K_CS_intercept*, low *K_CS_slope*, low *S_CS_intercept*).

These parameter combinations result in a fast and large drawdown in the coal seam, which cannot be replenished quickly enough through the interburden because of its low *Kv*. The pumping rate required to maintain the prescribed head in the CSG wells becomes increasingly small, which gives rise to numerical precision errors that in turn result in 'Not a Number' values for the CSG pumping rate. CSG pumping is implemented as a two-stage process (see Section 2.6.2.5). Pumping rate is computed in the first stage from a prescribed head boundary condition that will be implemented in a second stage as a prescribed flux.

In the failed runs, the prescribed flux is not available and hence the CRDP run fails. A case can be made to assign a zero-prescribed CSG pumping rate to the failed runs and run these again to at least simulate the cumulative impact of coal mining in the weathered zone for these parameter combinations. Another option is to limit the range of the parameters in the sensitivity analysis run, to ensure failed runs do not occur. As both options represent a manipulation of the model runs, these options are not implemented and in the further analysis, the failed model runs are omitted. The information from the failed runs will, however, be incorporated in specifying the prior distributions of the parameters and their covariance for the uncertainty analysis (Section 2.6.2.8).

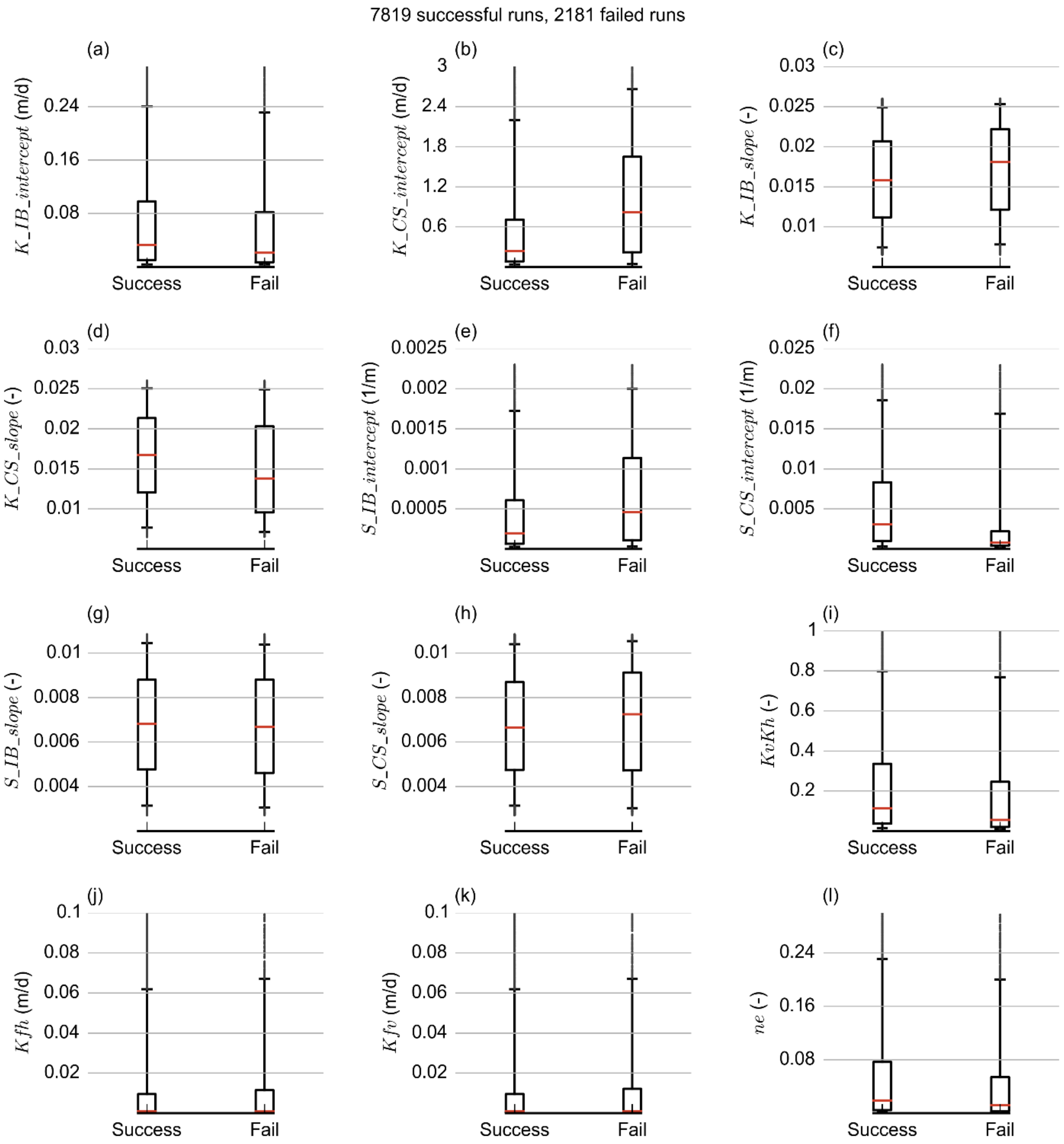

Figure 23 Boxplots of the parameter combinations of the regional analytic element groundwater model that lead to successful and failed model runs for the Gloucester subregion

A failed run is a run which returned a 'Not a Number' value for *dmax* and *tmax* for at least one receptor. Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 1)

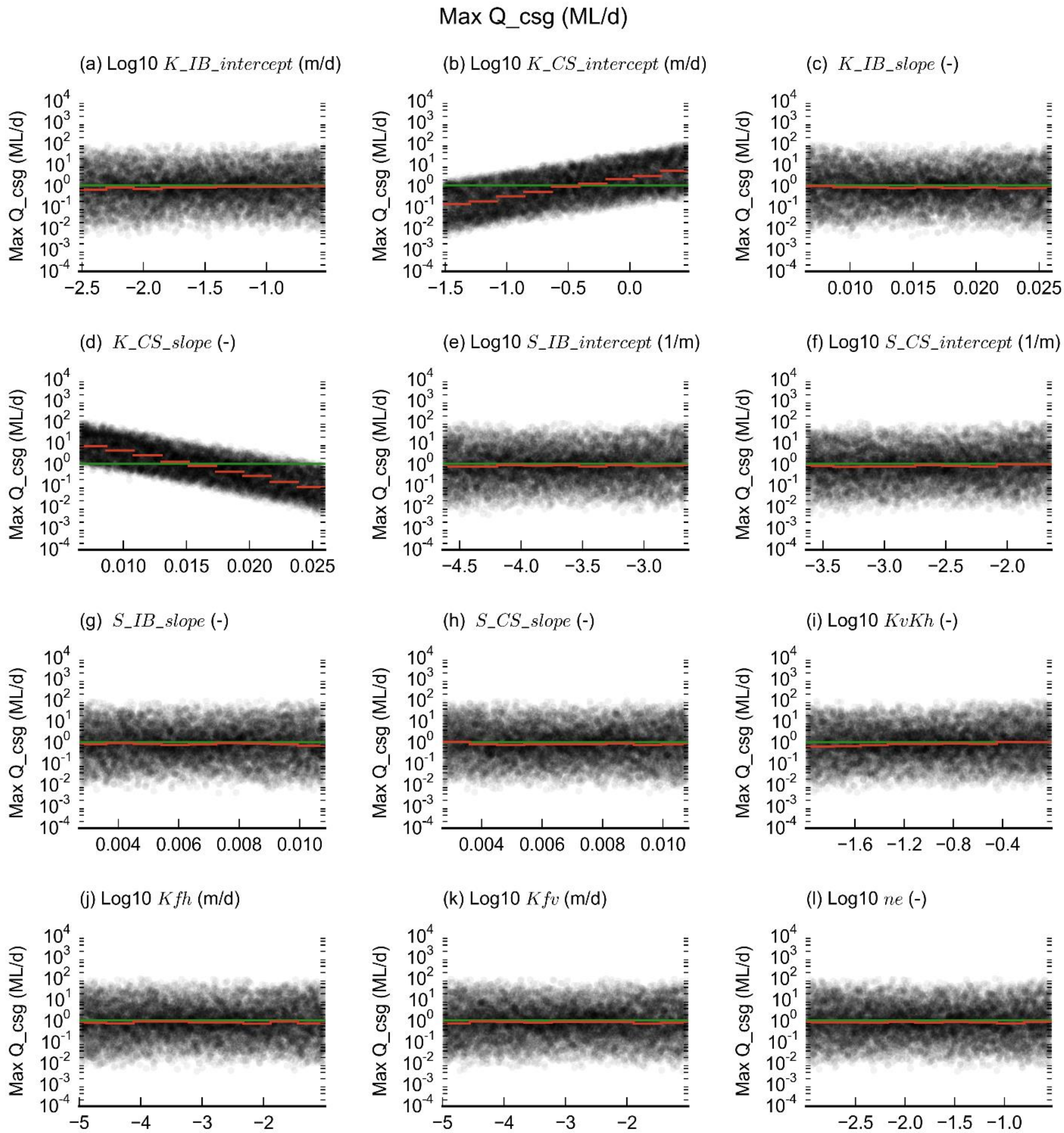

Figure 24 Scatterplots of parameter values versus maximum coal seam gas water production rate (Q_csg) for the Gloucester subregion

Each dot represents a single simulation. The red lines show the median value of *dmax* over the parameter range spanned by the line. The green line is the maximum water production rate threshold of 1.1 ML/day based on AGL Energy Limited (2015) predicted water extraction rates. Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 1)

The values of *dmax* and *tmax* are discussed in depth in Section 2.6.2.8, when the final posterior distributions of the *dmax* and *tmax* for each receptor are available. To gain a better understanding of model behaviour, however, the effect of the parameters on the maximum CSG production rate (Figure 24) and on the *dmax* values for receptor GLO_156, 2 km north from the Stratford Mining Complex and 2 km south of the Rocky Hill Coal Project (Figure 25), are examined. Rather than plotting the *dmax* values directly, they are transformed by taking the cubed root. This transformation increases the resolution for both positive and negative values.

From Figure 24 it is apparent that the maximum CSG production rate is controlled by the hydraulic conductivity of the coal seams (*K_CS_intercept* and *K_CS_slope*). The log of the maximum water production rate increases linearly with increasing hydraulic conductivity. An increase in the intercept of the exponential decrease function leads to higher conductivity values at depth. A decrease in the slope of equation 6 in Section 2.6.2.6 will have the same effect, higher conductivity at depth.

Almost half of the parameter combinations of the design of experiment result in maximum CSG water production rates in excess of 1.1 ML/day, the threshold value above which maximum water production rates are considered unrealistically high (see Section 2.6.2.7.1). This indicates that a sizeable proportion of the wide parameter range sampled in the design of experiment (Figure 25 and Figure 22) gives rise to unrealistically high CSG water production rates. Section 2.6.2.8 describes how the parameter range is constrained in the uncertainty analysis to avoid these unrealistic parameter combinations in the posterior parameter ensemble that is used to generate the posterior prediction ensemble.

Figure 25 shows the variation of the maximum difference in drawdown, *dmax,* in function of the parameter values of the design of experiment. One of the most striking features in Figure 25 is the presence of negative *dmax* values. These values appear to be limited to parameter combinations with high *K_CS_Intercept* and low *S_CS_intercept* values. These extreme and unlikely parameter combinations cause numerical instabilities which result in failed runs or negative drawdown due to additional coal resource development. The numerical instability occurs because the large fluxes generated by high hydraulic conductivity result in extremely high hydraulic gradients due to the low storage.

The red lines are the median of *dmax* in the parameter range spanned by the line. For this particular receptor, GLO_156, it is apparent that the two most influential parameters are *S_CS_intercept* and *K_CS_intercept*.

The intercept of the depth–*S* relationship for the coal seam, *S_CS_intercept*, shows a marked response in which drawdown increases with decreasing storage. This is likely an effect limited to the weathered zone, where, per definition of storage, for a volume of water extracted from an aquifer, small storage values result in large drawdowns and large storage values result in small drawdowns.

Decreasing the intercept of the depth–*K* relationship for the coal seam, *K_CS_intercept*, decreases both the *K* of the weathered zone and the *K* of the coal seams. A decrease of hydraulic conductivity in the weathered zone has a result that the cone of depression becomes deeper, as the resistance is higher for water to flow laterally to replenish the water extracted by the mines.

A detailed discussion for each receptor of these relationships is beyond the scope of the report. Figure 26 does show the sensitivity index of the cube root of *dmax* for each parameter–receptor combination, calculated with the density-based sensitivity index introduced by Plischke et al. (2013). Larger values of the sensitivity index indicate higher sensitivity of the prediction to the parameter. The cube root transform is chosen to compensate for the skewed distribution of most of the *dmax* values. It is apparent that the *K* and *S* intercept of the coal seams (and thus the weathered zone) are the dominant factors for most receptors.

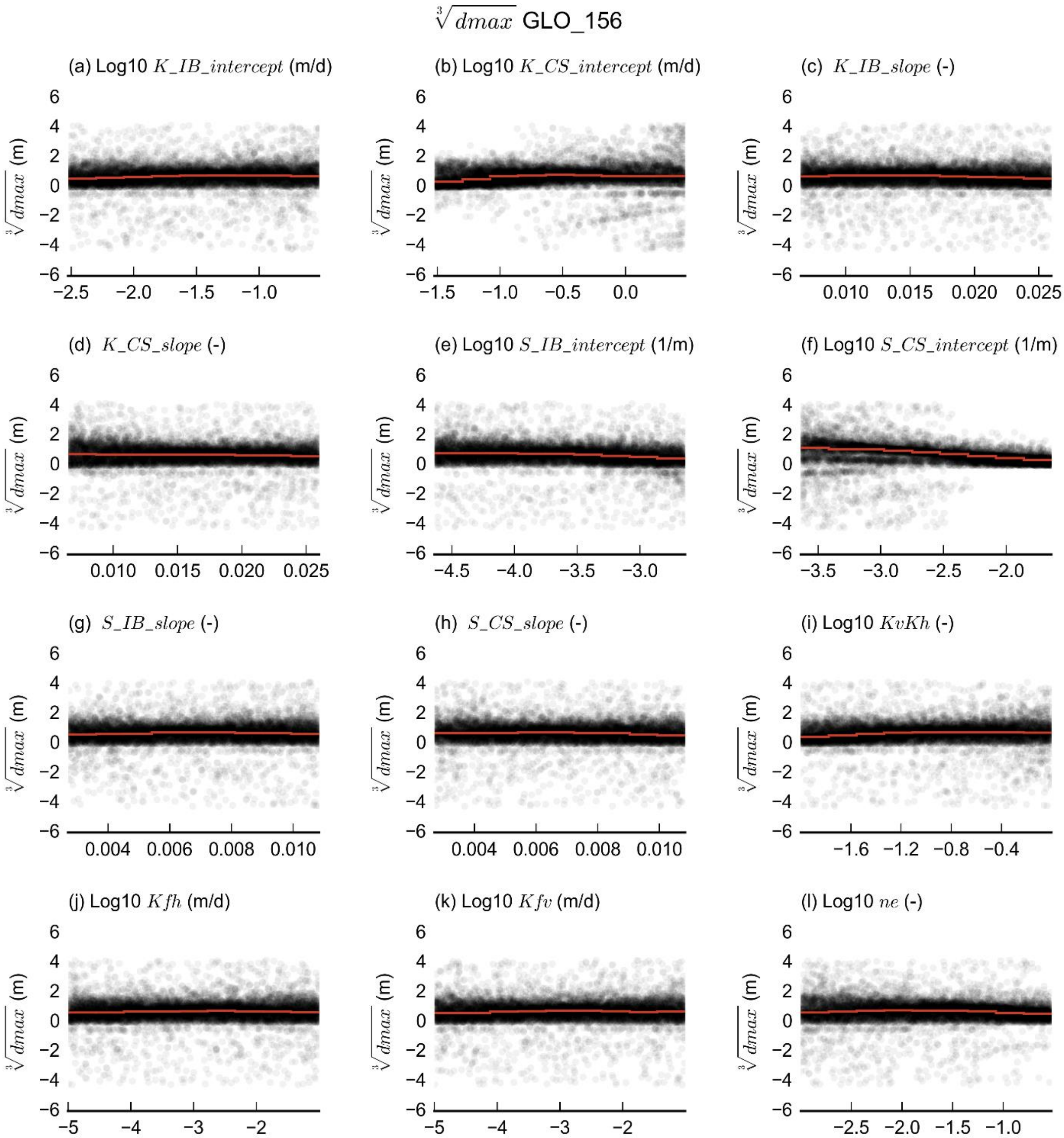

Figure 25 Scatterplots of parameter values versus cubed root of maximum difference in drawdown (*dmax*), due to the additional coal resource development (ACRD) for receptor GLO_156 for the Gloucester subregion

Each dot represents a single simulation. The red lines show the median value of *dmax* over the parameter range spanned by the line. Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 1)

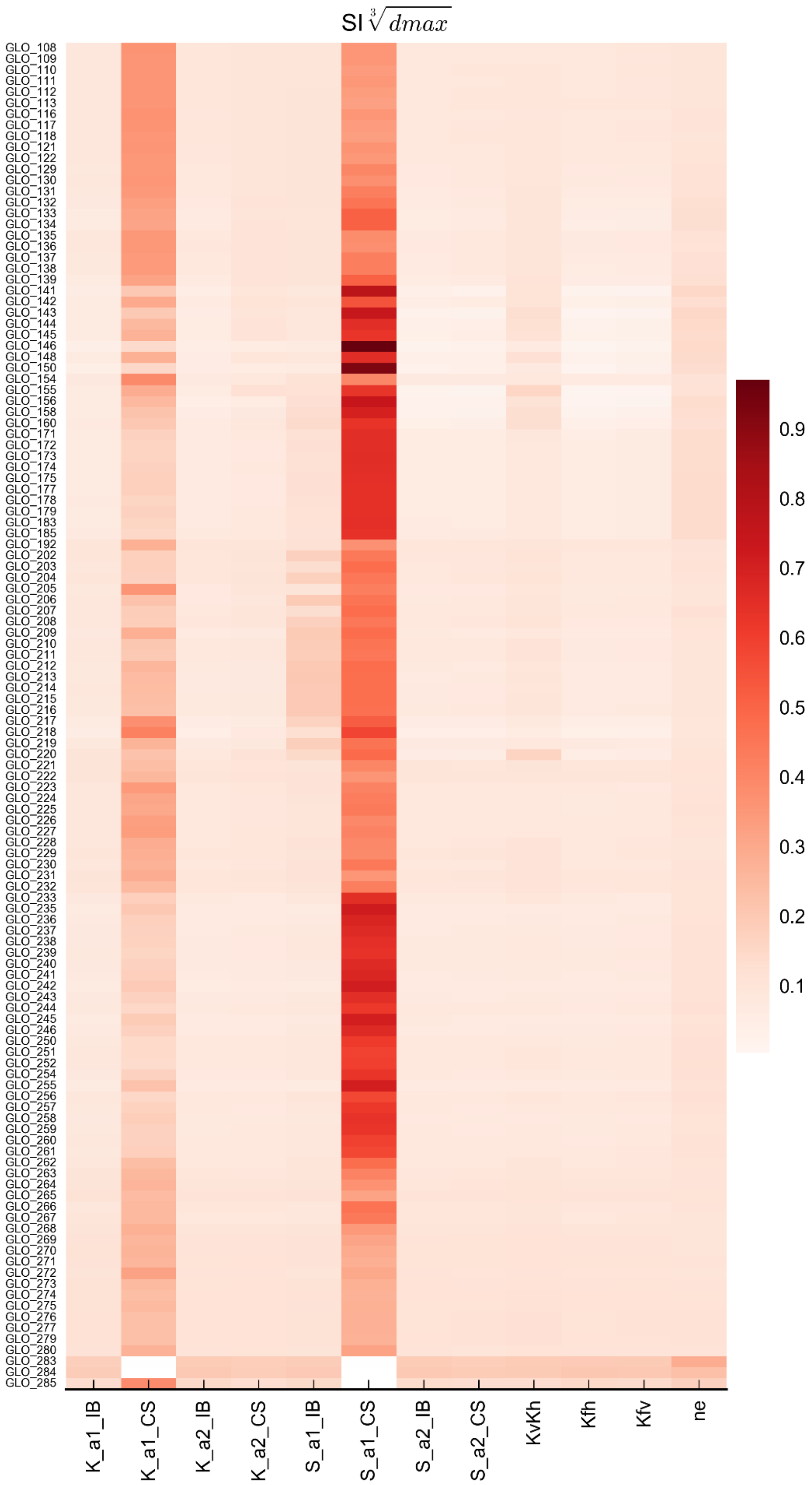

Figure 26 Sensitivity indices of the cube root of maximum difference in drawdown (*dmax*) for all parameter-receptor combinations, ordered from north (top) to south (bottom)

Larger values indicate higher sensitivity of a receptor to a parameter. Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms

Data: Bioregional Assessment Programme (Dataset 1)

2.6.2.7.3.2 Alluvial MODFLOW models

In the design of experiment of the sensitivity analysis of the Gloucester model chain, 10,000 parameter combinations of the MODFLOW Avon and Karuah models are generated and evaluated for both models. Figure 27 shows histograms of the parameter values in the design of experiment. The hydraulic conductivity of the weathered zone (*Khw*) and the alluvium (*Kha*) and the drainbed conductance are uniformly sampled in log10 space while the other parameters, the specific yield (*Sy*), the recharge multiplier (*Rmult*) and the constant head offset (*dh*) are uniformly sampled in native space.

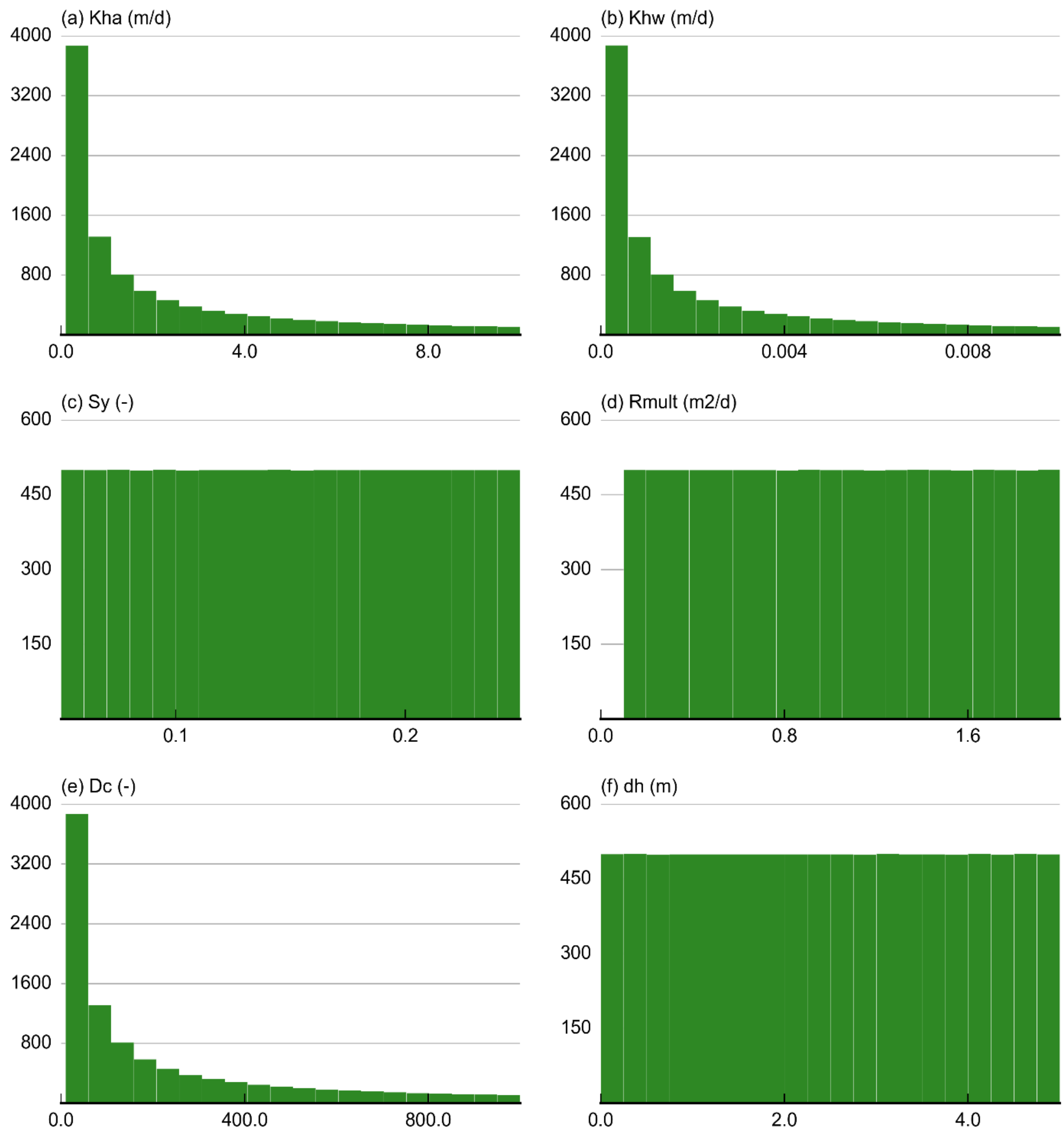

Figure 27 Histograms of the Latin Hypercube sampling of the parameter space of the alluvial Avon and Karuah models for the sensitivity analysis for the Gloucester subregion

(a) Saturated hydraulic conductivity of top alluvial layer (*Kha* (m/day)); (b) Saturated hydraulic conductivity of lower weathered layer (*Khw* (m/day)); (c) Specific yield of the top alluvial layer (*Sy* (-)); (d) Hydraulic conductance of lower boundary of drain bed (*Dc* (m^2/day); (e) Multiplier for monthly recharge (*Rmult* (-)); and (f) Depth to water in the lower weathered layer (*dh* (m)). Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 5)

From the 10,000 runs, 723 failed to converge. Figure 28 shows that failed model runs are associated with high hydraulic conductivity values for the alluvium (*Kha)* and a low specific yield (*Sy*). This physically unrealistic combination of parameters allows for the alluvial layer to drain too quickly and become dry. This causes numerical instability preventing the model to converge.

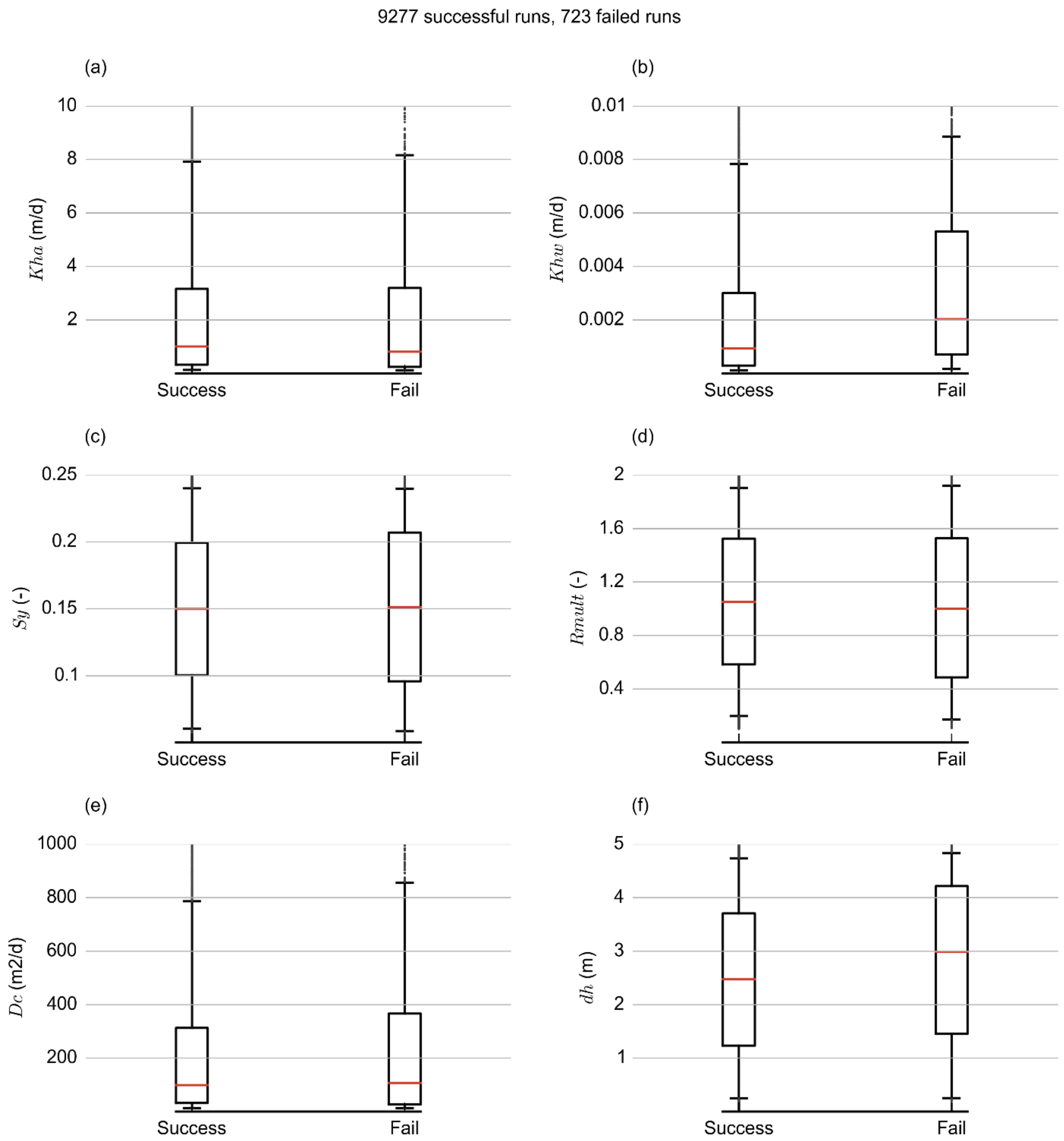

Figure 28 Boxplots of the parameter combinations of the Avon and Karuah models that led to successful and failed model runs for the Gloucester subregion

(a) Saturated hydraulic conductivity of top alluvial layer (*Kha* (m/day)); (b) Saturated hydraulic conductivity of lower weathered layer (*Khw* (m/day)); (c) Specific yield of the top alluvial layer (*Sy* (-)); (d) Hydraulic conductance of lower boundary of drain bed (*Dc* (m^2/day); (e) Multiplier for monthly recharge (*Rmult* (-)); and (f) Depth to water in the lower weathered layer (*dh* (m)). Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 5)

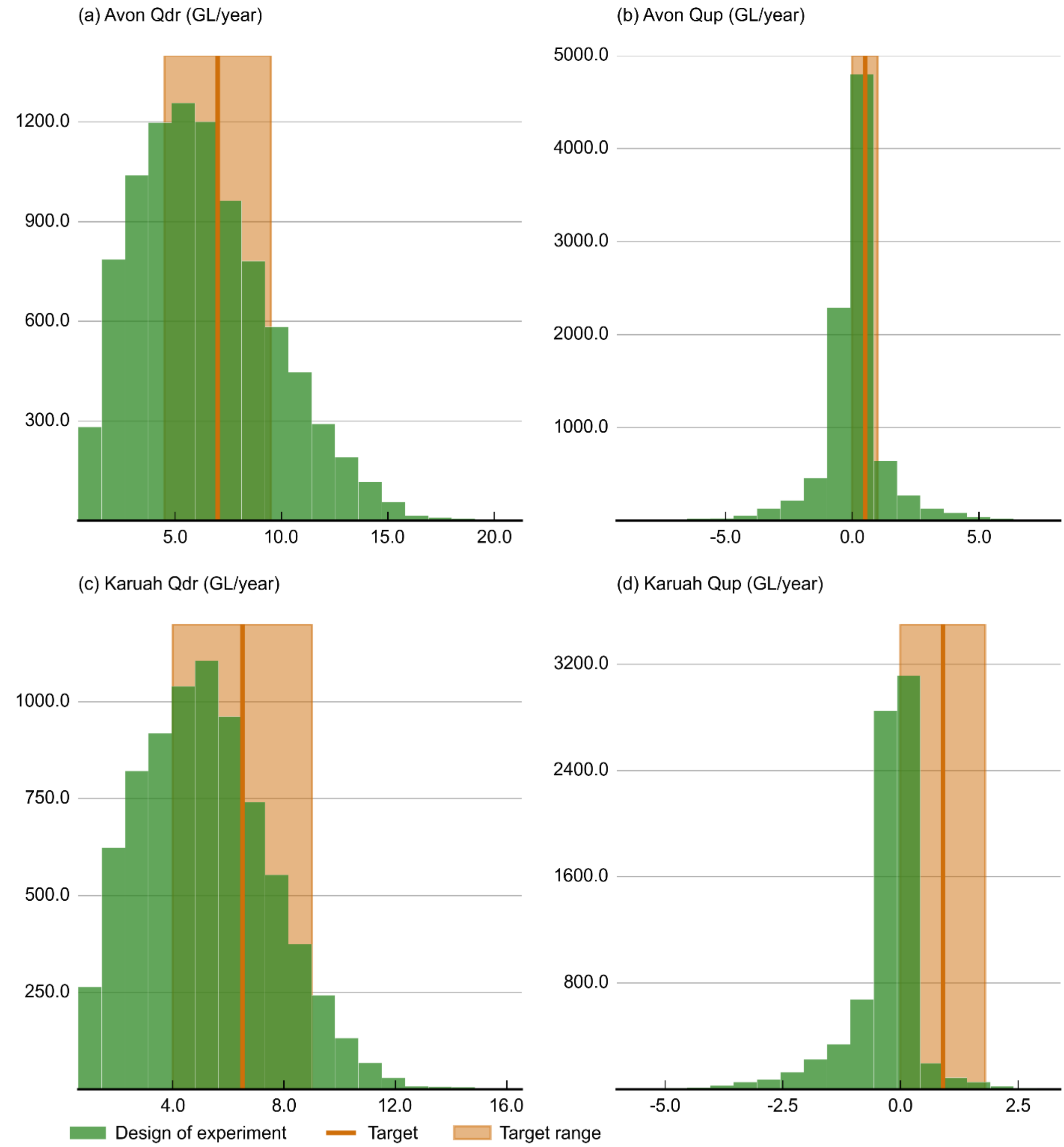

Figure 29 Histograms of drainage and upward fluxes simulated in the design of experiment runs for the Avon and Karuah models, compared to the target distribution, for the Gloucester subregion

Qdr = drainage flux; *Qup* = alluvium – weathered zone exchange flux
Data: Bioregional Assessment Programme (Dataset 5)

Figure 29 shows histograms of the simulated drainage fluxes and upward fluxes into the alluvium for the Avon and Karuah models, compared to their target range from Table 7. The simulated drainage fluxes are close to the target distributions, while the current range of parameters evaluated in the design of experiment appears to underestimate the upward flux, especially for the Karuah model. During the uncertainty analysis, a Markov chain Monte Carlo simulation is carried out to select parameter combinations that are in agreement with the target distributions.

Figure 30 shows the response of the drainage and upward fluxes to variations in parameter values for the Avon and Karuah models.

The drainage flux in both Avon and Karuah models is controlled by the hydraulic conductivity of the alluvium and the recharge multiplier, where increases in these parameters lead to increases in drainage flux. The other parameters do affect the drainage flux, but to a much lesser extent.

The magnitude of the upward flux is completely dominated by the hydraulic conductivity of the weathered zone. The direction of flow appears to be controlled primarily by the offset of the specified head boundary condition. Secondary controlling factors are the hydraulic conductivity of the alluvium and the recharge multiplier. The upward flux is a function of the hydraulic gradient between the alluvium and the weathered zone. Large *dh* values result in fluxes towards the weathered zone. Elevated groundwater levels in the alluvium, through low *Kha* or high *Rmult*, will also result in fluxes towards the weathered zone.

Figure 31 illustrates the response of drawdown due to additional coal resource development at the receptor locations to variations in parameter values for two representative receptors: GLO_147 in the Avon model and GLO_248 in the Karuah model. These plots include the two parameters that control drawdown in the weathered zone from the regional model, namely *K_CS_intercept* and *S_CS_intercept*.

For both receptors it is clear that the most important parameter is the hydraulic conductivity in the weathered zone (*Khw*), followed by the weathered zone parameters of the regional model. The hydraulic conductivity and storage in the alluvium are of lesser importance, as is the recharge multiplier and drainbed conductance and constant head offset. This indicates that the drawdown due to additional coal resource development is dominated by the magnitude of the change in flux at the bottom of the alluvium.

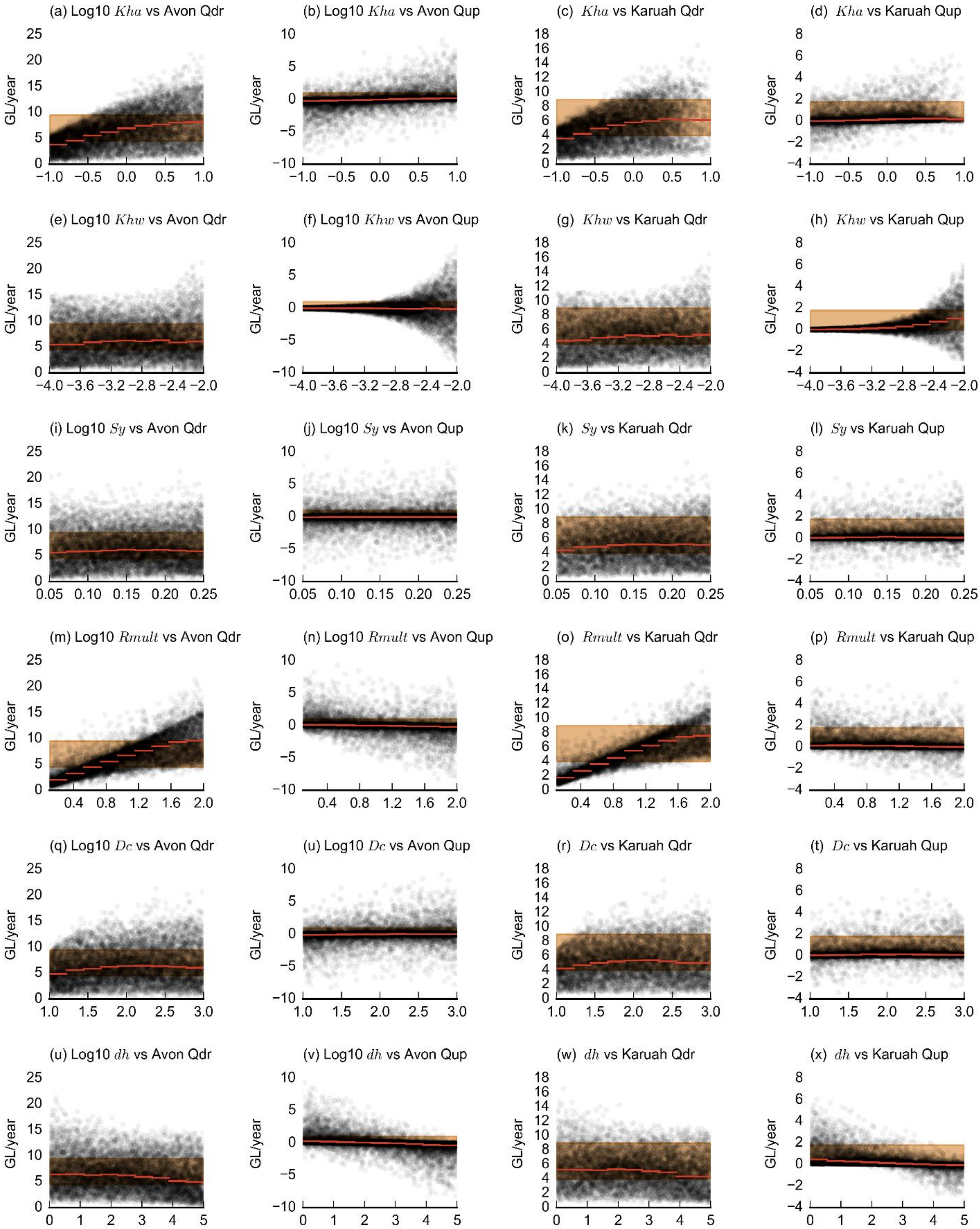

Figure 30 Scatterplots of the simulated drainage (1st and 3rd column of figures) and upward fluxes (2nd and 4th column of figures) versus parameter values for the Avon (1st and 2nd column of figures) and Karuah (3rd and 4th column of figures) MODFLOW models for the Gloucester subregion

The red lines indicate the median y-axis value over the range spanned by the width of the line. The orange band indicates the target range of the y-axis. *Qdr* = drainage flux; *Qup* = alluvium – weathered zone exchange flux. Refer to Table 5 in Section 2.6.2.6.1 for definitions of other terms.

Data: Bioregional Assessment Programme (Dataset 5)

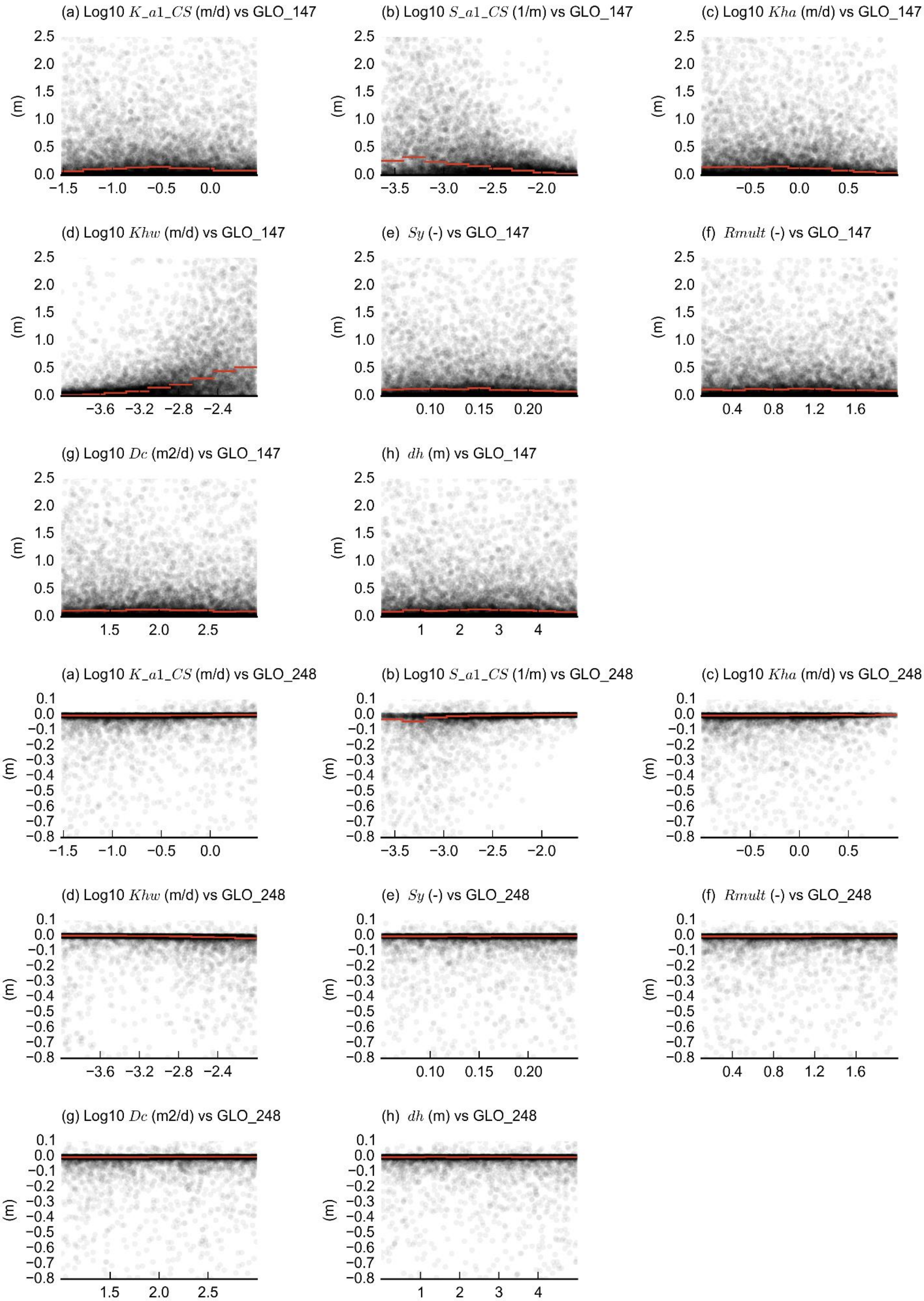

Figure 31 Scatterplots of maximum difference in drawdown (*dmax*) versus parameter values for receptors GLO_147 ((a) through (h)) and GLO_248 ((a) through (h)) for the Gloucester subregion

Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 5)

In Figure 32 this sensitivity is quantified for all *dmax* parameter–receptor combinations with the density-based sensitivity index introduced by Plischke et al. (2013). Rows in the figure without colour coding indicate receptors with an impact too small to analyse. The sensitivity indices confirm that, in general terms, *S_CS_intercept*, *K_CS_intercept* and *Khw* dominate the magnitude of *dmax* for most receptors. Note that the water balance targets are not able to greatly constrain these parameters.

2.6.2.7.4 Emulators

The purpose of a statistical emulator is to provide a computationally efficient surrogate for a computationally expensive model. These emulators provide a way to quantify the predictive distribution for a prediction of interest, given a new set of parameters at which the model was not run. The statistical emulation approach employed herein is called Local Approximate Gaussian Processes (LAGPs) as implemented through the 'aGP' function of the 'laGP' package (Gramacy, 2014) for R (R Core Team, 2013). LAGPs were chosen because: (i) they can be built and run very rapidly in the 'laGP' R package; (ii) unlike some other popular emulation approaches (e.g. standard Gaussian process emulators), they allow for nonstationarity in the model output across the parameter space which provides the emulator with more flexibility to match model output; and (iii) they were found to have excellent performance when compared to a range of other emulation techniques (Nguyen-Tuong et al., 2009; Gramacy, 2014).

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

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

In constructing the emulators for drawdown at the receptor locations, cubed-root transforms of the model outputs were used, while the emulators for year of maximum change were trained on untransformed model outputs. The design of experiment model parameters were either used in their natural forms (i.e. parameters *K_IB_slope*, *K_CS_slope*, *S_IB_slope* and *S_CS_slope*) or log10-transformed (i.e. *K_IB_intercept*, *K_CS_intercept*, *S_IB_intercept*, *S_CS_intercept*, *KvKh*, *Kfh*, *Kfv* and *ne*) depending upon the range sampled in the design of experiment.

When evaluating a trained LAGP emulator for a new parameter combination, the emulator provides a mean and standard deviation of the prediction the emulator is trained for. The mean can be considered the best estimate of the prediction value corresponding to the new parameter combination, while the standard deviation provides as estimate of the uncertainty related to using the emulator.

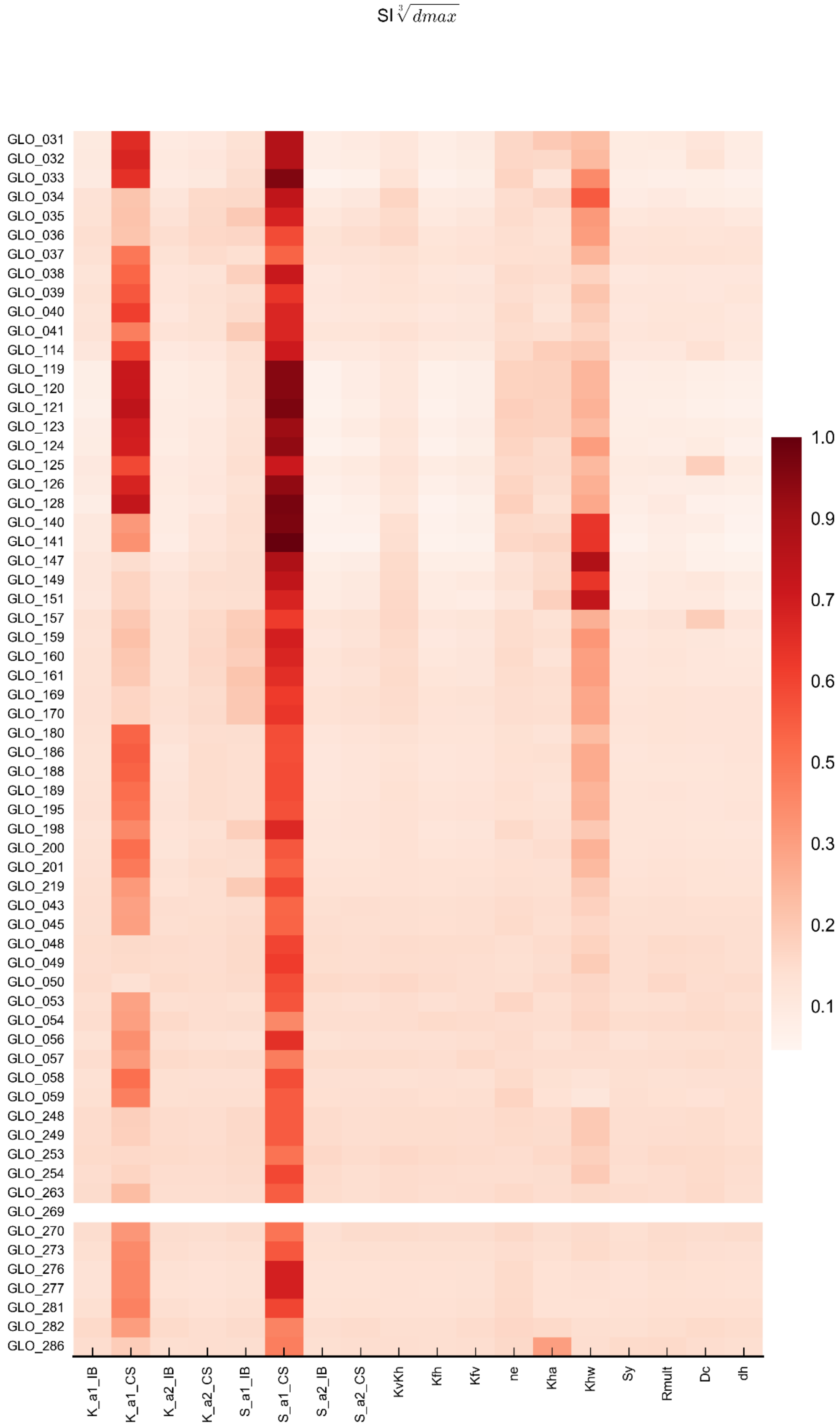

Figure 32 Sensitivity indices of maximum difference in drawdown (*dmax*) for all parameter–receptor combinations for the Avon and Karuah models for the Gloucester subregion, ordered from north (top) to south (bottom)

Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 5)

The predictive capability of an LAGP emulator 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. These plots were verified to ensure that close to 95% of values were contained in these intervals. Figure 33(a) and Figure 33(b) show two examples of these plots for the *dmax* values of receptor GLO_150. The blue dotted line in Figure 33(a) shows the 1:1 line and the orange lines show the 95% predictive intervals from the LAGP emulator. The points plotted in Figure 33(b) show the hit rates achieved by the emulator in each of the 30 folds of cross validation used. These are all well above the target of 95%.

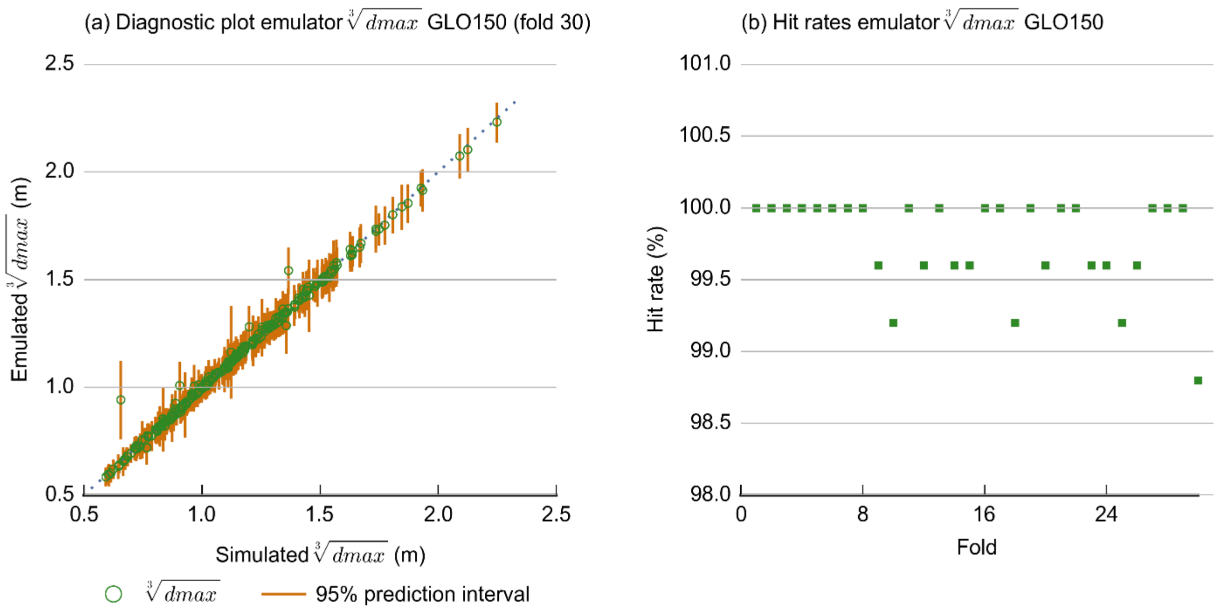

Figure 33 (a) Diagnostic plot for the 30th fold of the cross validation and (b) hit rates from each of the 30 folds of cross validation for the emulator of GLO_150 maximum difference in drawdown (*dmax*) for the Gloucester subregion

Data: Bioregional Assessment Programme (Dataset 1)

When the emulator is used to evaluate a new parameter combination in the Monte Carlo step of the uncertainty analysis (Figure 6 in Section 2.6.2.1), a random sample is generated from the normal distribution defined by the mean and standard deviation of the emulator output. Only emulators with a hit rate in excess of 95% are used in the Monte Carlo analysis. This ensures that the emulator results are true to the original model output and that the predictive uncertainty is overestimated, rather than underestimated.

For some receptors it will not be possible to create an emulator with sufficient precision and it will not be possible to adequately estimate the predictive posterior ensemble for those. These receptors are labelled as such in Dataset 2 (Bioregional Assessment Programme, Dataset 2) and the median of the design of experiment is used as their predicted value.

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Dataset 2 Bioregional Assessment Programme (2016) GLO AEM Model v02. Bioregional Assessment Derived Dataset. Viewed 4 May 2016, http://data.bioregionalassessments.gov.au/dataset/e76e05a1-3d3c-4014-a163-66a342278ea2.

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Dataset 5 Bioregional Assessment Programme (2016) GLO MFdmax v01. Bioregional Assessment Derived Dataset. Viewed 4 May 2016, http://data.bioregionalassessments.gov.au/dataset/df0ff3b6-b131-4cf7-9d86-33d1de01634d.

2.6.2.8 Uncertainty analysis

Summary

In the uncertainty analysis, the uncertainty in the model parameters is propagated through the analytic element model and the alluvial MODFLOW models and constrained with the available observations to obtain ensembles of predicted maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development and year of maximum change (*tmax*) at the receptors. In addition to that, maps of the probability of drawdown due to additional coal resource development (additional drawdown) exceeding 0.2 m are presented for the surface weathered and fractured rock layer and for the alluvia of the Avon and Karuah.

Normal prior distributions are specified for most parameters, either in native or log space, with a mean equal to the center of the range sampled in the design of experiment. The variance is chosen such that 99% of the probability mass is within the sampled range. A covariance is specified between the parameters controlling hydraulic conductivity and storage and between parameters controlling horizontal and vertical fault hydraulic properties. For the parameters controlling the decrease with depth of hydraulic properties and the fault hydraulic conductivity, the mean is not chosen to be equal to the center of the sampled range to ensure the hydrologic change is overestimated rather than underestimated.

The prior parameter distributions of the analytic element model are constrained with the maximum coal seam gas (CSG) water production rate which resulted in posterior probability distributions for *dmax* and *tmax* indicating that: (i) the effect on *dmax* is highly localised around the mine pits; (ii) it is unlikely to have drawdowns due to additional coal resource development in excess of 1 m, except in close proximity of the mine pits; (iii) the largest *dmax* values are attained within or shortly after the production life of the coal mines and CSG field. Smaller additional drawdowns, further away from the center of the development activity, are realised at later times, where the smallest noticeable drawdowns due to additional coal resource development are not fully realised within the simulation timeframe; and (iv) in the modelled drawdowns, the effect of CSG production and the presence of faults and fractures cannot be distinguished from the effect of coal mining in the Gloucester subregion.

The prior parameter distributions for both alluvial MODFLOW models are constrained with historical estimates of the water balance. The resulting posterior ensembles of predictions indicate that: (i) hydrological change is limited to the immediate vicinity of coal mines and (ii) it is very unlikely to have drawdown due to additional coal resource development in excess of 1 m in the alluvial aquifers; and that (iii) it is very unlikely that the drawdown will cause the groundwater levels to drop below the drainage base of the stream network.

The qualitative uncertainty analysis lists the main model assumptions and choices and discusses their potential effect on the predictions. The model choices with the greatest perceived potential impact on the predictions are related to the implementation of the coal resource development pathway (CRDP). Other model assumptions, such as the hybrid modelling approach, the choice for drainage boundary to represent the stream network and

the length of the simulation period are shown to be conservative choices (i.e. the hydrological change is overestimated rather than underestimated).

The uncertainty analysis is divided in two sections: quantitative uncertainty analysis and qualitative uncertainty analysis. As outlined in submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016), quantitative uncertainty analysis is the numerical propagation of the uncertainty in parameters defined in the parameterisation section through the model chain into an ensemble of predictions. Qualitative uncertainty analysis on the other hand is a structured discussion and scoring of the model choices and assumptions in function of their impact on predictions.

2.6.2.8.1 Quantitative uncertainty analysis

The workflow of the uncertainty analysis (see Section 2.6.2.1 and submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016)) starts with defining the prior parameter distributions. These are subsequently constrained by the available observations through Markov chain Monte Carlo sampling to generate the posterior parameter ensembles. These posterior parameter ensembles are then sampled to generate the ensembles of predictions.

2.6.2.8.1.1 Prior parameter distributions

Analytic element model

Table 8 Prior parameter distributions for the regional analytic element groundwater model

Parameter	Distribution	Mean	Standard deviation	Units
K_a1_IB	Normal in Log10 space	-3.58	0.6	m/d
K_a1_CS	Normal in Log10 space	-1.37	0.6	m/d
K_a2_IB	Normal	0.01	0.001	na
K_a2_CS	Normal	0.01	0.001	na
S_a1_IB	Normal in Log10 space	-8.41	0.6	1/m
S_a1_CS	Normal in Log10 space	-6.07	0.6	m/d
S_a2_IB	Normal	0.0054	0.0005	na
S_a2_CS	Normal	0.0054	0.0005	na
KvKh	Normal in Log10 space	-2.41	0.6	na
Kfh	Normal in Log10 space	-7.66	0.4	m/d
Kfv	Normal in Log10 space	-5.38	0.4	m/d
ne	Normal in Log10 space	-2.35	0.8	na

Data: Bioregional Assessment Programme (Dataset 1)

The factors included in the formal uncertainty analysis for the regional analytic element groundwater model (GW AEM) are the parameters listed in Table 5 in Section 2.6.2.6. The specification of the prior parameter distributions, shown in Table 8, was mostly driven by the geology and hydrogeology information presented in the context statement (companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). Figure 34 shows the prior distributions of each individual parameter.

All parameters are chosen to be normally distributed, either on the log scale or on the natural scale. The distribution for the intercepts of *K* (hydraulic conductivity) and *S* (storage) for interburden and coal seams (*K_IB_intercept*, *K_CS_intercept*, *S_IB_intercept*, *S_CS_intercept*) is chosen to be centred around the middle of the design of experiment range (Table 5) with a variance that ensures at least 99% of the probability mass of the prior distribution is within the bounds of the parameter range.

The slopes of the depth–hydraulic property relationship are chosen at the lower end of the range in Table 5, for both interburden and coal seams and for *K* and *S*. This ensures that when the depth–hydraulic property is evaluated, for the majority of the prior distributions, *K* and *S* values throughout the model domain are above the lower threshold values for hydraulic conductivity and storage (1×10^{-6} m/day and 1×10^{-7}, respectively) defined in Section 2.6.2.6. As the relationship between the log of coal seam hydraulic conductivity and simulated coal seam gas (CSG) water production is linear (Figure 24 in Section 2.6.2.7.3), this choice of prior distributions will exclude very low CSG water production rates. This will lead to an overestimation rather than underestimation of hydrological change.

The ratio between horizontal and vertical *K* is chosen to be normally distributed on a log10 scale, centred in the middle of the Latin Hypercube sampling (LHS) range with a variance that ensures the prior distribution of the *KvKh* ratio spans an order of magnitude and that at least 99% of the probability mass of the prior distribution is within the bounds of the parameter range. The variances of the fault hydraulic conductivities are also chosen to span an order of magnitude, where the mean for the horizontal hydraulic conductivity is at the lower end of the LHS spectrum and the mean for the vertical hydraulic conductivity is at the higher end. While there are very few observations to justify these prior distributions, this choice of prior distribution is inspired by the precautionary principle as low horizontal fault hydraulic conductivity and high vertical fault hydraulic conductivity increases the potential propagation of the CSG depressurisation to the surface weathered and fractured rock layer.

The effective porosity of the leaky layer on top of the model is chosen to be centred on 0.1 with a variance that ensures at least 99% of the probability mass of the prior distribution is within the bounds of the parameter range.

Table 9 Variance – covariance matrix of the prior distributions of the analytic element model

	K_a1_IB	K_a1_CS	K_a2_IB	K_a2_CS	S_a1_IB	S_a1_CS	S_a2_IB	S_a2_CS	KvKh	Kfh	Kfv	ne
K_a1_IB	0.36	0	0	0	0.14	0	0	0	0	0	0	0
K_a1_CS	0	0.36	0	0	0	0.14	0	0	0	0	0	0
K_a2_IB	0	0	10^{-6}	0	0	0	10^{-7}	0	0	0	0	0
K_a2_CS	0	0	0	10^{-6}	0	0	0	10^{-7}	0	0	0	0
S_a1_IB	0.14	0	0	0	0.36	0	0	0	0	0	0	0
S_a1_CS	0	0.14	0	0	0	0.36	0	0	0	0	0	0
S_a2_IB	0	0	10^{-7}	0	0	0	2.5×10^{-7}	0	0	0	0	0
S_a2_CS	0	0	0	10^{-7}	0	0	0	2.5×10^{-7}	0	0	0	0
KvKh	0	0	0	0	0	0	0	0	0.36	0	0	0
Kfh	0	0	0	0	0	0	0	0	0	0.16	0.09	0
Kfv	0	0	0	0	0	0	0	0	0	0.09	0.16	0
ne	0	0	0	0	0	0	0	0	0	0	0	0.64

Source: Bioregional Assessment Programme (Dataset 1)

For five parameter combinations a covariance is specified as well (Table 9 and Figure 35). A covariance is defined between K_IB_intercept and S_IB_intercept, K_CS_intercept and S_CS_intercept, K_IB_slope and S_IB_slope, and K_CS_slope and S_CS_slope. There are insufficient joint measurements of hydraulic conductivity and storage to empirically establish these covariance rates. The covariance specified is based on a trial-and-error process design to decrease the likelihood of sampling unrealistic parameter combinations (high K – low S or vice versa) that lead to non-converging model runs (Figure 23, Section 2.6.2.7.3).

Covariance is also defined for the vertical and horizontal fault hydraulic conductivity. While these properties are not correlated, the covariance is specified to ensure that vertical fault hydraulic conductivity is more likely to be higher than the horizontal fault hydraulic conductivity. While this is not inspired by the observed fault-related flow in the basin, it adheres to the conceptualisation of faults as barriers of flow horizontally and conduits vertically.

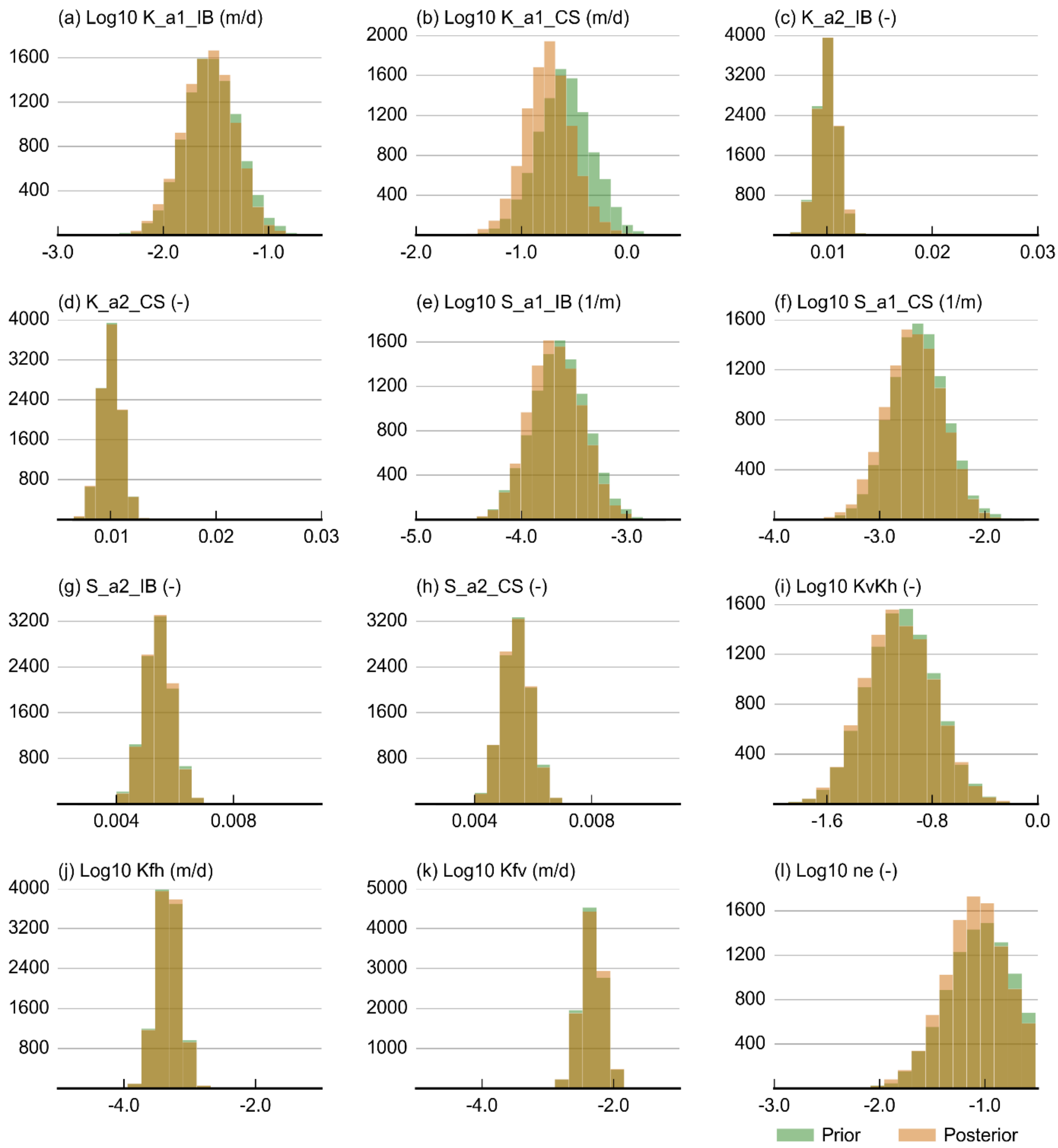

Figure 34 Histograms of prior and posterior distributions of the regional analytic element model ((a) through (l)) for the Monte Carlo analysis for the Gloucester subregion

The extent of the x-axis in each plot corresponds to the range of parameters sampled during the design of experiment. Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.

Data: Bioregional Assessment Programme (Dataset 1)

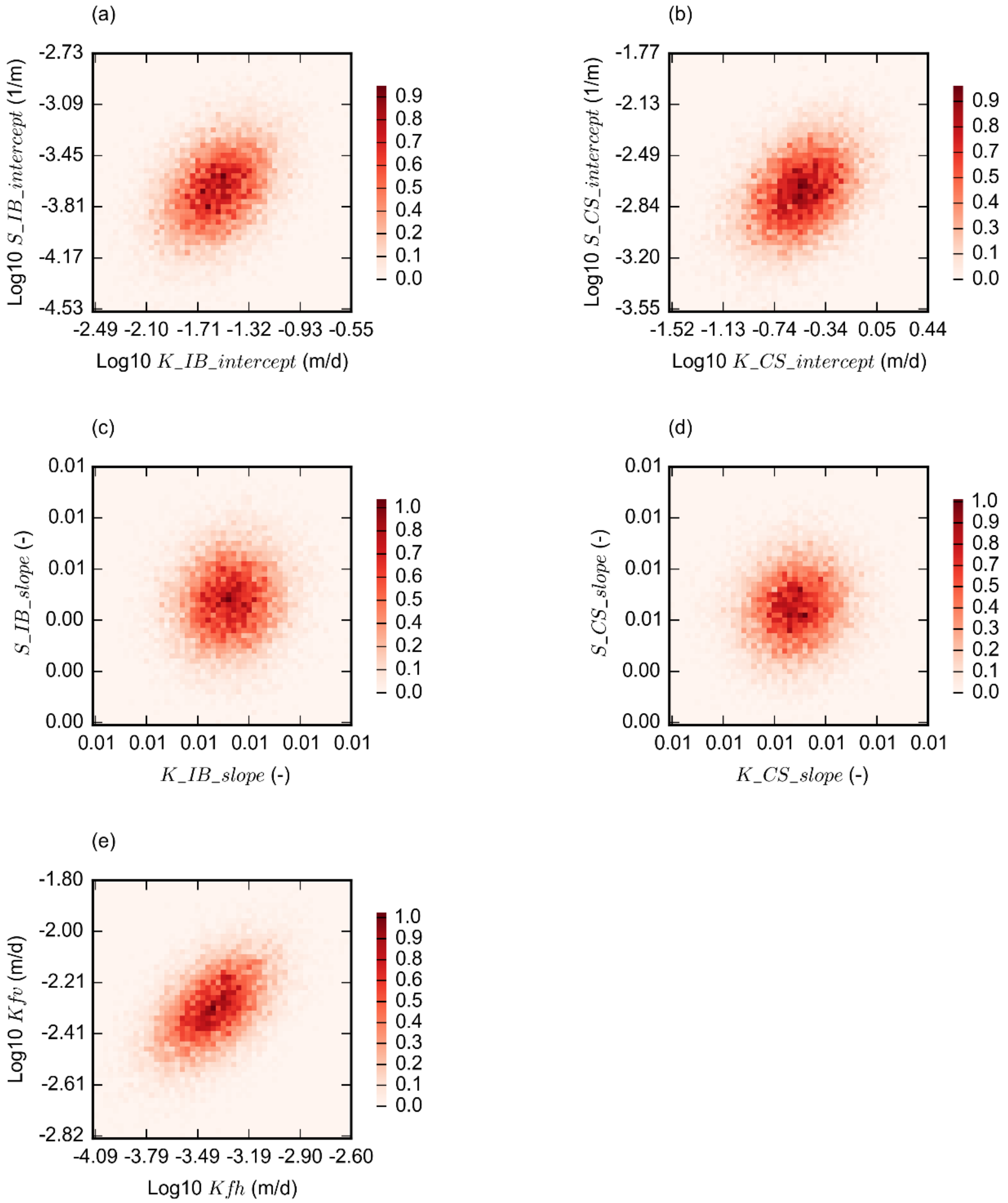

Figure 35 Covariance of the regional analytic element groundwater model posterior parameter distributions ((a) through (e)) for the Gloucester subregion

The colour scale is proportional to the density of points. Refer to Table 5 in Section 2.6.2.6.1 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 1)

Alluvial MODFLOW models

Table 10 Prior parameter distributions specified for the Avon and Karuah MODFLOW models

Parameter	Distribution	Mean[a]	Standard deviation[b]	Units
Kha	Normal in Log10 space	0	0.3	m/d
Khw	Normal in Log10 space	–3	0.3	m/d
Sy	Normal	0.15	0.025	na
Rmult	Normal	1	0.3	na
Dc	Normal in Log10 space	2	0.3	m2/d
dh	Weibull	1.5	1.5	m

[a]scale parameter for Weibull distribution
[b]shape parameter for Weibull distribution
See Table 6 in Section 2.6.2.6.2 for definition and description of parameters.
Data: Bioregional Assessment Programme (Dataset 2)

The factors included in the formal uncertainty analysis are the parameters listed in Table 10. The specification of the prior parameter distributions was mostly driven by the geology and hydrogeology information presented in the contextual statement (companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)) and the data analysis (companion product 2.1-2.2 (Frery et al., 2018)). Figure 36 shows the prior distributions of each individual parameter.

The means of the prior parameter distributions are chosen to coincide with the centre of the range sampled in the design of experiment. The standard deviations are chosen to ensure at least 99% of the probability mass is within the range used in the design of experiment. The exception is *Khw*, for which the mean is chosen at the high end of the range and the standard deviation so that the probability mass covers at least one order of magnitude. The choice of higher *Khw* values in the prior makes, when considering the high sensitivity of *dmax* to this parameter, this choice a conservative one.

For the constant head offset, *dh*, a Weibull distribution is chosen as it allows a skewed distribution that does not exceed specified bounds. The latter is especially important on the lower bound, making sure the offset does not become negative.

No covariance between parameters is specified for the alluvial MODFLOW models.

2.6.2.8.1.2 Markov chain Monte Carlo sampling

Analytic element model

The prior parameter distributions are sampled with a Markov chain Monte Carlo sampling with a rejection sampler based on the Approximate Bayesian Computing (ABC) methodology (Beaumont et al., 2002; Vrugt and Sadegh, 2013) to generate the posterior parameter ensembles.

The available observation data on the regional groundwater system are too limited to empirically establish a formal likelihood function to evaluate the likelihood of a given parameter set in a traditional sense. The evaluation of a given parameter set happens through a summary statistic of the state variables of the groundwater model. During the Markov chain Monte Carlo sampling, only the proposed parameter combinations that meet a predefined threshold of the summary statistic are accepted into the posterior parameter ensemble.

As mentioned previously, the summary statistic chosen for the regional groundwater model is the maximum CSG water production rate. As outlined in Section 2.6.2.7, the rejection threshold for the maximum production rate is chosen equal to 1.1 ML/day.

An emulator is created to reproduce the effect of the parameters on the maximum CSG water production rate. The Markov chain Monte Carlo sampler uses this emulator to sample the prior distribution and only retains those parameter combinations with a CSG water production rate less than 1.1 ML/day. The sampler is run until a predefined number of 10,000 samples are retained in the posterior parameter distribution.

The resulting posterior parameter distribution is shown in Figure 34. It is apparent that most of the posterior parameter distributions are almost identical to the prior distribution. The most noteworthy exception is *K_CS_Intercept*. This is not surprising as Figure 24 (Section 2.6.2.7.3.1) does show that this is the dominant factor affecting *Q_csg*. This also implies that the most dominant factor for prediction of drawdown, *S_CS_Intercept*, is hardly constrained by the CSG water production rate. The posterior parameter distribution is therefore almost identical to its prior distribution.

Figure 35 shows the covariance of the posterior parameter distributions. The Markov chain Monte Carlo sampling has retained the covariance structure outlined in the discussion of the prior distributions.

Alluvial MODFLOW models

The summary statistics chosen for the alluvial MODFLOW models are based on the degree to which a simulation matches the target water balance estimates (Section 2.6.2.5.1). The summary statistic ss_{Avon} for the Avon model is, with Q_{up} the exchange flux between alluvium and GW AEM and Q_{dr} the drainage flux through the drainage boundary:

$$s_1 = 1 - \frac{|Q_{up} - 0.5|}{0.5} \quad (11)$$

$$s_2 = 1 - \frac{|Q_{dr} - 7.0|}{3.0} \quad (12)$$

$$ss_{Avon} = |s_1 s_2| \quad (13)$$

For the Karuah model a similar summary statistic is defined:

$$s_1 = 1 - \frac{|Q_{up} - 0.9|}{0.9} \quad (14)$$

$$s_2 = 1 - \frac{|Q_{dr} - 6.5|}{3.0} \quad (15)$$

$$ss_{Karuah} = |s_1 s_2| \quad (16)$$

These summary statistics are only positive when both the simulated upwards flux and drainage flux are within the target range. The better the agreement between simulated fluxes and the optimum estimate, the closer the summary statistic is to 1.

Two emulators are created to reproduce the effect of the parameters on the summary statistic. The Markov chain Monte Carlo sampler uses these emulators to sample the prior distribution and only retains those parameter combinations with summary statistics larger than zero. The sampler is run until a predefined number of 10,000 samples are retained in the posterior parameter distribution.

The resulting posterior parameter distribution is shown in Figure 36. It is apparent that most of the posterior parameter distributions are almost identical to the prior distribution and that the differences between both models are limited. Only *dh* differs between the parameter distributions for the Avon and Karuah models. The larger estimate of the upwards flux requires higher offset values for the constant head boundary. Less pronounced differences are the slightly lower median values for *Kha* and *Khw* for the Avon model.

The small differences between prior and posterior parameter distributions imply that the majority of parameter combinations from the prior parameter distributions will result in model simulations that are in agreement with water balance estimates.

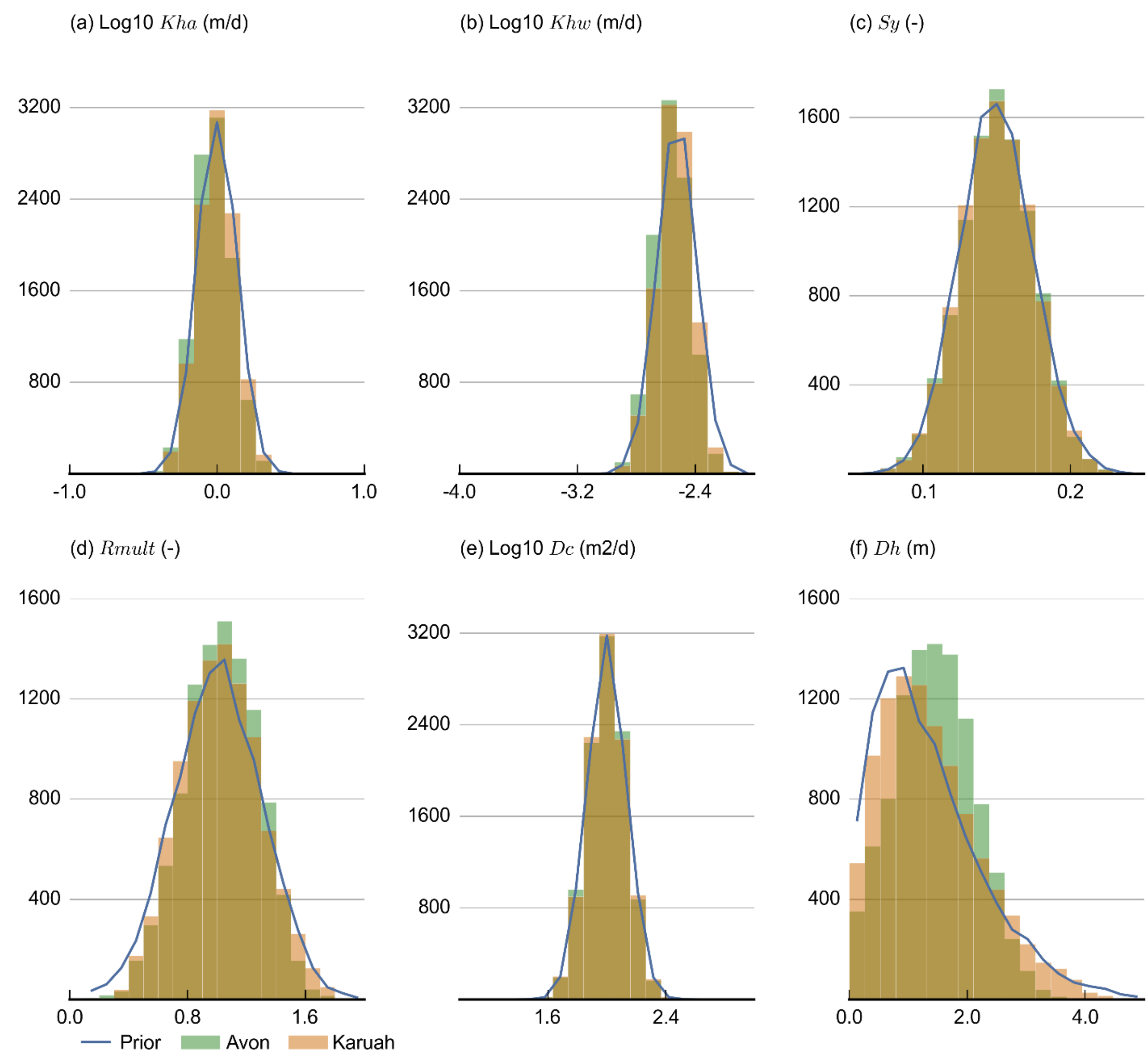

Figure 36 Histograms of prior and posterior distributions of the Avon and Karuah models for the Markov chain Monte Carlo analysis for the Gloucester subregion

Refer to Table 5 in Section 2.6.2.6 for definitions of terms.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.2.8.1.3 Predictions

Analytic element model

The 10,000 posterior parameter ensembles in Figure 34 are evaluated for each receptor location using the tailor-made emulator for that particular *dmax* or *tmax* prediction. A limited set of 200 parameter combinations, randomly selected from the posterior parameter ensembles is evaluated with the original model to compute *dmax* and *tmax* at the output nodes shown in Figure 19 (Section 2.6.2.7.2.1). This dataset is used to visualise the spatial variation in *dmax* and *tmax* illustrated in Figure 37 as the probability of drawdown exceeding 0.2 m. This threshold is the smallest of the drawdown thresholds defined in the aquifer interference policy and it corresponds to the threshold for impact on groundwater-dependent ecosystems.

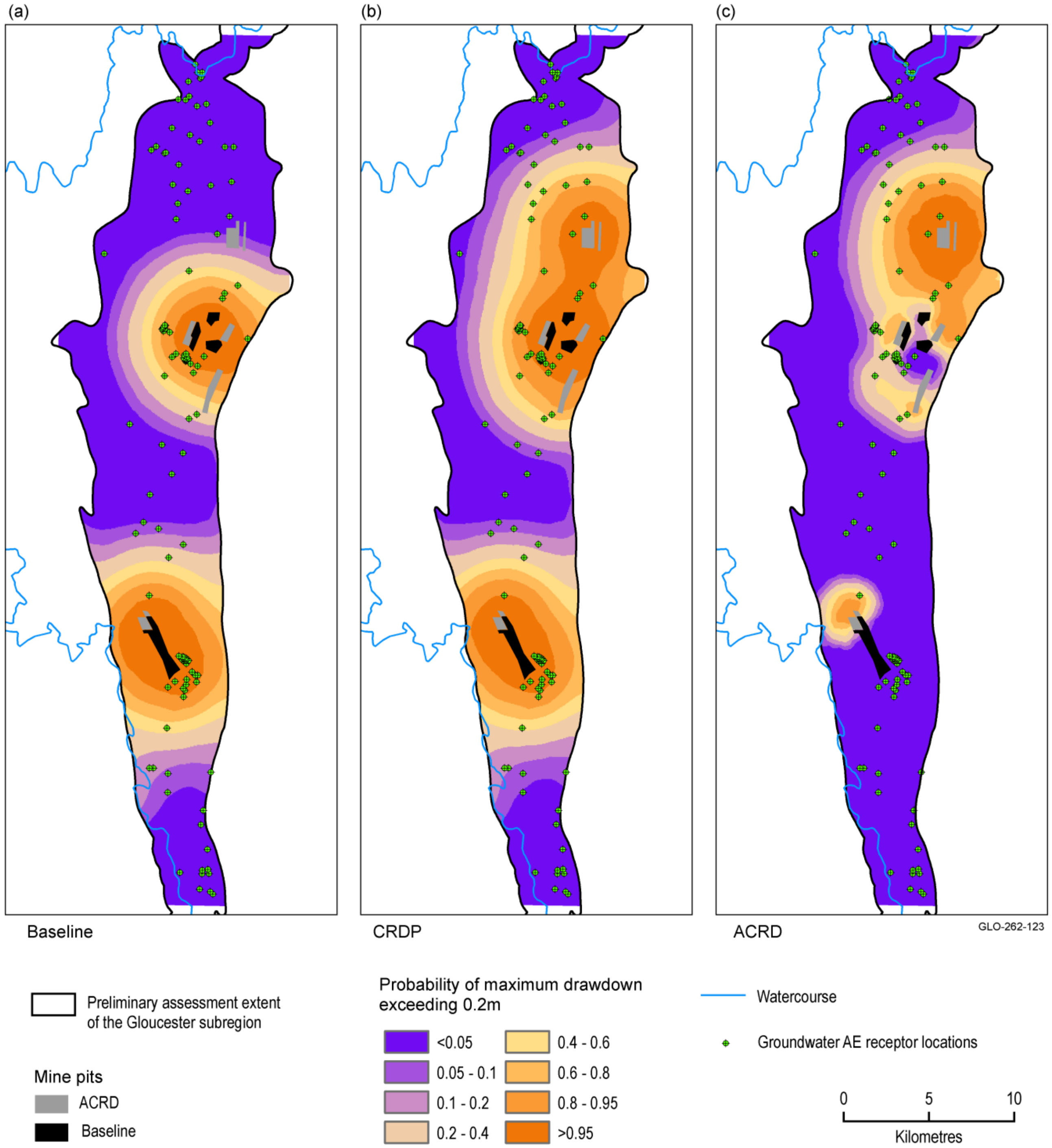

Figure 37 Probability of drawdown exceeding 0.2 m in the surface weathered and fractured rock layer for baseline coal resource development (a), coal resource development pathway (CRDP) (b) and the additional coal resource development (ACRD) (c)

Data: Bioregional Assessment Programme (Dataset 1)

The map in Figure 37 shows the drawdown under baseline coal resource development (baseline) (a), under the coal resource development pathway (CDRP) conditions (b) and the difference between both, due to the additional coal resource development (c). The contour of a 5% probability of exceeding 0.2 m drawdown is situated slightly more than 5 km from the mine complexes. The effect of the lateral no-flow boundaries, representing the lateral boundary of the Gloucester geological basin, is clearly visible, especially to the east and west of the Duralie Coal

Mine. The extent of the drawdown due to additional coal resource development is limited to the north of the Duralie Coal Mine, close to the planned extension. From Figure 37 (a) and (b), it is apparent that the majority of the drawdown of Duralie Coal Mine is realised under baseline conditions, where the extension to the north only results in minor drawdown due to additional coal resource development. A similar observation can be made for the Stratford Mining Complex. Central in the mine complex, the probability of the drawdown due to additional coal resource development exceeding 0.2 m is very small as most of the drawdown is realised under baseline conditions. The proposed Rocky Hill Coal Mine results in the largest area with high probability of drawdowns exceeding 0.2 m as there is no development under baseline conditions. There are no clear spatial patterns in drawdown that can be associated with CSG development.

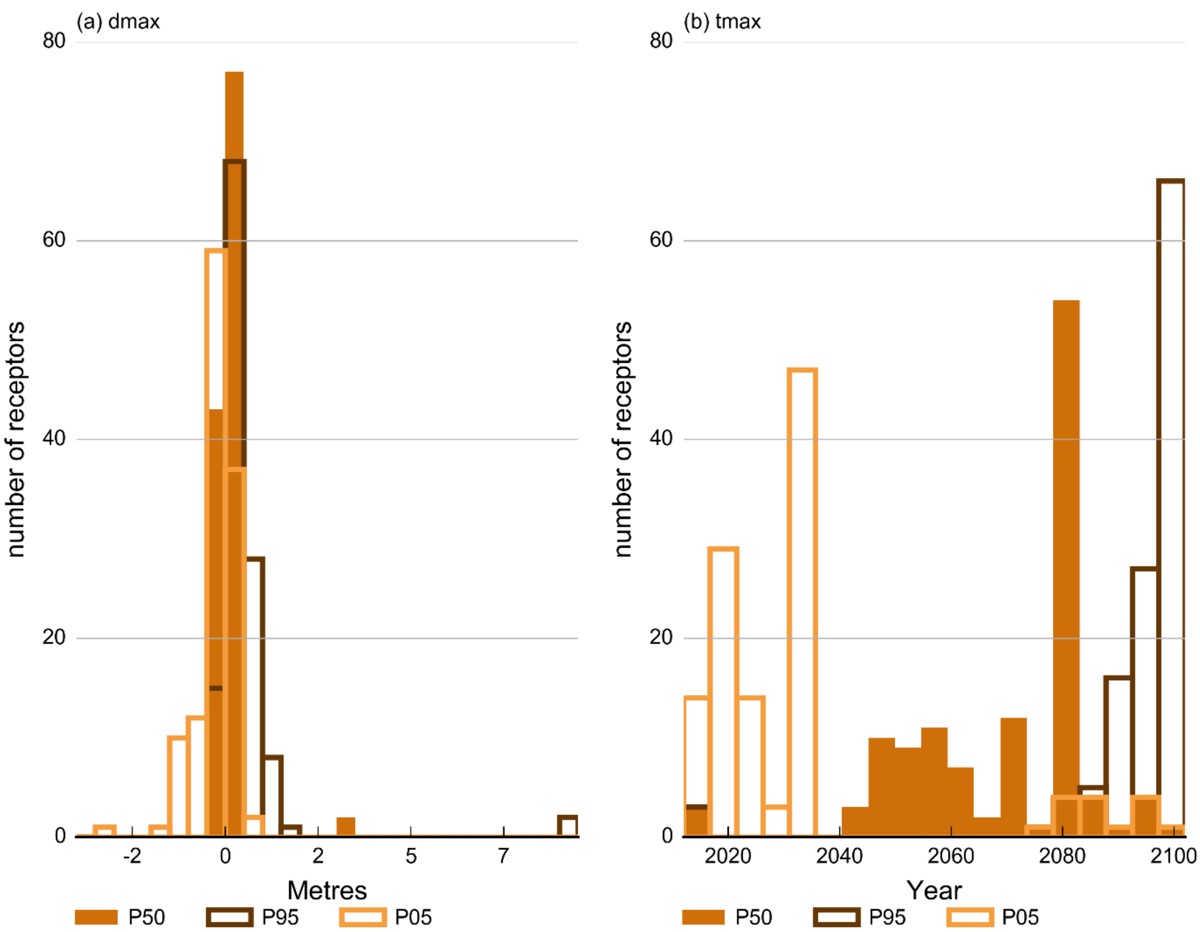

Figure 38 Histograms of the median (P50), 5th percentile (P05) and 95th percentile (P95) of additional drawdown (a) and year of maximum change (b) at the regional analytic element groundwater model receptor locations

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

Figure 38 shows histograms of selected percentiles of the ensemble of *dmax* and *tmax* predictions at the receptor locations of the GW AEM. The most striking feature of this plot is that for the majority of receptors the median of the ensemble of drawdowns due to additional coal resource development is between –0.2 and 0.2 m. Only three receptors have a *dmax* value in excess of a meter. These are the three receptors in the immediate vicinity of the proposed Rocky Hill Coal

Mine (Figure 37). At these locations the 95th percentile of *dmax* is close to 10 m. For some of the receptors situated in the close vicinity of the south-east corner of the Duralie Coal Mine, the 5th percentile of drawdown due to additional coal resource development can be as small as –1 m. This indicates that the GW AEM simulates a recovery of groundwater levels by 1 m as a result of the northwards extension of the mine (see Figure 20, Section 2.6.2.7.2.1).

The variation in year of maximum change due to additional coal resource development is much more variable, although for the majority of receptors the maximum change is only realised after 2040, after the planned coal mining and CSG operations in the Gloucester subregion have ceased.

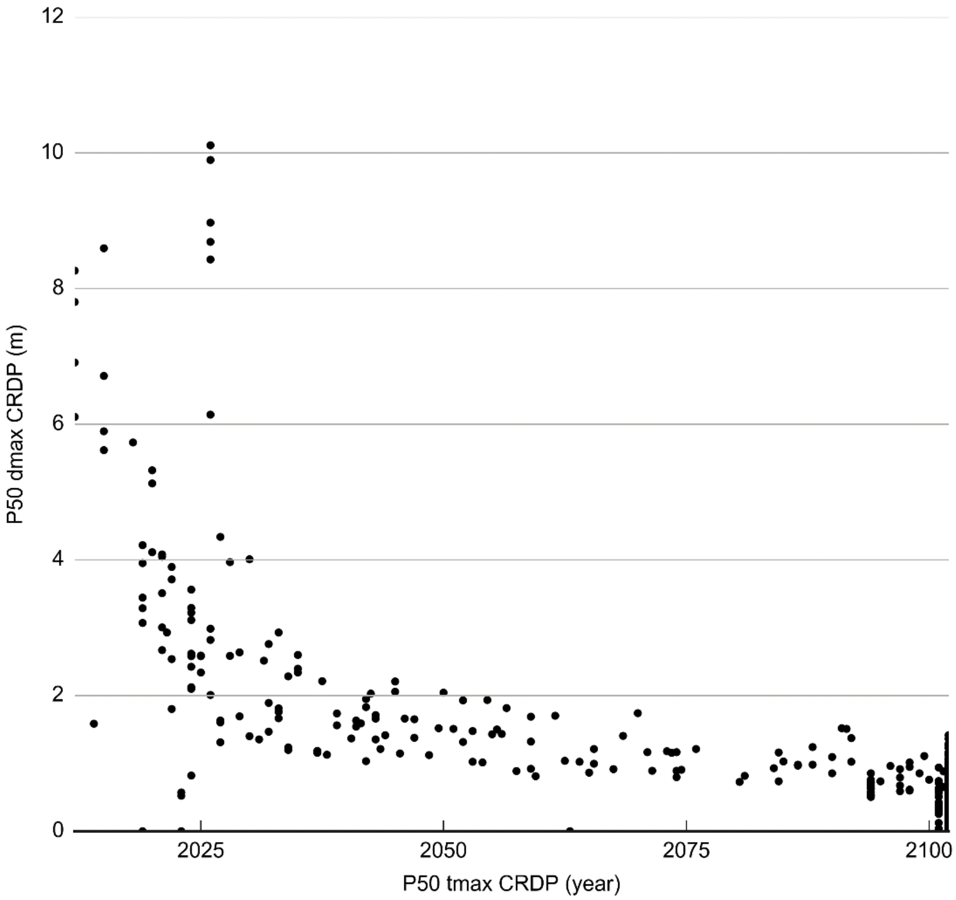

Figure 39 Median of the year of maximum change (tmax) for coal resource development pathway vs median of the drawdown for coal resource development pathway at the analytic element output nodes

dmax = maximum difference in drawdown
Data: Bioregional Assessment Programme (Dataset 1)

Figure 39 shows a scatterplot of the median predicted year of maximum change against the median predicted drawdown under coal resource development pathway at the analytic element output nodes. It is clear that drawdown decreases with time, that is, the largest drawdowns are realised the earliest and the drawdowns that occur towards the end of the simulation period are smaller than those that occur sooner.

Alluvial MODFLOW models

The posterior parameter ensembles of the alluvial MODFLOW models are combined with the posterior parameter ensemble of the analytic element model as the sensitivity analysis of the alluvial MODFLOW models highlighted that some of the analytic element parameters can affect the alluvial MODFLOW *dmax* and *tmax* predictions.

To generate the predictive ensembles at the receptor locations, the 10,000 parameter combinations are evaluated through the relevant emulators. A smaller set of 200 randomly selected parameter combinations from the posterior parameter ensembles, is evaluated with the original model to visualise the spatial patterns of drawdown shown in Figure 40.

The map in Figure 40 shows the drawdown under baseline conditions (a), under the CRDP conditions (b) and the difference between both, due to the additional coal resource development (c). The extent of the hydrological change is less than in the surface weathered and fractured rock layer. Probabilities of exceeding 0.2 m drawdown are limited to the immediate vicinity of the mine complexes. Drawdown due to additional coal resource development in excess of 0.2 m is only predicted to occur in the alluvium west and south of the proposed Rocky Hill Coal Mine. In the vicinity of the Stratford Mining Complex and Duralie Coal Mine, the probability of drawdown due to additional coal resource development exceeding 0.2 m is generally less than 5%.

It is noteworthy that underneath the rivers or, more correctly, the grid cells assigned a drain boundary condition, the probability of drawdown is very small. Only in the alluvium south of the proposed Rocky Hill Coal Mine and the alluvium flanked by the Stratford Mining Complex development are drawdowns in excess of 0.2 m predicted. This is not predicted to occur in the alluvium in the vicinity of the Duralie Coal Mine.

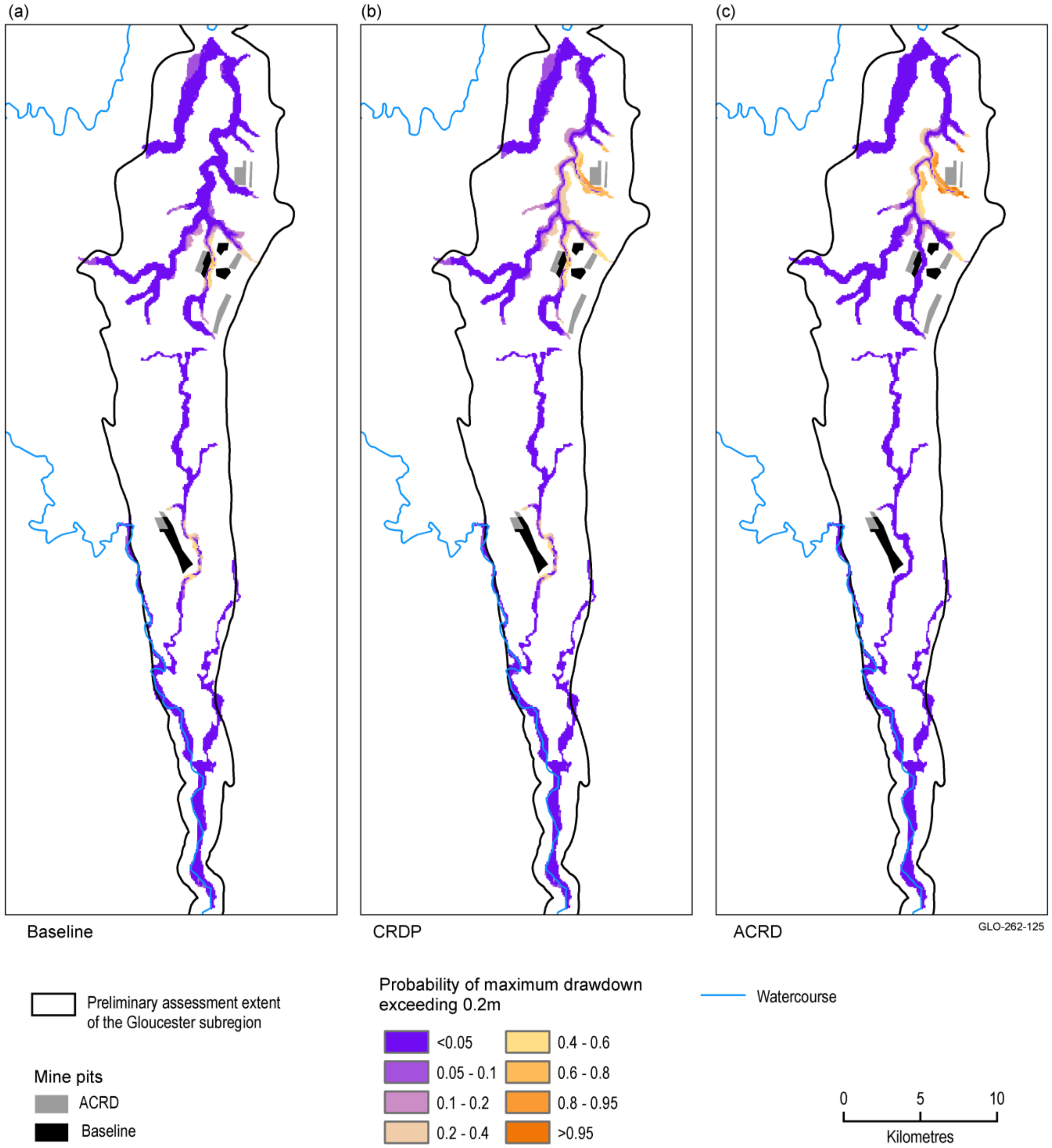

Figure 40 Probability of drawdown exceeding 0.2 m in the alluvium of the Avon and Karuah under baseline (a) and coal resource development pathway (CRDP) (b), and the difference in results between baseline and CRDP, which is the change due to additional coal resource development (ACRD) (c)

Maximum drawdown refers to the maximum difference in drawdown (*dmax*) 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 2)

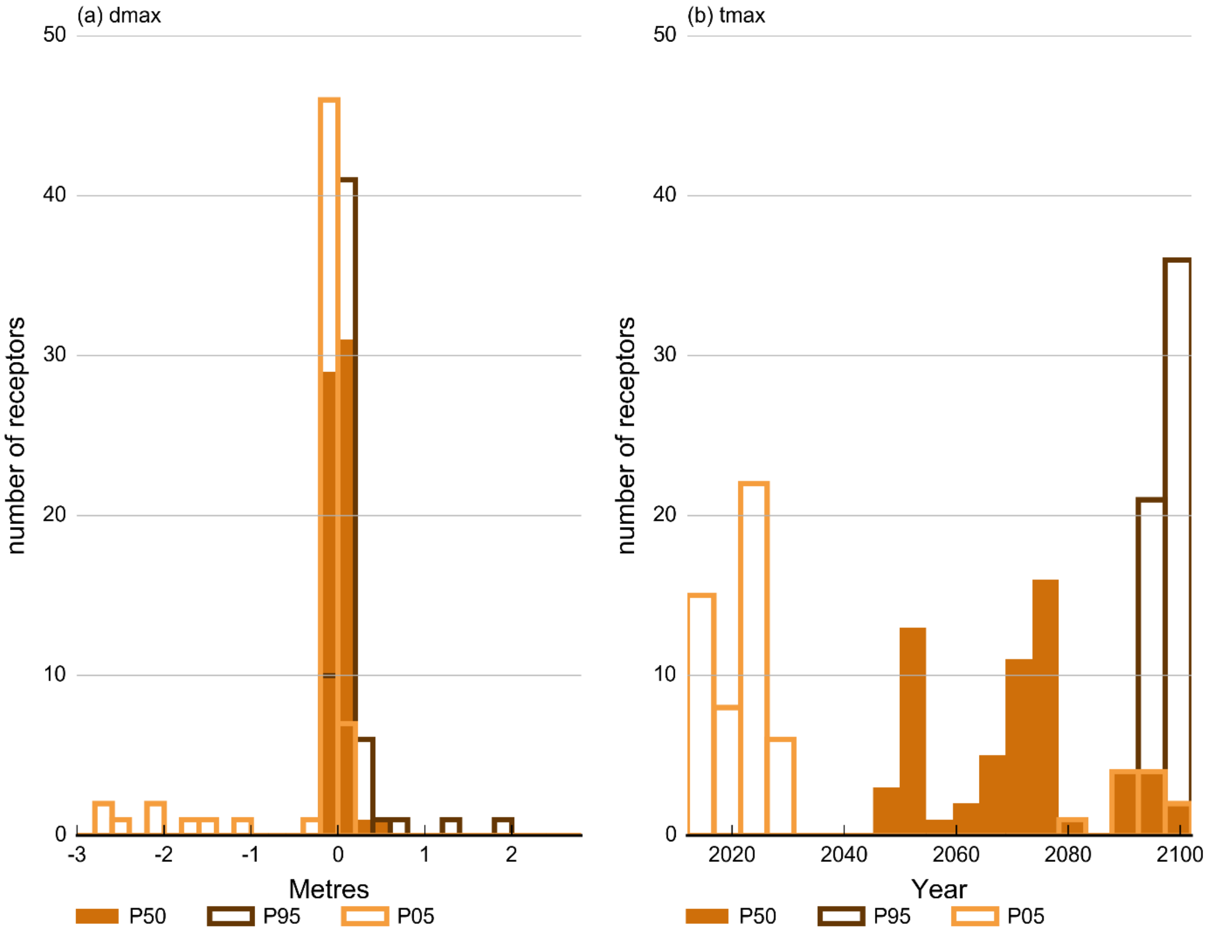

Figure 41 Histograms of the median (P50), 5th percentile (P05) and 95th percentile (P95) of additional drawdown (a) and year of maximum change (b) at the alluvial MODFLOW model receptor locations

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

The histograms of drawdown due to additional coal resource development and year of maximum change at the alluvial MODFLOW model receptor locations are shown in Figure 41. The median predicted values of drawdown due to additional coal resource development values are between –0.2 m and 0.6 m. For more than 90% of the receptors, the drawdown due to additional coal resource development is between –0.2 m and 0.2 m. Receptors in the vicinity of Duralie Coal Mine (Figure 10, Section 2.6.2.3.3.2) are predicted to recover, with the 5th percentile of *dmax* at some locations smaller than –2.5 m. Receptors close to the proposed Rocky Hill Coal Mine are simulated to have the 95th percentile of *dmax* in excess of 1.5 m.

The median values of the year of maximum change due to additional coal resource development are very similar to those of the analytic element model, ranging from 2040 to 2100, beyond the time water extraction for coal resource development in the region is planned to cease. The 5th percentile of *tmax* does indicate that it is possible for drawdown due to additional coal resource development to be achieved during the active water extraction. This occurs at receptor locations close to mine footprints. Receptors further away from the mine footprints experience the drawdown at the end of or beyond the simulation period. As shown in submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016) and Figure 39, *dmax* realised at large *tmax* are smaller than *dmax* realised at earlier times.

2.6.2.8.1.4 Comparison with existing models

Section 2.6.2.2 provides a review of the development and results of previous modelling projects in the subregion. A direct comparison between these model results and the predictions provided in this study is not straightforward. The existing models are all deterministic (i.e. they provide a single estimate of hydrological change based on a single parameter combination that is considered optimal), while the bioregional assessment (BA) provides probabilistic ensembles of predictions, based on a range of likely parameter combinations. The BA models have selected the drawdown due to additional coal resource development as the primary prediction, where most regional models only provide outputs at selected times in the future. A final factor complicating a direct comparison is the difference in conceptualisation, boundary conditions and, most importantly, the implementation of coal resource development.

The models reviewed in Section 2.6.2.2 all predict negligible drawdowns at existing production bores. This is in line with the findings in this study, where the median of the drawdown due to additional coal resource development at the receptors, which include the production bores, is close to zero (Figure 38 and Figure 41).

The probabilistic modelling presented in this product does indicate that there is a 5% probability to exceed 0.2 m drawdown up to about 5 km from the mine footprint in the surface weathered and fractured rock layer. This is comparable with the estimate for the Stratford Mining Complex modelling, where 1 m of drawdown was predicted at the end of mining (December 2024) out 1 km around all pits, except south of Roseville West Pit where it may extend to 1.6 km. The Stratford Mining Complex modelling included a scenario in which coal seams in AGL's Stage 1 gas field development area are dewatered to represent the cumulative impact of CSG extraction and coal mining. In this scenario very large drawdowns are realised in the surface weathered and fractured rock layer. The corresponding pumping rates are, however, not reported and it is therefore not possible to judge if the water production rates from CSG production are in the same order of magnitude of the water production rates simulated by AGL or used in the modelling presented in this product.

The modelling reports for the proposed Rocky Hill Coal Mine and Duralie Coal Mine did not provide estimates of drawdown in the surface weathered and fractured rock layer amenable for comparison with the BA modelling.

The surface water network in the Stratford Mining Complex, proposed Rocky Hill Coal Mine and Duralie Coal Mine groundwater models is represented using the RIVER package in MODFLOW. As outlined previously, this allows for drawdown to be compensated by influx of water through the river bed. These groundwater models therefore predict very limited drawdown in the alluvium, while the BA models indicate that there is a probability of exceeding 0.2 m drawdown in alluvial systems in the immediate vicinity of mines.

As mentioned in Section 2.6.2.1 and Section 2.6.2.7, the components of the water balance are reported in companion product 2.5 for the Gloucester subregion (Herron et al., 2018, Table 6, Table 7 and Table 8).

2.6.2.8.2 Qualitative uncertainty analysis

The major assumptions and model choices underpinning the Gloucester subregion groundwater models are listed in Table 11. The goal of the table is to provide a non-technical audience with a systematic overview of the model assumptions, their justification and effect on predictions, as judged by the modelling team. This table is aimed to assist in an open and transparent review of the modelling.

In the table, each assumption is scored on four attributes using three levels; high, medium and low. Beneath the table, each of the assumptions are discussed in detail, including the rationale for the scoring. The ‘data’ attribute is the degree to which the question ‘if more or different data were available, would this assumption/choice still have been made?’ would be answered positively. A ‘low’ score means that the assumption is not influenced by data availability while a ‘high’ score would indicate that this choice would be revisited if more data were available. Closely related is the ‘resources’ attribute. This column captures the extent to which resources available for the analysis and processing of the available data and the modelling, such as computing resources, personnel and time, influenced this assumption or model choice. This attribute does explicitly not consider spending additional resources on data acquisition, as this is covered in the data attribute. Again, a ‘low’ score indicates the same assumption would have been made with unlimited resources, while a ‘high’ value indicates the assumption is driven by resource constraints. The ‘technical’ attribute deals with the technical and computational issues. A score of ‘high’ is assigned to assumptions and model choices that are dominantly driven by computational or technical limitations of the model code. These include issues related to spatial and temporal resolution of the models.

The final, and most important column, ‘effect on predictions’, addresses the ‘so what?’ question, the effect of the assumption or model choice on the predictions. This is a qualitative assessment by the modelling team of the extent to which a model choice will affect the model predictions, with ‘low’ indicating a minimal effect and ‘high’ a large effect. Especially for the assumptions with a large potential impact on the predictions, it will be discussed that the precautionary principle is applied; that is, the hydrological change is overestimated rather than underestimated.

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

Table 11 Qualitative uncertainty analysis as used for the Gloucester subregion

Assumption / model choice	Data	Resources	Technical	Effect on predictions
Hybrid analytic element – MODFLOW model methodology	high	medium	high	low
Principle of superposition	medium	low	low	low
Horizontally spatially uniform hydraulic properties	high	medium	medium	low
Hydraulic properties vary with depth, not with stratigraphy	high	low	low	medium
Stochastic representation of coal seams and faults	high	low	low	low
Random location of CSG wells and assigning pumping interval to random coal seams	high	low	low	low
CSG wells as constant head wells	high	medium	high	medium
Open-cut mines as prescribed pumping rate	high	low	low	high
Specification of prior distributions	high	medium	low	low
River network implemented as drainage boundary	medium	low	low	low
Constrain model with flux estimates rather than head observations	high	low	low	low
Simulation period from 2012 to 2102	low	high	medium	low

CSG = coal seam gas

Hybrid analytic element-MODFLOW methodology

Section 2.6.2.1 outlines the overarching hybrid methodology in which analytic element modelling is used at the regional scale in combination with a high resolution MODFLOW model to represent the alluvium. Although not widespread, several studies are available in which analytic element models are combined with MODFLOW models (Hunt, 2006; Abrams et al., 2015).

The choice for the hybrid methodology in this case is mostly driven between the spatial and temporal scale mismatch between the regional groundwater flow in the surface weathered and fractured rock layer and deeper sedimentary basin and the local groundwater flow in the alluvial deposits. To simulate groundwater flow dynamics in both systems in a single model would necessitate a high spatial and temporal resolution. The hybrid approach allows to simulate the regional groundwater flow with a low spatial and temporal resolution, while the alluvial models are simulated with a high spatial and temporal resolution.

Although a geological model was developed to gain additional insight in the stratigraphy and structural features of the region, its resolution and extent are not sufficient to justify such a high-resolution regional-scale finite-difference groundwater model (see companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)). Additionally, the data availability, especially in the surface weathered and fractured rock layer, is too limited to parameterise a complex model or reliably constrain its state variables through observations of head, flux or environmental tracers. The data availability attribute is therefore scored ‘high’.

Developing the regional and alluvial models as separate models at different scales allowed for a focus of efforts and thus required less resources (such as time and computational resources) to develop than would be needed to develop a complex integrated model. The resources column is scored 'medium' to reflect that even with more resources available for modelling, an integrated model would not be warranted because of the limited data availability and technical issues.

Recently, the United States Geological Survey published a new version of MODFLOW, MODFLOW-USG (Panday et al., 2015) that allows for grids with spatially varying resolution. At the time of the start of the numerical modelling project in February 2014, this software was not available. While other codes, such as HydroGeoSphere, have that capability and were available, their numerical complexity posed too great a risk in terms of numerical stability and computational resources required for them to be applied in the probabilistic BA framework. The technical column is therefore scored 'high' as the above-mentioned technical limitations of the modelling codes available at the start of the modelling project did not allow models with spatially varying grid resolutions.

Notwithstanding the limitations in data and technical issues, the effect on predictions is scored 'low'. In an integrated model of the deeper basin and the alluvium, there is a two-way interaction between both systems; the groundwater flow in the deeper basin and surface weathered and fractured rock layer will affect the alluvial groundwater flow and in turn, changes in alluvial groundwater will affect the flow in the deeper basin. In the hybrid approach there is only a one-way interaction: changes in groundwater flow in the deeper basin can lead to increases or decreases in the alluvial model in the exchange flux between the alluvial and the weathered zone. Changes in the alluvial model will, however, not lead to changes in the analytic element model. Predictions of change in drawdown or change in flux in the alluvial MODFLOW are therefore not compromised by adopting the hybrid approach. The absence of feedback from the alluvial MODFLOW models to the analytic element models means that drawdowns in the surface weathered and fractured rock layer and deeper sedimentary basin cannot be compensated by increased inflow from the alluvium. This means the drawdowns in the analytic element model are overestimated, which is in line with the precautionary principle.

Principle of superposition

A crucial assumption in the analytic element model is the validity of the principle of superposition, that is, that solutions to the groundwater flow equations are additive as long as the system behaves linearly, as outlined in Section 2.6.2.1. This assumption allows for simulating the change in the system due to coal resource development directly, rather than to simulate all fluxes and stores for two different futures and obtain the change as the difference between those two futures.

The data analysis in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018) highlighted the limited data availability on the current groundwater flow conditions in the surface weathered and fractured rock layer and deeper sedimentary basin. The data attribute is nevertheless scored 'medium'. The reasoning behind this scoring is that additional data would only warrant to revisit the assumption if the principle of superposition would be shown not to be applicable, that is, if the additional data shows the surface weathered and fractured rock layer and deeper basin do not behave as a confined groundwater system.

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

The effect on predictions is scored ‘low’ as Reilly et al. (1987) and Rassam et al. (2004) showed that for mild violations of the linearity assumptions, the deviations in predictions caused by the non-linearity are generally very small and only become apparent in extreme cases.

Horizontally spatially uniform hydraulic properties

The transmissivity (the product of hydraulic conductivity and layer thickness) and storage are considered spatially uniform, at least in the horizontal direction, in both the analytic element model and in the alluvial MODFLOW models.

The limited data available on these hydraulic properties does show that these properties are heterogeneous (companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)). The data density is, however, too limited to empirically establish a spatial correlation structure to characterise the spatial variability in these properties. The sparse head observation dataset does not allow for estimating spatial variability through inverse modelling. The data attribute is therefore scored ‘high’.

Incorporating spatial variability in the modelling would require additional resources as it takes time to develop spatial fields from the available data. In addition to that, incorporating spatial variability will increase the dimensionality of the parameter space. This increases the computational load as more model runs need to be added to the design of experiment to fully explore the larger parameter space. The resources attribute is therefore scored ‘medium’.

In MODFLOW it is trivial to incorporate spatially varying fields. This is less so in the analytic element code, which is not designed to handle spatial variability in hydraulic properties. The technical column is therefore scored ‘medium’.

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

Hydraulic properties vary with depth, not with stratigraphy

Most of the sedimentary rocks in the geological Gloucester Basin have a low permeability and no clear correlation between measured hydraulic properties and lithology/stratigraphy is present. In this basin an exponential decrease in depth of the hydraulic properties is, however, observed (Parsons Brinckerhoff, 2015). This warranted the approach of changing hydraulic properties with depth, albeit differently for interburden and coal seams.

The data attribute is scored ‘high’. The data shown in Figure 16 (Section 2.6.2.6.1) on which the depth–hydraulic conductivity relationship is based, are mostly from drill-stem tests and small-scale permeability measurements. Additional data, including pumping tests, are needed to reliably constrain the large-scale hydraulic properties and their variation with lithology and depth.

The choice of varying hydraulic properties with depth is not motivated by operational constraints or technical limitations.

The effect on predictions is scored as 'medium'. The hydraulic properties of the coal seams control the amount of water that needs to be extracted in CSG wells to achieve the necessary depressurisation and they control the propagation of the cone of depression to the surface weathered and fractured rock layer (Figure 24 and Figure 25). This is mitigated by specifying a wide range for the hydraulic properties, in both the design of experiment (Figure 17 and Figure 22 and the prior parameter distributions (Figure 34), and constraining the prior parameters with a maximum CSG water production rate.

Stochastic representation of coal seams and faults

The coal seams in the Gloucester Basin are difficult to correlate between boreholes because of their heterogeneous deposition and the tectonic history of the basin with the associated faulting. The number and position of coal seams at any location is very difficult to predict. Likewise, the number, throw and orientation of faults, especially subseismic faults, are nearly impossible to assess deterministically. The stochastic representation of number and position of coal seams and of the position and extent of faults allows capture of, at least at a basic level, the compartmentalisation of the sedimentary basin. In this conceptualisation, faults act as horizontal barriers and vertical conduits.

The data attribute is scored 'high'. Additional seismic data and borehole information will undoubtedly reduce the uncertainty in the position and extent of the major faults. The stochastic generation of subseismic faults in the analytic element model is mostly based on international datasets of fault geometry. Additional data, such as high resolution seismic data, is needed to validate and improve the stochastic fault generation.

Resources are scored 'low'. A considerable amount of the available resources in the project is invested in developing the geological model (companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)) to gain insight in the position and extent of faults and in integrating that information in the numerical model stochastically to ensure the available information is used to its fullest extent.

The technical attribute is likewise scored 'low'. One of the main reasons for selecting the analytic element method was the capability to represent linear features stochastically, which is not straightforward in codes such as MODFLOW. Note that MODFLOW-USG provides enhanced functionality to represent linear features.

Throughout the parameterisation of the faults, the precautionary principle is applied by favouring parameter combinations in which faults act as vertical conduits and horizontal barriers. While there is little evidence in observations for this hydraulic fault behaviour, it will result in maximum propagation of the depressurisation in the coal seams to the surface weathered and fractured rock layer. The stochastic approach means that while no individual realisation and resulting predictions will accurately reflect the field conditions, a very wide range of potential fault distributions are incorporated in the numerical modelling. Despite the density of faults and their parameterisation, the drawdown predictions in the surface weathered and fractured rock layer were not very sensitive to any of the fault parameters (Figure 25 and Figure 26), which is why the effect on predictions attribute is scored 'low'.

Random location of coal seam gas wells and assigning pumping interval to random coal seams

At the time of defining the CRDP, the exact location and target coal seams for the AGL Stage 1 gas field development were not available. 110 CSG wells are located in the analytic element model through a random process that adheres to the implementation plan outlined by AGL in Parsons Brinckerhoff (2015).

The data attribute is scored 'high' as the exact locations are not known. The resources and technical attributes are scored 'low' as it is trivial to change the location of CSG wells in the analytic element model.

The effect on predictions is scored 'low'. While the random realisation of well locations and coal seams pumped will, in all probability, not correspond to the wellfield that will potentially eventuate, the density of wells ensures that the simulated effect will at least be comparable in size of impact.

Coal seam gas wells as constant head wells

The amount of water extracted from CSG wells is a function of the gas content and the coal permeability. As such it is difficult to predict at the regional scale with a single phase model. Specifying CSG wells as head-dependent boundaries allows for the extraction rate to vary with hydraulic properties.

The data attribute is once more scored 'high' as the exact water extraction rates are not known.

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

As the pumping rate is the main CSG-related stress on the system, its magnitude is very important and can greatly affect the predictions. The effect is partly mitigated by biasing the prior parameter combinations in favour of combinations that lead to elevated water extraction rates, while simultaneously constraining the parameters with an upper limit to the extraction rates. This process avoids both unrealistically high and unrealistically low extraction rates.

The spatial patterns of drawdown in the surface weathered and fractured rock layer (Figure 37) are heavily influenced by the mine footprints. Any spatial patterns linked to the location of the CSG wells is hard to distinguish. This is to be expected as the pumping rates assigned to the mines (Figure 15) are almost an order of magnitude larger than the maximum CSG water production rates.

The effect on predictions is therefore scored 'medium'.

Open-cut mines as prescribed pumping rate

Pumping rates to dewater open-cut coal mines depend largely on local conditions. As local conditions are not well captured in the GW AEM, the choice was made to use reported historical or locally modelled extraction rates in the model.

The data attribute is scored 'high'. To implement open-pit mine dewatering it is essential to know the exact elevation of the mine dewatering level as well as the proposed dewatering scheme. This information is beyond the spatial resolution of the geological model.

The resources and technical attributes are scored 'low' as it is trivial to specify the mine pit dewatering as head-dependent flux boundary conditions and it does not appreciably increase the computational demand or processing time.

The effect on predictions is scored 'high' as a change in pumping rate will greatly affect predictions, and the reliability of the predictions of this model hinge on the quality of the pumping rates reported by the mining companies. The prescribed pumping rates are at least consistent with the modelling done by the mining companies which incorporates a large amount of local detail on the geology and mine planning that is beyond the resolution of the BA modelling.

River network implemented as drainage boundary

The river network in the alluvial MODFLOW models implemented a drainage boundary condition, which is a boundary condition that only allows water to leave the groundwater system. The RIVER package in MODFLOW allows for two-way surface water – groundwater interaction.

The data attribute is scored 'high'. To implement the drainage boundary, it suffices to specify a drainbed elevation and drainbed conductance. The drainbed elevation can be estimated from a high resolution digital elevation model. For a river boundary, the river stage needs to be specified as well. The limited availability of gauging stations in the Gloucester subregion requires that river stages be interpolated over large distances. The specification of river stage in the future is even more problematic as it requires converting the simulated streamflow predictions of the Australian Water Resource Assessment Landscape module (AWRA-L) to river stages using a rating curve. Rating curves are not constant in time and are known to have large uncertainties, especially for low-flow conditions (Tomkins, 2014). The data requirements to implement a river boundary are much higher and will introduce considerable additional uncertainty.

The resources and technical attributes are scored 'low' as it is straightforward to implement a river boundary in MODFLOW and the effect on runtime and processing is negligible.

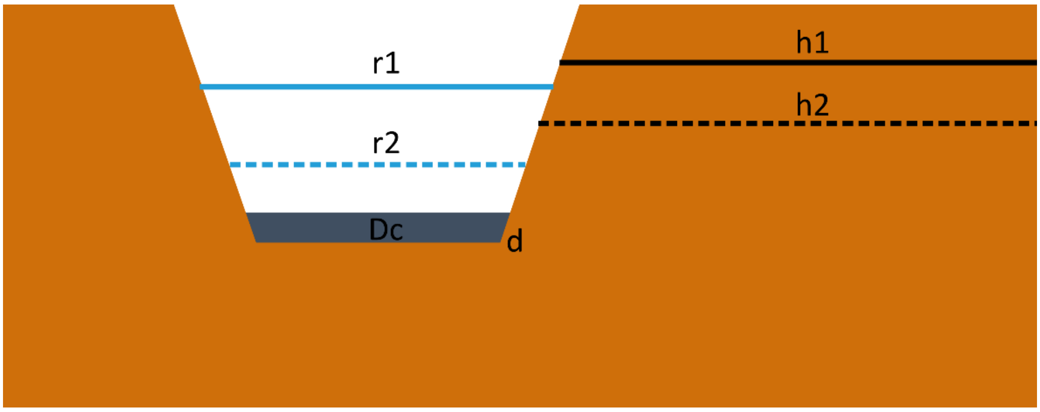

Figure 42 Conceptual diagram to illustrate the difference in flux estimate between a river and a flux boundary

h1 = groundwater level before coal resource development; h2 = groundwater level after coal resource development; r1 = river stage before coal resource development; r2 = river stage after coal resource development; d = drainbed elevation; Dc = conductance

The effect on predictions is scored 'low'. Drawdowns in the alluvium will be overestimated as the drainage boundary does not allow drawdown to be compensated by induced inflow from the river. As long as the river system is connected and the groundwater level is above the drainbed conductance, the drain boundary condition will ensure that the change in flux due to coal resource development is overestimated under both gaining and losing conditions. This is illustrated in Figure 42. The change in flux estimated with a river boundary condition (ΔQ_{riv}) is equal to:

$$\Delta Q_{riv} = D_c(h_1 - r_1) - D_c(h_2 - r_2) = D_c(h_1 - h_2 + r_2 - r_1) \quad (17)$$

where h_1 is groundwater level before coal resource development; h_2 is groundwater level after coal resource development; r_1 is river stage before coal resource development; r_2 is river stage after coal resource development; and D_c is conductance.

The change in flux estimated with a drainage boundary condition (ΔQ_{dr}) can be written as:

$$\Delta Q_{dr} = D_c(h_1 - d) - D_c(h_2 - d) = D_c(h_1 - h_2) \quad (18)$$

where d is drainbed elevation. The change in flux computed with a drain boundary condition will therefore always be larger than the flux computed with a river boundary condition, as long as the river stage after coal resource development (r_2) is equal to or smaller than the river stage before coal resource development (r_1). This condition is always satisfied in the numerical modelling of the impact of coal resource development on surface water.

The equations above are only valid as long as the groundwater levels are above the drainbed elevation. The probability maps of exceeding 0.2 m drawdown in the alluvium (Figure 40) show that these conditions only occur very locally.

Constrain model with flux estimates rather than head observations

Traditionally, groundwater models are evaluated based on the agreement of observed head observations and their simulated equivalent. In this modelling exercise, head observations are not formally used to constrain the model; only water balance estimates are used. Water balance estimates are chosen because they represent a spatially and temporally integrated estimate of the state variables and are therefore more robust to constrain spatially uniform parameters in the MODFLOW models.

This assumption is mostly driven by data availability and scores 'high' on this attribute. The data density of groundwater level observations is considered too low to reliably constrain the uniform hydraulic properties and boundary conditions.

The resources attribute is scored 'low' as constraining the model with additional observations would not require additional resources.

The technical attribute is scored 'low' as well as the uncertainty workflow is able to integrate head observation. An example of integrating groundwater level observation in the BA uncertainty analysis workflow can be found in companion product 2.5 for the Clarence-Moreton bioregion (Cui et al., 2016).

The effect on predictions of integrating head observation is considered to be small and therefore the attribute receives a 'low' score. The predictions of drawdown are most sensitive to the hydraulic properties in the weathered zone, both in the MODFLOW model and the analytic element model (Figure 32). The water balance estimates are not able to greatly constrain these parameters (Figure 36). Groundwater level observations in the alluvium are mostly affected by local conditions, such as river stage, recharge and local hydraulic properties. It is unlikely that such observations contain enough information to constrain the hydraulic properties relevant to the maximum additional drawdown predictions as is illustrated in the uncertainty analysis of the Clarence-Moreton bioregion groundwater model (see companion product 2.5 for the Clarence-Moreton bioregion (Cui et al., 2016)).

Specification of prior parameter distributions

The specification of prior distributions is of great importance in any uncertainty analysis. The process to specify the prior distributions is outlined in Section 2.6.2.8.1.1.

Once more, the data attribute is scored 'high', reflecting the limited data availability in the region. Due to operational constraints, it was not possible to organise an elicitation workshop with local experts to establish the prior distributions. The resources attribute is therefore scored 'medium'.

The technical column is scored 'low' as the uncertainty analysis methodology allows to specify a wide variety of prior distributions.

The effect on predictions is scored 'medium' as there is limited data available to constrain the prior distributions, especially the distributions of the parameters the predictions are most sensitive to. The effect is mitigated by specifying prior distributions with a high variance, in the case of hydraulic properties to cover at least one order of magnitude. This is likely to represent a conservative estimate of the actual parameter distributions.

Simulation period from 2012 to 2102

Across the Bioregional Assessment Programme, the simulation period is chosen to be from 2012 to 2102 as discussed in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) and companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). For some parameter combinations and some receptors this means that the maximum drawdown is not realised within the simulation period, as shown in Figure 20, Figure 38 and Figure 39.

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

The effect on predictions, however, is scored 'low'. Figure 39 indicates that the maximum drawdown decreases with increasing time to maximum drawdown. This is in line with the theoretical assessment of the relationship between *dmax* and *tmax* presented in submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). It can be shown that any drawdown due to additional coal resource development realised after 2102, will always be smaller than the drawdowns realised before 2102. This is in line with the precautionary principle as it means that by limiting the simulation period, the hydrological change will not be underestimated.

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2.6.2.9 Limitations and conclusions

Summary

The simulations indicate that it is unlikely for the drawdown due to additional coal resource development to exceed 1 m in the surface weathered and fractured rock layer. At receptors in the alluvium, it is unlikely for the drawdown due to additional coal resource development to exceed 0.2 m.

The effect of coal seam gas depressurisation and the effect of faults as conduits to propagate depressurisation to the surface weathered and fractured rock layer is not distinguishable from the effects of coal mining.

The model choices and assumptions, such as the hybrid modelling approach and the representation of surface water – groundwater interaction, are shown to be conservative. Despite this conservative modelling approach, the predicted hydrological changes are in line with those predicted in earlier local modelling efforts.

The modelling framework is tailored to the specific coal resource development pathway and receptors and therefore should not be used for any other purpose without a rigorous reassessment of the validity of the model assumptions.

The modelling did highlight that improved characterisation of hydraulic properties of the surface weathered and fractured rock layer and more detailed information of local geology around development have the most potential to reduce predictive uncertainty.

2.6.2.9.1 Data gaps and opportunities to reduce predictive uncertainty

In companion products 1.1 (McVicar et al., 2014), 2.1-2.2 (Frery et al., 2018) and 2.3 (Dawes et al., 2018) for the Gloucester subregion, data and knowledge gaps are highlighted. The sensitivity analysis presented in Section 2.6.2.7.3 and the discussion on the qualitative uncertainty analysis presented in Section 2.6.2.8.2, however, indicated that not all of these data gaps have the same effect on predictions.

The overall, high level conceptualisation of the Gloucester subregion outlined in companion product 2.3 (Dawes et al., 2018) is well-established. There is, however, still considerable discussion and uncertainty on the geometry of the stratigraphic units, including the position and number of coal seams and the presence, position and hydrogeological functioning of faults.

A more detailed geological model that covers the entire subregion will allow for more nuanced, less conservative numerical modelling. Such a geological model will, for example, allow to address the main source of predictive uncertainty, the mine pumping rates. Local information on the position and extent of coal seams will allow to independently estimate the mine dewatering rates.

Additional information on the presence, position and nature of large and small-scale faults will allow for a more robust stochastic generation of the fault network. This is especially needed for the stochastic generation of subseismic faults, which to date is largely based on international literature. The current parameterisation of the hydrogeological functioning of faults is conservative, that is, biased to overestimating drawdowns. More detailed research on the hydrogeological behaviour of faults, as presented in Parsons Brinckerhoff (2015), will enable this parameterisation to be nuanced. Note that in the current modelling, despite the conservative approach, faults do not appear to influence the predictions much.

The sensitivity analysis in Section 2.6.2.7.3 did highlight that the drawdown predictions are very sensitive to hydraulic properties of the deeper sedimentary basin, especially those of the surface weathered and fractured rock layer. To better constrain the predictions there is a need to improve the knowledge of the hydraulic properties of the surface weathered and fractured rock layer, especially the storage. In addition to that, more depth-specific information on hydraulic conductivity and storage is needed to more robustly establish the variation of hydraulic properties with depth and lithology.

The dataset of groundwater level observations is limited, especially with regards to long time series of groundwater level observations. As such, the groundwater level observations, especially in the alluvium, have limited potential to directly constrain the most sensitive regional-scale parameters (see Section 2.6.2.8.2). Such measurements, however, are invaluable to establish local flow conditions and local hydrogeological properties. These estimates can subsequently be upscaled to regional scale. Any observations that integrate spatial and temporal scales, such as water balance estimates or environmental tracers, also have great potential to constrain the regional-scale properties of the surface weathered and fractured rock layer.

2.6.2.9.2 Limitations

The qualitative uncertainty analysis in Section 2.6.2.8.2 lists the major assumptions and model choices that form the basis of the probabilistic assessment of the impacts of coal resource development on groundwater-related receptors in the Gloucester subregion. Within the context of the goal of the Bioregional Assessment Programme, the bioregional assessment for the Gloucester subregion (the Assessment) modelling team deemed these assumptions valid and acceptable. There is no guarantee, however, that these assumptions will hold or be acceptable to address any other water management questions in the region; therefore, the Assessment modelling team recommends not using these models for any other purpose without a formal assessment of the suitability of the conceptualisation, parameterisation and implementation for the changed objective.

Should these models be considered for any other purpose, there should be a formal re-evaluation of the suitability of the conceptual model and model assumptions, in line with the *Australian Groundwater Modelling Guidelines* (Barnett et al., 2012). All model files and executables are available through the Bioregional Assessment Information Platform (Bioregional Assessment Programme, 2016). It is recommended to contact the model development team for detailed information on the groundwater models.

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

The models are designed within a probabilistic framework. This implies there is not a single parameter combination that provides a 'best fit' to observations and a corresponding single set of predictions. Any evaluation or further use of both the parameter combinations used in the models or the predictions need to take into account the full posterior distributions reported in Section 2.6.2.8. These are also available through the Bioregional Assessment Information Platform (Bioregional Assessment Programme, 2016).

The utmost care has been devoted to ensuring the results presented are in accordance with the conceptual understanding of the system and the stresses imposed on it. This is mostly done by targeted spot checks of model outputs as presented in Figure 20 and visual examination of the response of model outputs to varying parameter values, such as presented in Figure 24 and Figure 25. While these checks minimise the risk that artefacts have gone undetected, as in any modelling exercise of this scale, there is no guarantee that there are no artefacts of modelling included in the results.

2.6.2.9.3 Conclusions

For the Bioregional Assessment Programme, a chain of groundwater and surface water models is developed to probabilistically estimate the hydrological change due to coal resource development in the Gloucester subregion. The regional-scale analytic element groundwater model of the surface weathered and fractured rock layer, the alluvial groundwater models of the Avon and Karuah systems and the Australian Water Resource Assessment Landscape module (AWRA-L) surface water model are tailored to maximally exploit the relevant temporal and spatial scale and are designed to be conservative, that is, the models overestimate the hydrological change rather than underestimate the change.

The simulations indicate that it is unlikely for the drawdown due to additional coal resource development to exceed 1 m at receptors in the surface weathered and fractured rock layer. In the immediate vicinity of coal mines, less than 1 km from the mine footprint, larger drawdowns may be realised. The year of maximum change increases with increasing distance to the mine footprints. This also means the largest drawdowns due to additional coal resource development occur within or shortly after the active mining period.

At receptors in the alluvium, it is unlikely for the drawdown due to additional coal resource development to exceed 0.2 m. In the Avon alluvium adjacent to the proposed Rocky Hill Mine Complex there is a non-negligible probability of drawdown due to additional coal resource development exceeding 0.2 m. The median year of maximum change at the receptors occurs in the decades after mining operations in the subregion are planned to cease.

The effect of coal seam gas depressurisation and the effect of faults as conduits to propagate depressurisation to the surface weathered and fractured rock layer is not distinguishable from the effects of coal mining.

From the sensitivity analysis, it is apparent that the drawdown predictions are most sensitive to the hydraulic properties of the surface weathered and fractured rock layer. The qualitative uncertainty analysis highlighted that the mine dewatering pumping rates are crucial to the predictions. The model choices and assumptions, such as the hybrid modelling approach and the representation of surface water – groundwater interaction, are shown to be conservative. Despite this conservative modelling approach, the predicted hydrological changes are in line with those predicted in earlier local modelling efforts.

The modelling framework is tailored to the specific coal resource development pathway and receptors and therefore should not be used for any other purpose without a rigorous reassessment of the validity of the model assumptions. The modelling did highlight that improved characterisation of hydraulic properties of the surface weathered and fractured rock layer and more detailed information of local geology around baseline and additional coal resource developments have the most potential to reduce predictive uncertainty.

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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.

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

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

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

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.

Bioregional Assessment Data Store: the component of the Bioregional Assessment Repository dedicated to storing datasets, maps and products

Bioregional Assessment Metadata Catalogue: the component of the Bioregional Assessment Repository dedicated to storing metadata

Bioregional Assessment Repository: a collection of systems that together store source and derived datasets, products and maps, accompanying metadata, lineage and supporting material. It consists of the Data Store, Metadata Catalogue and the Repository website. The Repository is not available to the public.

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).

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

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

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

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

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), change in the quantity 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

Gloucester subregion: The Gloucester subregion covers an area of about 348 km². The Gloucester subregion is defined by the geological Gloucester Basin. It is located just north of the Hunter Valley in NSW, approximately 85 km north-north-east of Newcastle and relative to regional centres is 60 km south-west of Taree and 55 km west of Forster.

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

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

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

groundwater system: see water system

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

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

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

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

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

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

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

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

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

likelihood: probability that something might happen

model chain: a series of linked models where the output of one model becomes an input to another model node: a point in the landscape where hydrological changes (and their uncertainty) are assessed. Hydrological changes at points other than model nodes are obtained by interpolation.

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

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

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

preliminary assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed

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

receptor register: a simple and authoritative list of receptors in a specific bioregional assessment

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

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

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

source dataset: a pre-existing dataset sourced from outside the Bioregional Assessment Programme (including from Programme partner organisations) or a dataset created by the Programme based on analyses conducted by the Programme for use in the bioregional assessments (BAs)

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

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

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

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

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

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

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

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

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

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

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