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

Australian Government

BIOREGIONAL ASSESSMENTS

Surface water numerical modelling for the Clarence-Moreton bioregion

Product 2.6.1 from the Clarence-Moreton Bioregional Assessment

18 October 2016

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

The Bioregional Assessment Programme

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

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

Department of the Environment and Energy

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

Bureau of Meteorology

The Bureau of Meteorology is Australia's national weather, climate and water agency. Under the *Water Act 2007*, the Bureau is responsible for compiling and disseminating Australia's water information. The Bureau is committed to increasing access to water information to support informed decision making about the management of water resources. For more information, visit http://www.bom.gov.au/water/.

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ISBN-PDF 978-1-925315-56-1

Citation

Gilfedder M, McJannet D, Wang B, Peeters L, Rojas R, Pagendam D, Zhang Y, Peña-Arancibia J, Shi X, Marvanek S, Viney N, Hartcher M, Pickett T, Crosbie R, Yang A, Vaze J, Lingtao L, Cui T, Raiber M and Rassam D (2016) Surface water numerical modelling for the Clarence-Moreton bioregion. Product 2.6.1 from the Clarence-Moreton Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/CLM/CLM/2.6.1.

Authorship is listed in relative order of contribution.

Cover photograph

Rainforest waterfall in Border Ranges National Park, NSW, 2008

Credit: Liese Coulter, CSIRO

Australian Government

Department of the Environment and Energy

Bureau of Meteorology

Geoscience Australia

CSIRO

v20170210

Executive summary

Coal and coal seam gas (CSG) development can potentially affect water-dependent assets (either negatively or positively) through direct impacts on surface water hydrology. This product presents the modelling of surface water hydrology within the Clarence-Moreton bioregion.

First, the methods are summarised and existing models are reviewed, followed by details regarding the development of the model. The product concludes with predictions of the hydrological characteristics of the system that may change due to coal resource development (referred to as hydrological response variables) also taking into account uncertainty.

Results are reported for two potential futures considered in the Clarence-Moreton Bioregional Assessment (BA):

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

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

The Clarence-Moreton bioregion baseline includes one existing coal mine, the Jeebropilly Coal Mine in the Bremer river basin. An additional coal resource development is the Metgasco West Casino CSG project near Casino, NSW, in the Richmond river basin. As the baseline coal mine is far from the additional coal resource development, and there is no hydraulic connectivity between the Richmond and Bremer river basins, the conceptual hydrogeological model focuses on the geological, hydrogeological and hydrological characteristics of the Richmond river basin.

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

Surface water modelling in the Clarence-Moreton bioregion follows the approach outlined in companion submethodology M06 for surface water modelling. No river modelling has been carried out because the effects of regulation are small. There is an existing river system model of the Richmond River that uses Department of Primary Industries' (DPI Water's) Integrated Quantity and Quality Model (IQQM). Alternatively, the integrated modelling environment software known as Source IMS could be used to develop a Richmond River model. Neither IQQM nor Source IMS will be used in BAs. The Richmond river basin has low levels of stream regulation, so the routing parameters in IQQM are not needed for impact predictions. Instead, predicted streamflow is obtained by accumulating output from the Australian Water Resources Assessment landscape model (AWRA-L). AWRA-L has an accessible code, is relatively easy to set up and calibrate, and there is ready access to local expertise. AWRA-L performed well at estimating streamflow in the Richmond river basin and surrounding area.

The conceptual model for the Clarence-Moreton bioregion in product 2.3 (Conceptual modelling for the Clarence-Moreton bioregion) indicates, based on current information, no new coal mines are expected in the foreseeable future and CSG development is restricted to the Richmond river basin of north-eastern NSW. The surface water modelling domain comprises parts of the Richmond river basin and includes 16 model nodes, which are located where daily streamflow predictions are reported as output. The model simulation period is from 2013 to 2102. Seasonal climate scaling factors are used that result in a reduction in mean annual precipitation of 1.8% per degree of global warming for the Clarence-Moreton bioregion.

The AWRA-L model was regionally calibrated at nine unregulated streamflow gauging stations using two calibration schemes: one biased towards high streamflow and another towards low streamflow. Two parameter sets obtained from the two model calibrations were used as starting points to generate 10,000 parameter sets that can be used for the uncertainty analysis. It is noted that when the regional model is calibrated against observations from the nine streamflow gauging stations it does not generate a uniform model performance. While in general, model calibration results performed well across both the high- and low-streamflow calibrations, they both perform poorly in some areas.

Quantitative and qualitative uncertainty analyses were undertaken for surface water modelling in the Clarence-Moreton bioregion to provide a systematic overview of the model assumptions, their justifications and the effect on predictions. In the uncertainty analysis the optimised parameters are used to inform the prior parameter distributions.

The quantitative uncertainty analysis highlights the importance of constraining parameters with observations of the same type as the prediction, and it is clear that the hydrological response variables are sensitive to different parameters. For the high-flow metrics, the most important parameters are those controlling the quick-flow and interflow components of the hydrograph. The low-flow hydrological response variables are most responsive to the variable that controls the slow-flow component of the simulated hydrograph.

The qualitative uncertainty analysis provides a summary of the major assumptions and model choices underpinning the Richmond river basin surface water model.

The change in surface water hydrology predicted due to the additional coal resource development in absolute terms is predicted to have a median decrease of less than 0.01 GL/day, which corresponds to a change of about 0.01%. These changes are several orders of magnitude smaller than the observed mean streamflow. Their effect on mean and high-flow hydrological response variables will therefore be minimal. Even the effect on low-flow hydrological response variables will be very small, especially in the perennial streams.

In addition to this, such low changes in flow are extremely hard to observe as the largest uncertainties in the rating curves used to transfer measured stage heights to flows are associated with low-flow measurements.

The modelled impacts indicate that the number of zero-flow days (ZFD) across the region will not increase, with the exception of two nodes (CLM_007 and CLM_006). CLM_006 is at the downstream end of Shannon Brook where the median change in the number of ZFD is 3 days. The 95th percentile of change in zero-flow days is 120 days. As noted earlier, small changes in simulated flow can result in large changes in the number of zero-flow days, as zero-flow days are defined as days with streamflow less than 0.01 ML/day. The modelling of measurement of such low flows are problematic and uncertainty in these predicted impacts is high.

Accurately measuring and simulating low-flow conditions is very challenging and requires further efforts. The surface water numerical modelling described in this product provides input into product 2.6.2 (groundwater numerical modelling) for the Clarence-Moreton bioregion. The impact and risk analysis (product 3-4) will not be conducted in the Clarence-Moreton bioregion due to very small hydrological changes predicted at or near the surface due to the additional coal resource development. Outcome synthesis (product 5) is the final technical product being developed for the Clarence-Moreton bioregion.

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Acknowledgements

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

This technical product is the result of the work from many people. We thank them all for their contributions.

Introduction

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

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

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

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

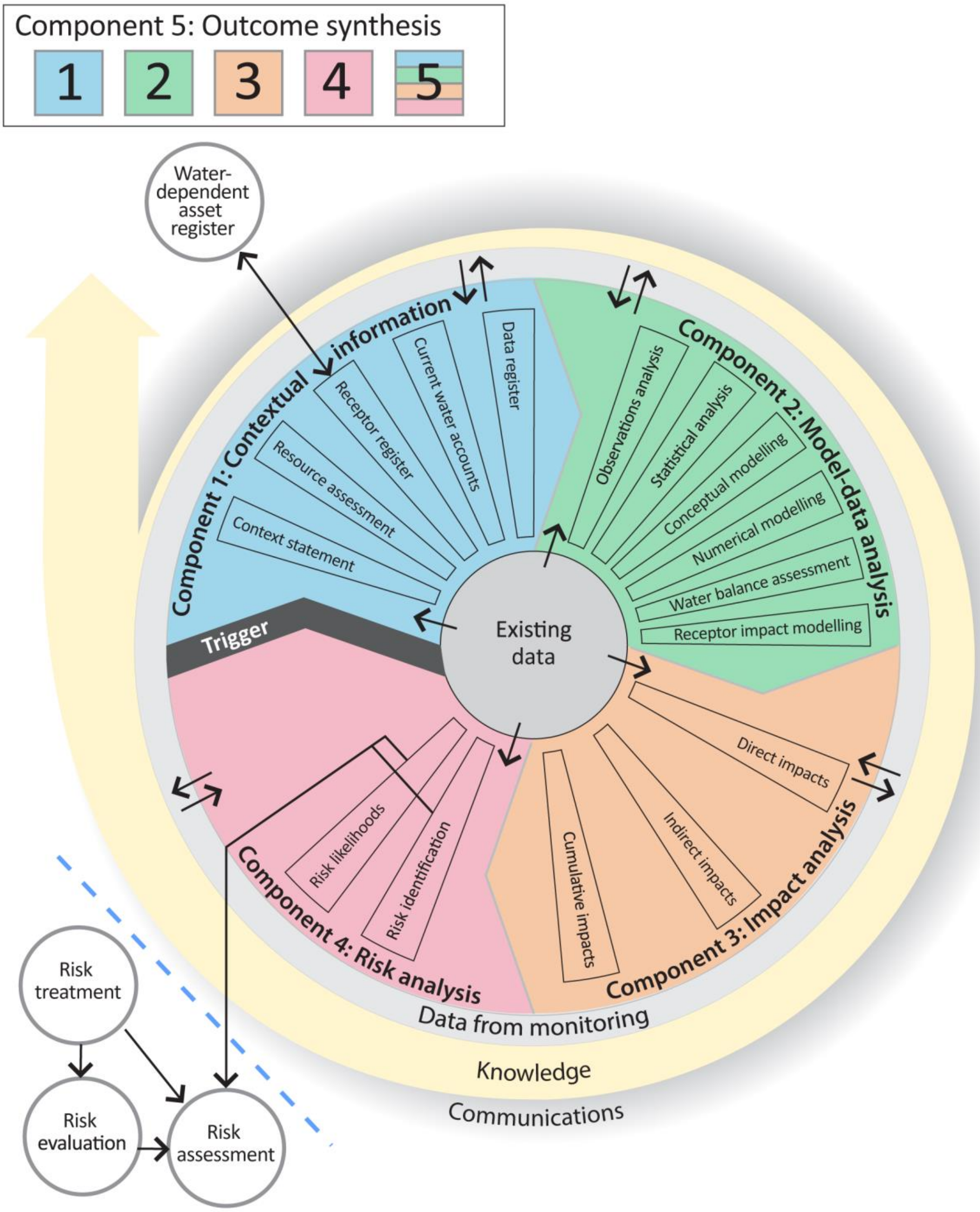

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

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

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

Table 1 Methodologies

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

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

Technical products

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

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

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

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

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

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

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

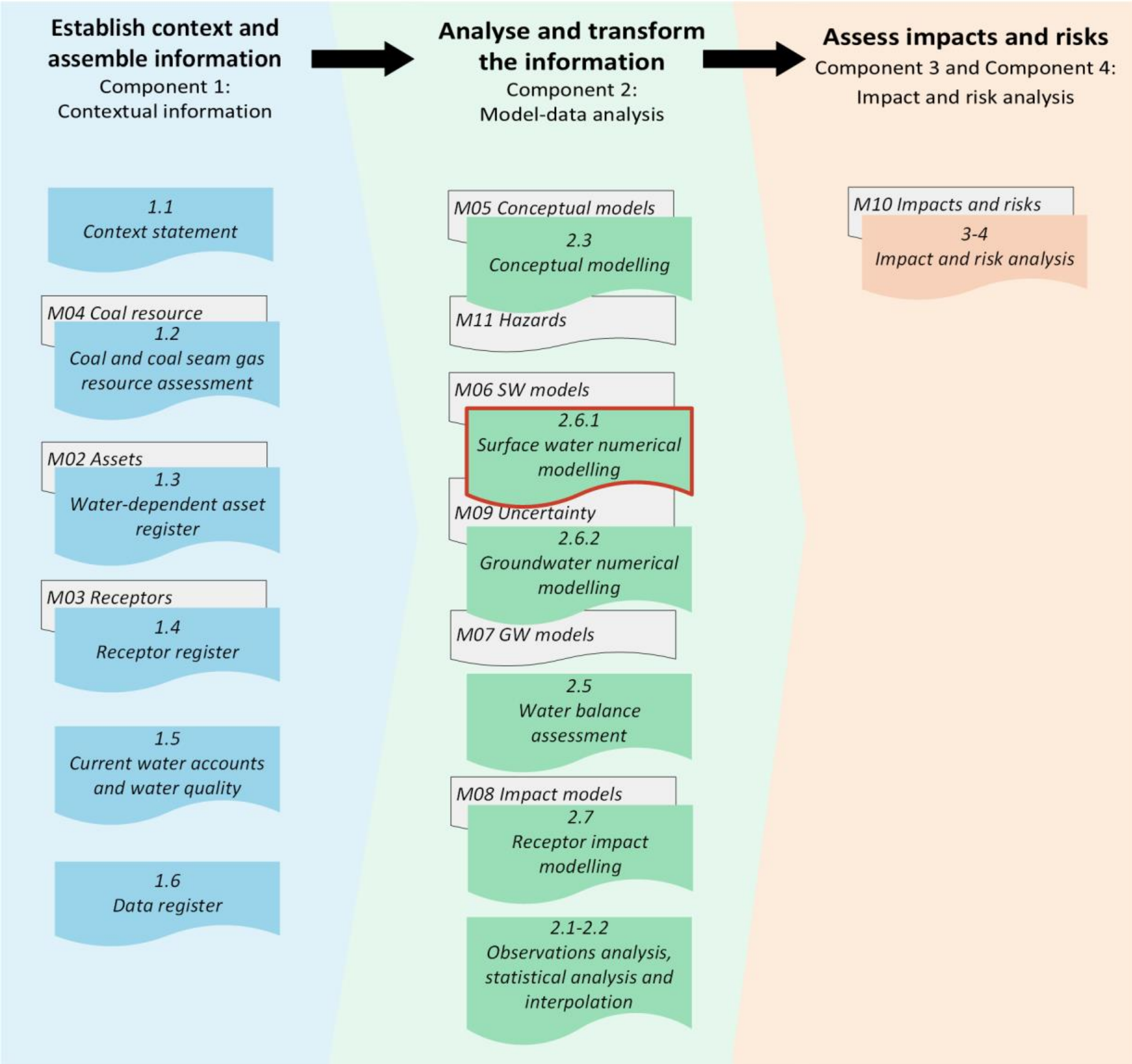

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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

Table 2 Technical products delivered for the Clarence-Moreton bioregion

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

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

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

About this technical product

The following notes are relevant only for this technical product.

- All 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 Clarence-Moreton bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived Datasets, the created date is used.

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Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 6 December 2016, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 6 December 2016, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

2.6.1 Surface water numerical modelling for the Clarence-Moreton bioregion

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

First, the methods are summarised and existing models reviewed, followed by details regarding the development and parameterisation of the Australian Water Resources Assessment landscape model (AWRA-L). 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 surface water. Similarly, potential hydrological changes are estimated for groundwater in product 2.6.2 (groundwater numerical modelling).

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

2.6.1.1 Methods

Summary

A generic methodology for surface water modelling in the Bioregional Assessment Programme is reported in companion submethodology M06 (as listed in Table 1) (Viney, 2016). Section 2.6.1.1 describes the departures from that generic methodology that have been applied in the Clarence-Moreton bioregion. The main difference is that in the Clarence-Moreton bioregion, no river modelling is done because the effects of regulation are small. Instead, streamflow is predicted by accumulating output from the Australian Water Resources Assessment landscape model (AWRA-L).

2.6.1.1.1 Surface water model choice

The conceptual model for the Clarence-Moreton bioregion (reported in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)) indicates that coal seam gas (CSG) development has the potential to directly affect the regional groundwater system and that this direct effect may propagate through to the alluvium of the Richmond River systems. Any impact on the groundwater in the alluvium of those rivers in turn has the potential to affect streamflow (and therefore surface water resources) in the Richmond River.

The Richmond River does not have major surface water storages that exert high levels of regulation on the system. As a result, the simulation of river management or routing of streamflow through the river network with a river model is not necessary as the salient features of streamflow can be simulated solely with a rainfall-runoff model (see companion submethodology M06 for surface water modelling (Viney, 2016)). In the absence of significant regulation and consumptive water use, there is little benefit in implementing the Australian Water Resources Assessment river model (AWRA-R).

For these reasons, surface water resources in the Clarence-Moreton bioregion are modelled using the Australian Water Resources Assessment landscape model (AWRA-L) (version 4.5; Viney et al., 2014) (Bioregional Assessment Programme, Dataset 1). Gridded output from AWRA-L is accumulated to the model nodes without any lagged routing. That is, there is no explicit transmission delay algorithm.

In all other respects, the surface water modelling in the Clarence-Moreton bioregion follows the methodology set out in companion submethodology M06 (Viney, 2016).

2.6.1.1.2 Model sequencing

As of mid-2015, the baseline includes one existing coal mine (Jeebropilly Mine, west of Ipswich) and the coal resource development pathway (CRDP) includes the Jeebropilly Mine and one additional coal resource development for CSG (Metgasco Limited's West Casino Gas Project). This CSG development is located in the Richmond river basin near Casino, NSW. As the baseline coal mine is far from the additional coal resource development, and there is no hydraulic connectivity between the Richmond and Bremer river basins, the conceptual hydrogeological model focuses on the geological, hydrogeological and hydrological characteristics of the Richmond river basin. The focus on this area is due to the presence of highly gas-saturated coal seams that have a relatively high permeability, which are located along the western side of the Casino Trough at depths as shallow as 250 m.

A recent decision by Metgasco (16 December 2015) to sell back their petroleum exploration licences (PELs) to the NSW Government, as well as withdraw their petroleum production lease application (PPLA), effectively means that future development of any CSG resources in the Clarence-Moreton bioregion is highly uncertain. However, as per companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), once the CRDP is determined, it is not changed for bioregional assessment (BA) purposes, even in cases such as this where Metgasco have discontinued their operations in the Clarence-Moreton bioregion.

In order to simulate hydrological changes caused by the additional coal resource development (i.e. the West Casino Gas Project), a model sequence is needed that simulates the impacts on the regional groundwater system, the alluvial groundwater system and the stream network. The Clarence-Moreton Bioregional Assessment adopts a model sequence that consists of a rainfall-runoff model that simulates the surface water system, and a numerical groundwater model that simulates the groundwater system. The surface water model is used to generate river stage heights, which are then used as an input to the groundwater model. The groundwater model then predicts the flux of water between the groundwater and surface water systems.

Potential groundwater impacts of CSG development in the geological Clarence-Moreton Basin were simulated using a regional-scale numerical groundwater model (MODFLOW–NWT; Niswonger et al., 2011) (Bioregional Assessment Programme, Dataset 2), chosen because it deals well with instabilities arising from dry cells in the unconfined model layers. The groundwater model predicts the change in surface water – groundwater flux through the MODFLOW River package. This flux is taken into account in the AWRA-L surface water model generated streamflow. The change in a number of hydrological response variables is modelled at various surface water model nodes.

The model sequence that was adopted to simulate the impacts of the CRDP is depicted in Figure 3. Figure 3 shows the relationship between the AWRA-L surface water model and the groundwater model. The stage height time series that is derived from AWRA-L drives the MODFLOW River package, and depending on the head differences and the streambed conductance, the river either loses water to, or gains water from, the alluvial aquifer.

The CRDP impacts on daily streamflow at each model node are estimated as the baseflow impact. The hydrological changes to baseflow are simulated using the numerical groundwater model, which is described in detail in Section 2.6.2.2.3 of companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016). The numerical groundwater model estimates monthly baseflow for each model node under the baseline and CRDP. The difference between CRDP and baseline simulations is taken as the monthly hydrological changes in baseflow, which is then equally partitioned to obtain the daily changes. The technical details of the model conceptualisation, parameterisation and implementation, together with the uncertainty analysis of the simulated impacts, are documented in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016).

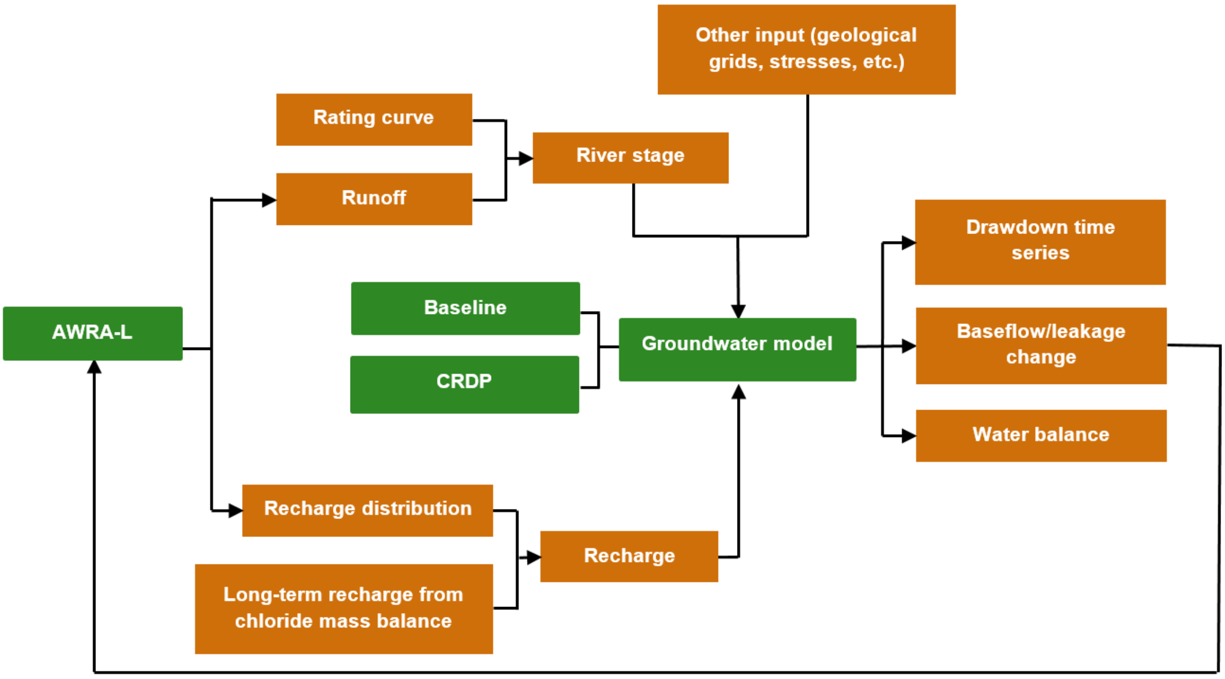

Figure 3 Model sequence for the Clarence-Moreton bioregion

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

As outlined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016), nine hydrological response variables have been chosen to characterise the impacts of coal resource development. These variables are intended to be representative of the flow characteristics that are important for assessing impacts on economic and ecological assets. Five of the hydrological response variables characterise low streamflow, two characterise high streamflow, and two characterise long-term flow variability.

The low-streamflow hydrological response variables are:

- **P01:** the daily streamflow rate at the 1st percentile (ML/day)
- **ZFD:** the number of zero-flow days per year. Zero flow is identified using the minimum detectable flow. For ease of applicability, a threshold of 0.01 ML/day is set for determining the number of ZFD for all surface water nodes
- **LFD:** the number of low-flow days per year. The threshold for LFD is the 10th percentile from the simulated 90-year period (2013 to 2102)
- **LFS:** the number of low-flow spells per year (perennial streams only). A spell is defined as a period of contiguous days of streamflow below the 10th percentile threshold
- **LLFS:** the length (days) of the longest low-flow spell each year.

The high-streamflow hydrological response variables are:

- **P99:** the daily streamflow rate at the 99th percentile (ML/day)
- **FD:** flood (high-flow) days, the number of days with streamflow greater than the 90th percentile from the simulated 90-year period (2013 to 2102).

In addition, two hydrological response variables that represent streamflow volume and variability are:

- **AF:** the annual streamflow volume (GL/year)
- **IQR:** the interquartile range in daily streamflow (ML/day). That is, the difference between the daily streamflow rate at the 75th percentile and at the 25th percentile.

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2.6.1.2 Review of existing models

Summary

There is an existing river system model of the Richmond River that uses Department of Primary Industries' (DPI Water's) Integrated Quantity and Quality Model (IQQM), although neither IQQM (Simons et al., 1996) nor Source IMS (Welsh et al., 2013) will be used in bioregional assessments (BAs). The Richmond river basin has low levels of stream regulation, so the routing parameters in IQQM are not needed for impact predictions, as well as for the reasons outlined in companion submethodology M06 (as listed in Table 1) for the surface water modelling (Viney, 2016).

The Integrated Quantity and Quality Model (IQQM) is a daily time step river system model which simulates many impacts on river flow including inflows, storage management, fixed demands, irrigation and industrial extractions, as well as water sharing rules (Simons et al., 1996). There is an existing IQQM of the Richmond River developed by DPI Water (formerly the NSW Office of Water), although neither IQQM (Simons et al., 1996) nor the integrated modelling environment software known as Source IMS (Welsh et al., 2013) will be used in bioregional assessments (BAs). The Richmond river basin has low levels of stream regulation, so the routing parameters in IQQM are not needed for impact predictions, as well as for the reasons outlined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

The surface water modelling has been undertaken using a rainfall-runoff model – the Australian Water Resources Assessment landscape model (AWRA-L) – which has been calibrated against observed streamflow at several gauging stations. For a discussion of the reasons for the choice of AWRA-L in the Bioregional Assessment Programme, see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

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2.6.1.3 Model development

Summary

Section 2.6.1.3 summarises the key steps taken in developing the surface water models for predicting the hydrological impacts of coal resource development in the Clarence-Moreton bioregion. It includes discussion of the spatial and temporal modelling domains, the spatial resolution of the modelling, the development of a future climate trend, and the estimation of additional coal resource development impacts on streamflow.

The modelling domain comprises parts of the Richmond river basin and includes 16 model nodes, which are located where daily streamflow predictions are reported as output. The model simulation period is from 2013 to 2102.

Seasonal climate scaling factors from the CSIRO Mk3.0 global climate model (Gordon et al., 2002) are chosen to provide a trended climate input over the course of the simulation period. This results in a reduction in mean annual precipitation of 1.8% per degree of global warming for the Clarence-Moreton bioregion.

2.6.1.3.1 Spatial and temporal modelling domains

As reported in Section 2.3.4 of companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016), there is no coal seam gas (CSG) development in the baseline coal resource development for the Clarence-Moreton bioregion and the only additional coal resource development in the bioregion is located in the western part of the Richmond river basin. Therefore, the modelling in the Clarence-Moreton bioregion has been restricted to the Richmond river basin.

The surface water modelling domain adopted in the bioregional assessment (BA) for the Clarence-Moreton bioregion includes the entire basin of the Richmond River above Casino, as well as the neighbouring areas to the east (Leycester Creek) and to the south (Shannon Brook and Myrtle Creek) (Figure 4). The tidal limit of the Richmond River extends to just below the gauging station at Casino. The modelling domain has been restricted to the areas of non-tidal influence.

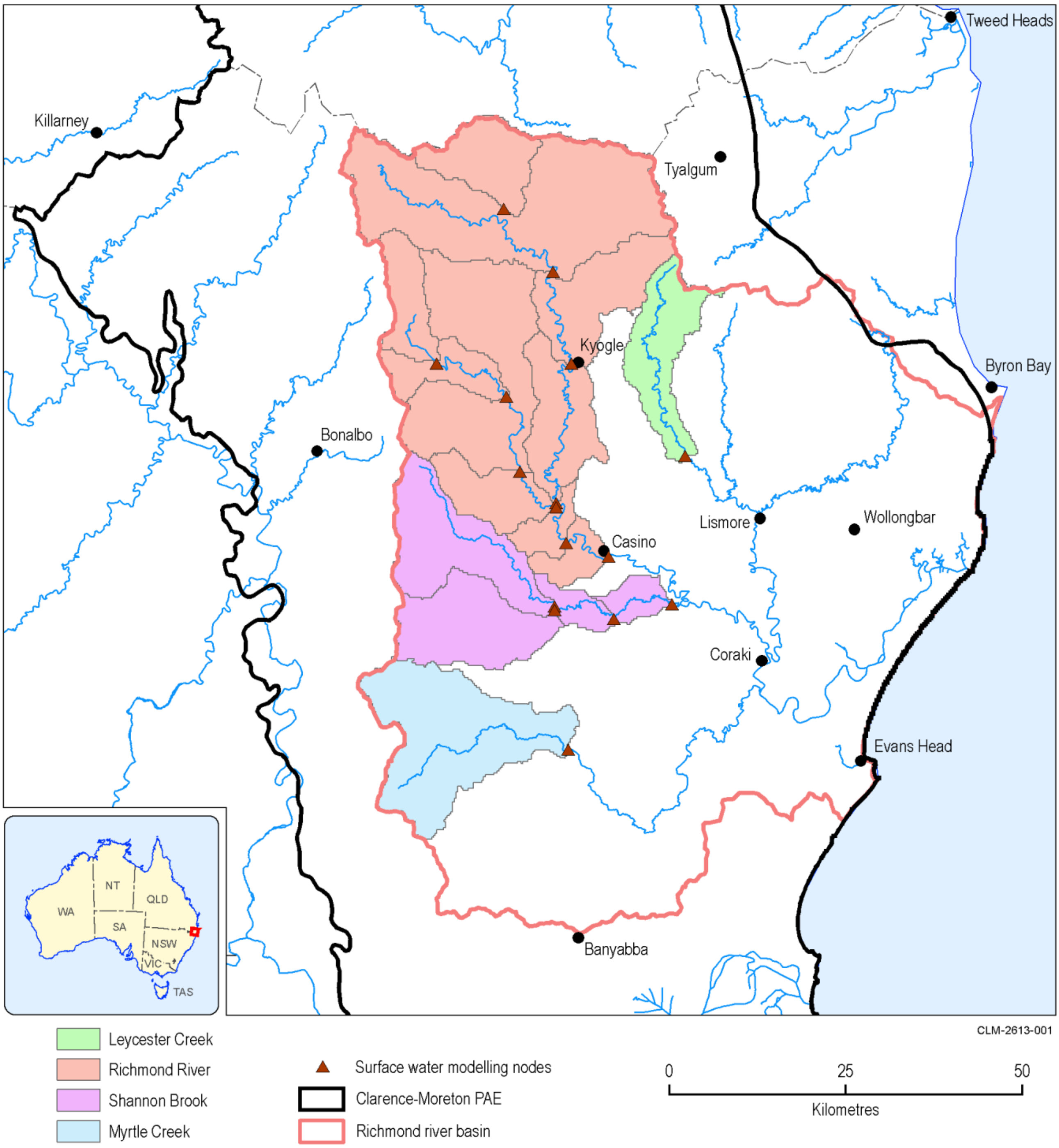

Figure 4 The surface water modelling domain (the four coloured areas) for the Richmond river basin

PAE = preliminary assessment extent

Simulations from 2013 to 2102 were undertaken for both baseline and coal resource development pathway (CRDP). However, the period from 1983 to 2012 is also modelled and acts as an extended warm-up period to reduce any bias in the predictions from starting conditions.

2.6.1.3.2 Location of model nodes

The surface water model nodes represent those locations at which streamflow predictions have been reported. These 16 model nodes are shown in Figure 5, and are located either:

- above major confluences (model nodes CLM001, CLM002, CLM004, CLM005)
- immediately below proposed CSG development projects (model node CLM003)
- at surface water gauging stations (model nodes CLM007 to CLM016)
- close to the limit of tidal influence (model node CLM006).

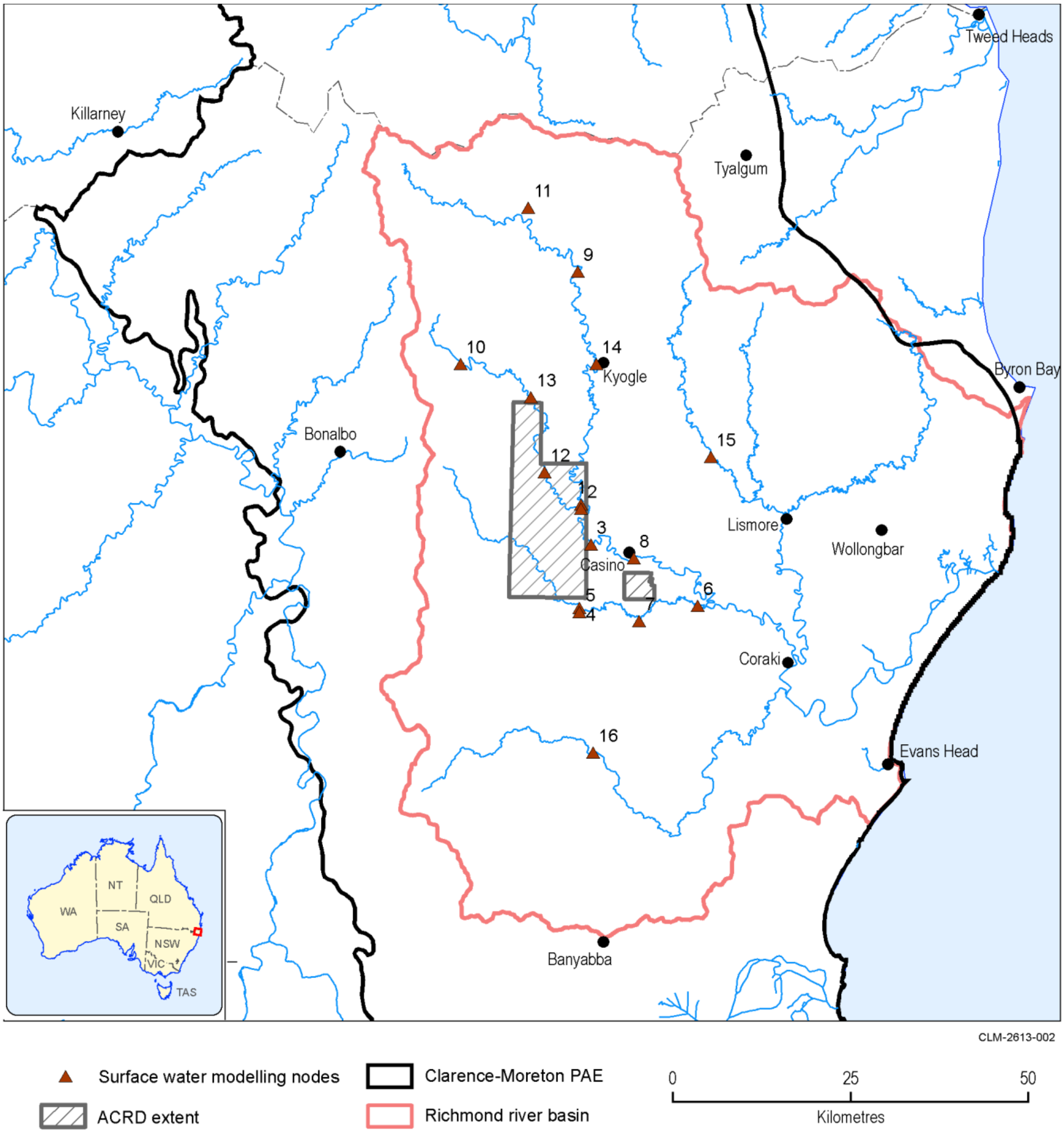

Figure 5 Location of surface water model nodes within the Richmond river basin

ACRD = additional coal resource development; PAE = preliminary assessment extent

2.6.1.3.3 Choice of seasonal scaling factors for climate trend

In order to generate a future climate trend for the BA, the objective is to choose the set of global climate model (GCM) seasonal scaling factors that give the median change in mean annual precipitation in the Clarence-Moreton bioregion.

There are 15 available GCMs with the seasonal scaling factors for each of the four seasons: summer (December–February), autumn (March–May), winter (June–August) and spring (September–November). For each GCM the change in mean seasonal precipitation that is associated with a 1 °C global warming is calculated. These seasonal changes are then summed to give a change in mean annual precipitation.

The resulting changes in mean annual precipitation for a 1 °C global warming in the Clarence-Moreton bioregion are shown in Table 3 for each GCM. The 15 GCMs predict changes in mean annual precipitation ranging from –6.9% (i.e. a reduction in mean annual precipitation) to 3.7% (i.e. an increase in mean annual precipitation). The GCM with the median change is CSIRO Mk3.0 (Gordon et al., 2002). The corresponding projected change in mean annual precipitation per degree of global warming is a reduction of 1.8%, or about 17.9 mm. The seasonal scaling factors for CSIRO Mk3.0 are +4.3% (summer), –5.7% (autumn), –2.5% (winter) and –7.5% (spring). In other words, projected increases in precipitation in the wettest season, summer, are offset by projected decreases in the other three seasons.

Table 3 List of 15 global climate models (GCMs) and their predicted change in mean annual precipitation across the Clarence-Moreton bioregion per degree of global warming

Global climate models (GCM)	Modelling group and country	Change in mean annual precipitation (%)
MIROC3	Centre for Climate Research, Japan	3.7%
NCAR-PCM	National Center for Atmospheric Research, USA	1.7%
CCCMA T63	Canadian Climate Centre, Canada	1.6%
MIUB	Meteorological Institute of the University of Bonn, Germany Meteorological Research Institute of KMA, Korea	0.6%
INMCM	Institute of Numerical Mathematics, Russia	–0.2%
CCCMA T47	Canadian Climate Centre, Canada	–0.3%
NCAR-CCSM	National Center for Atmospheric Research, USA	–0.8%
CSIRO MK3.0	CSIRO, Australia	–1.8%
GFDL2.0	Geophysical Fluid, Dynamics Lab, USA	–2.2%
IAP	LASG/Institute of Atmospheric Physics, China	–2.5%
MPI	Max Planck Institute for Meteorology DKRZ, Germany	–3.9%
CNRM	Meteo-France, France	–5.4%
MRI	Meteorological Research Institute, Japan	–6.1%
IPSL	Institut Pierre Simon Laplace, France	–6.7%
GISS-AOM	NASA/Goddard Institute for Space Studies, USA	–6.9%

Data: CSIRO (Dataset 1)

The seasonal scaling factors associated with CSIRO Mk3.0 are used to generate trended climate inputs for the years 2013 to 2102. The trends assume global warming of 1 °C for the period 2013 to 2042 (compared to 1983 to 2012). The global warming for 2043 to 2072 is assumed to be 1.5 °C and the corresponding scaling factors for this period are therefore multiplied by 1.5 (compared to 1983 to 2012). The global warming for 2073 to 2102 is assumed to be 2 °C (compared to 1983 to 2012).

Future climate input series are produced based on scaling the 1983 to 2012 (30 years) climate input series. The data for this period is repeated a further three times but with increasingly trended climate change scalars (2013 to 2042, 2043 to 2072, 2073 to 2102). The resulting annual precipitation time series for the Richmond river basin is shown in Figure 6. It can be seen from Figure 6 that the decrease in precipitation from 2013 to 2102 is substantially less than the typical inter-annual variability.

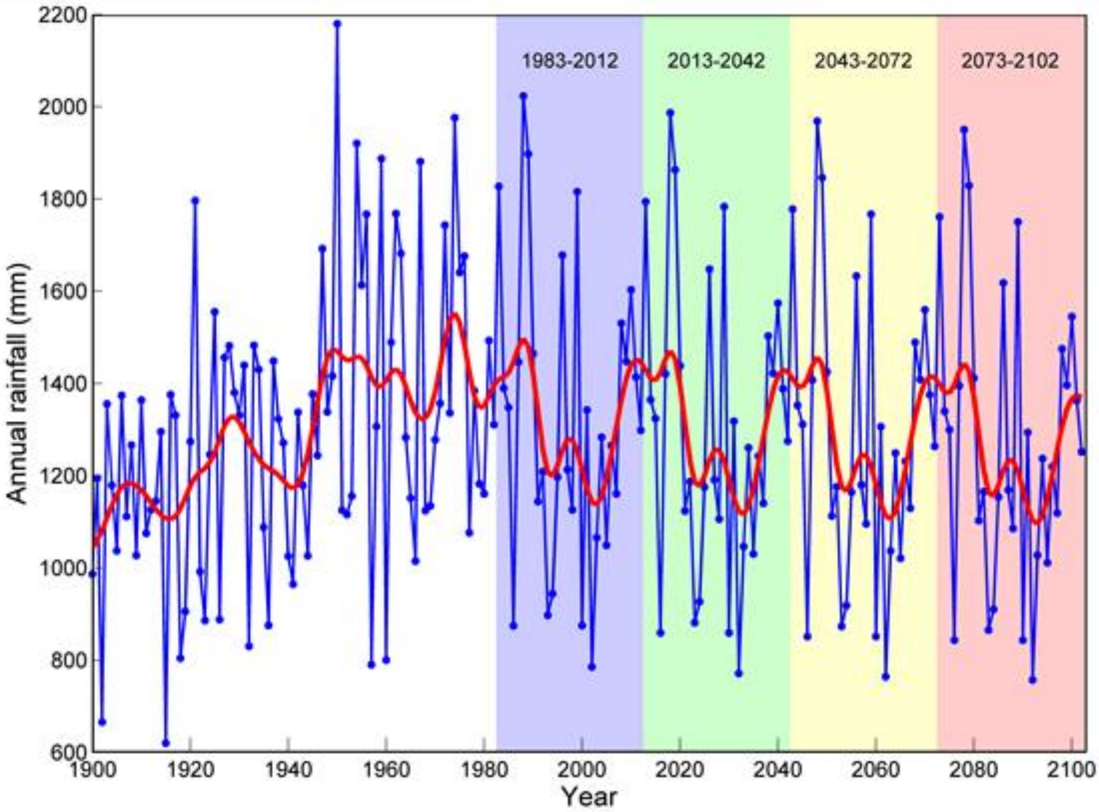

Figure 6 Time series of observed and projected annual precipitation averaged over the Richmond river basin (blue line); the red line is a centrally-weighted moving average

2.6.1.3.4 Mine footprints

No mine footprints are required here as the coal mine in the baseline is not modelled since it is far from the CSG development in the additional coal resource development, and because there are no coal mines in the additional coal resource development.

References

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2.6.1.4 Calibration

Summary

The Australian Water Resources Assessment landscape model (AWRA-L) was regionally calibrated using data from nine unregulated streamflow gauging stations using two calibration schemes: one biased towards high streamflow and another towards low streamflow. Both model calibration results performed adequately across both the high- and low-streamflow calibration.

2.6.1.4.1 Data

The input climate data used in the model were daily time series of maximum temperature, minimum temperature, incoming solar radiation and precipitation from 1953 to 2012 at 0.05 x 0.05 degrees (~5 x 5 km) grid cells from the gridded data generated by the Bureau of Meteorology (Dataset 1).

The streamflow data used for model calibration include daily streamflow data from nine unregulated streamflow gauging stations collated by the Bureau of Meteorology (Dataset 2) (Figure 7). Out of the nine, six contribute to the Richmond river basin, including Coopers Creek at Repentance (calibration gauging station 203002), Richmond River at Wiangaree (calibration gauging station 203005), Leycester Creek at Rock Valley (calibration gauging station 203010), Wilsons River at Eltham (calibration gauging station 203014), Myrtle Creek at Rappville (calibration gauging station 203030), and Shannon Brook at Yorklea (calibration gauging station 203040). Of the remaining catchments, one is in the Tweed river basin (calibration gauging station 201005), and two are in the Clarence river basin (calibration gauging stations 204043 and 204067).

Criteria for selecting the calibration streamflow gauging stations include that they:

- have long-term streamflow measurements (>20 years from 1980)
- are not impacted by coal mining or coal seam gas extraction
- have no significant streamflow regulation (e.g. dams)
- are not nested
- are close to the Richmond river basin and have similar areas and climate regimes.

Boundaries for the contributing areas for nine streamflow gauging stations were delineated using the Geofabric (Bureau of Meteorology, Dataset 3).

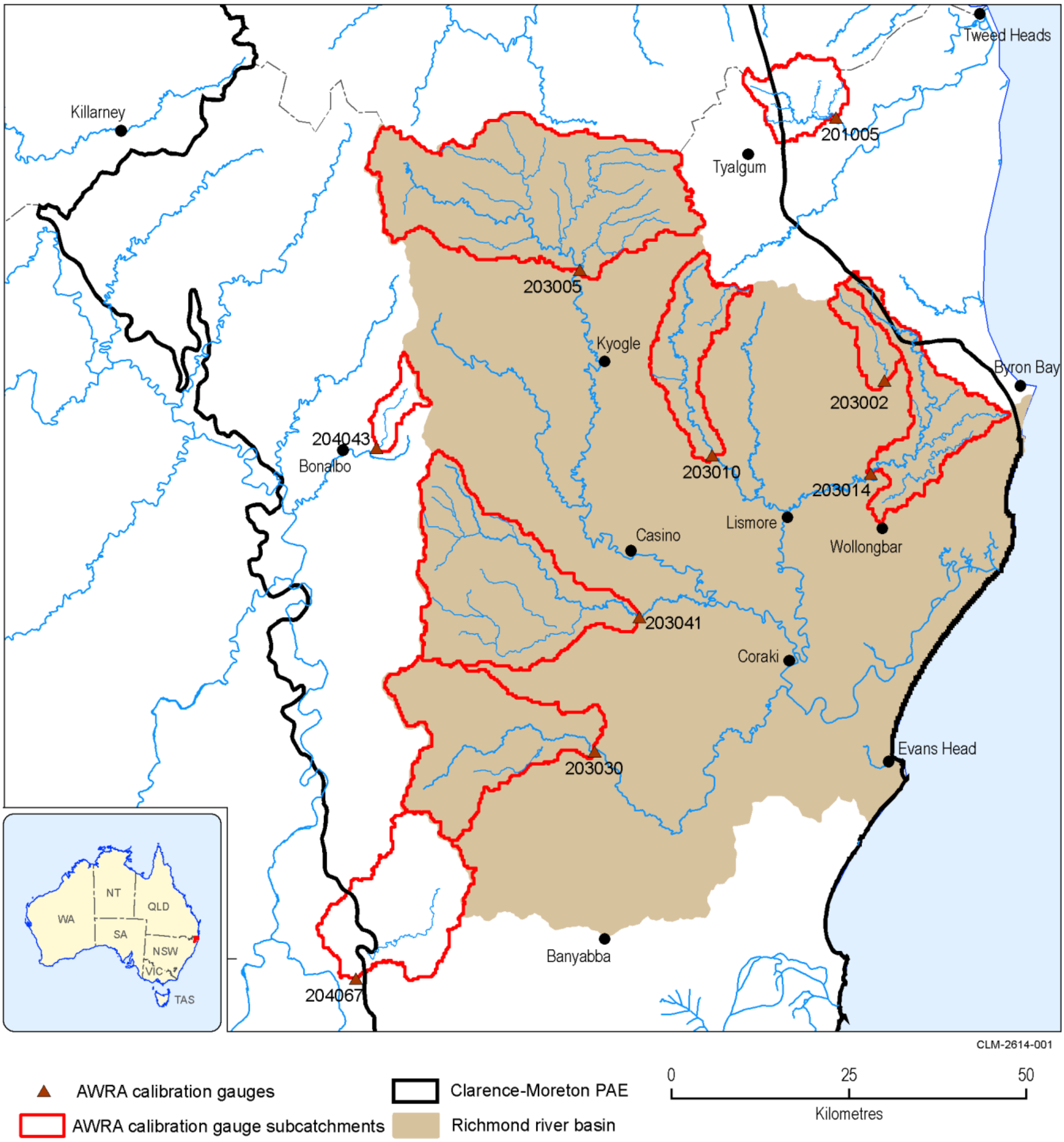

Figure 7 Location of the nine calibration streamflow gauging stations used for AWRA-L model calibration for the Richmond river basin

AWRA = Australian Water Resources Assessment; AWRA-L = AWRA landscape model; PAE = preliminary assessment extent

2.6.1.4.2 Model calibration results

Figure 8 and Table 4 summarise the regional model calibration results for the nine streamflow gauging stations. The bottom, middle and top of each box in Figure 8 represent the 25th, 50th and 75th percentiles, and the bottom and top whiskers represent the 10th and 90th percentiles. For both high-streamflow and low-streamflow calibrations, three metrics (F value, daily efficiency and model bias) are shown and their details are introduced in the Figure 8 notes. Details of each streamflow gauge metric are given in Table 4.

The high-streamflow calibration (F1) yields an overall reasonable Nash–Sutcliffe efficiency of daily streamflow (E_d(1.0)) and low model bias, indicated by a median E_d(1.0) of 0.64 and a median bias of 0.01. This is despite a poor calibration performance at streamflow gauge 203030 (0.08). The values of F1 are also encouraging (with a median of 0.74), with the exception of streamflow gauge 204043, and to a lesser extent streamflow gauge 203030. The reason for the poorer model performance at these two streamflow gauges is not known.

The low-streamflow calibration (F2) is evaluated against the daily streamflow data transformed with a power of 0.1, or a Box-Cox lambda value of 0.1 (Box and Cox, 1964), which can make sure the model evaluation is putting more weight on low streamflow than higher streamflow. The low-streamflow calibration yields overall good efficiency with the Box-Cox lambda value of 0.1 (E_d(0.1)), indicated by a median E_d(0.1) of 0.69. Note that streamflow gauge 203030 has a higher E_d(1.0) of 0.59 for the low-streamflow calibration indicating a better calibration using this objective function. The values of F2 are also encouraging (with a median of 0.71), with the exception of streamflow gauge 204043, and to a lesser extent streamflow gauge 203030.

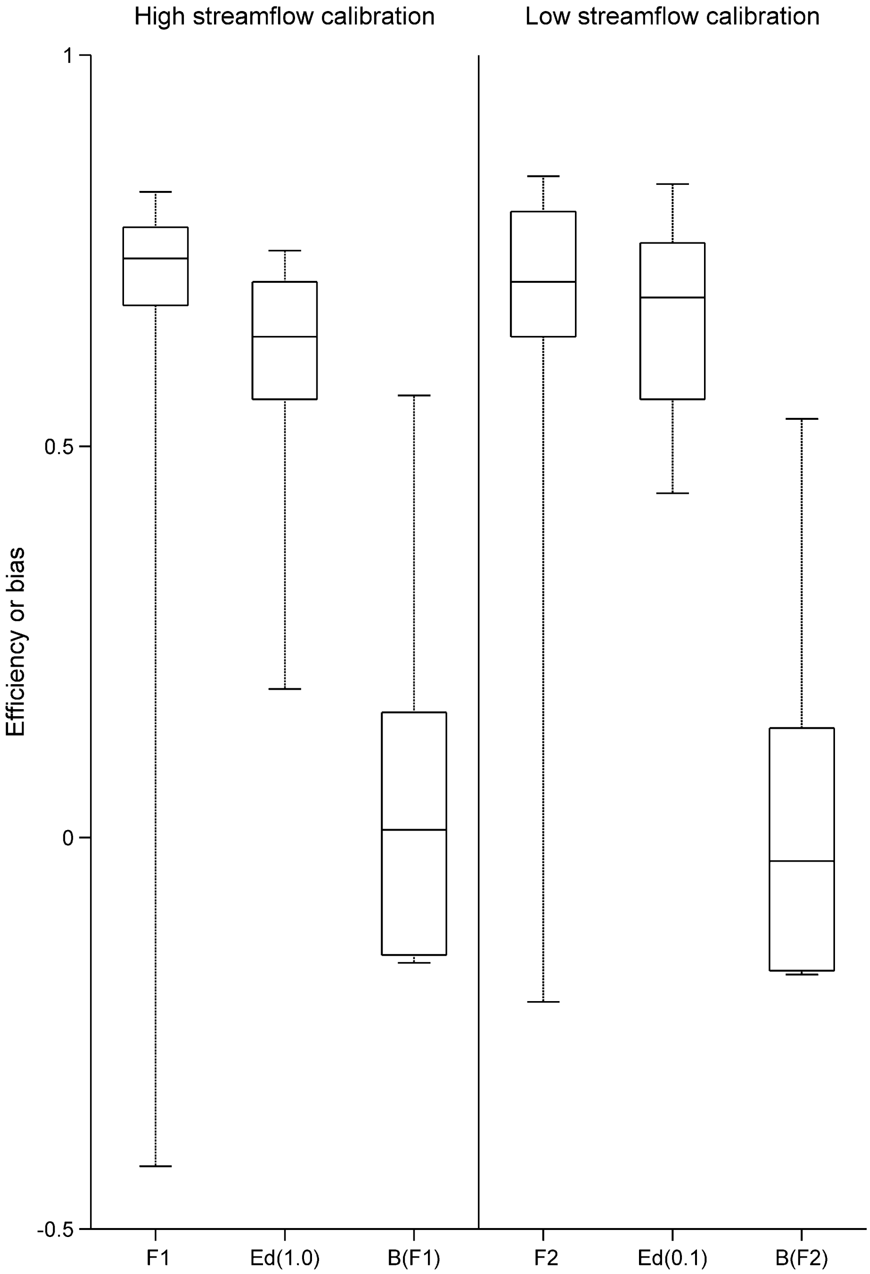

Figure 8 Summary of two AWRA-L model calibrations for the Richmond river basin (period is 1 January 1983 to 31 December 2013)

AWRA-L = Australian Water Resources Assessment landscape model
Left: high-streamflow calibration; right: low-streamflow calibration. In each boxplot, the bottom, middle and top of the box are the 25th, 50th and 75th percentiles, and the bottom and top whiskers are the 10th and 90th percentiles. F1 is the F value for high-streamflow calibration; F2 is the F value for the low-streamflow calibration; Ed(0.1) is the daily efficiency with a Box-Cox lambda value of 1.0; Ed(0.1) is the daily efficiency with a Box-Cox lambda value of 0.1; B is model bias.
Data: Bureau of Meteorology (Dataset 1, Dataset 2) and Bioregional Assessment Programme (Dataset 4)

Table 4 Summary of model calibration for nine calibration streamflow gauging stations in the Clarence-Moreton bioregion (1 January 1983 to 31 December 2013)

Streamflow gauge ID	Modelled mean annual streamflow (mm/y)	F1[a]	$E_d(1.0)$[a]	Bias (F1)[a]	F2[b]	$E_d(0.1)$[b]	Bias (F2)[b]
201005	691	0.68	0.64	–0.16	0.71	0.76	–0.17
203002	905	0.74	0.71	–0.15	0.77	0.84	–0.17
203005	303	0.85	0.78	0.01	0.83	0.76	–0.03
203010	455	0.78	0.64	–0.04	0.80	0.69	–0.06
203014	822	0.80	0.72	0.07	0.86	0.83	0.03
203030	201	0.12	0.08	0.37	0.44	0.59	0.33
203041	205	0.68	0.56	0.16	0.66	0.49	0.14
204043	238	–0.96	0.30	0.76	–0.86	0.39	0.74
204067	218	0.74	0.71	–0.16	0.64	0.56	–0.18
Median	303	0.74	0.64	0.01	0.71	0.69	–0.03

[a] $F1 = (E_d(1.0) + E_m)/2 - 5|\ln(1+B)|^{2.5}$ is the F value for high-streamflow calibration, where $E_d(1.0)$ is the daily efficiency with a Box-Cox lambda value of 1.0, E_m is the monthly efficiency and B is the bias.

[b] $F2 = E_d(0.1) - 5|\ln(1+B)|^{2.5}$ is the F value for low-streamflow calibration, where $E_d(0.1)$ is the daily Nash–Sutcliffe efficiency (NSE) with a Box-Cox lambda value of 0.1.

Data: Bureau of Meteorology (Dataset 1, Dataset 2) and Bioregional Assessment Programme (Dataset 4)

The calibration results show that the model can be calibrated against both high-flow and low-flow objective functions with reasonable results, as evidenced by both the median F values and median model efficiencies of around 0.6 to 0.7, and with median bias at low levels. An F value of unity would indicate a perfect fit, with F values approaching minus infinity reflecting poorer and poorer fits.

2.6.1.4.3 Implications for model predictions

The traditional hydrological modelling workflow is to first calibrate a hydrological model against streamflow observations at each streamflow gauging station, then regionalise the model parameters from a nearest streamflow gauging station to a target ungauged area for streamflow prediction (Chiew et al., 2009; Zhang and Chiew, 2009). As a result, model calibration performance is noticeably better than model predictions.

The workflow used here, however, follows a regional calibration for the reasons outlined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). Here, a regional calibration is first undertaken across multiple streamflow gauging stations in the broader area, and then this calibration is applied to all locations of interest (including ungauged). The regional model calibration results (Table 4 and Figure 8) suggest that the Australian Water Resources Assessment landscape model (AWRA-L) performs acceptably well at estimating streamflow in the Richmond river basin and its surrounding area when it is calibrated against in situ high streamflow and low streamflow, respectively.

It is noted that when the regional model is calibrated against observations from the nine streamflow gauging stations it does not generate a uniform model performance. Though the AWRA-L model performs well overall, it performs poorly at some streamflow gauging stations. For instance, the high-streamflow model calibration generates a poor model performance at streamflow gauge 203030 and 204043 and the low-streamflow model calibration exhibits a poor model performance at streamflow gauge 204043 (Table 4).

Compared to the local model calibration, the regional model calibration performs similarly between the streamflow gauging stations used for calibrations and those used for predictions (Viney et al., 2014; Zhang et al., 2011). The nine calibration streamflow gauging stations cover a wide range of climate and topographic conditions, where mean annual streamflow varies from 201 mm/year at streamflow gauging station 203030 to 905 mm/year at streamflow gauging station 203002 (Table 4).

Furthermore, the performance of the high-streamflow calibration for the nine streamflow gauging stations does not appear to be significantly affected by catchment wetness, although it does perform slightly better with a wetter climate. The performance of low-streamflow calibration appears less sensitive to catchment wetness, with the exception of three of the drier areas where model performance is lower.

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Datasets

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Dataset 4 Bioregional Assessment Programme (2016) Clarence-Moreton AWRA-L calibration results. Bioregional Assessment Derived Dataset. Viewed 16 March 2016, http://data.bioregionalassessments.gov.au/dataset/f045bb10-27a5-4cf5-8cd4-fc4c13e73453.

2.6.1.5 Uncertainty

Summary

In the quantitative uncertainty analysis a large number of parameter combinations are evaluated and combined with the results of the groundwater modelling to obtain the maximum raw change, the year of maximum change and the relative change between baseline and coal resource development pathway (CRDP) conditions for the nine hydrological response variables.

The fit between observed and simulated historical hydrological response variable values is used to constrain the Australian Water Resources Assessment landscape model (AWRA-L) parameters while the simulated coal seam gas extraction rate and the simulated surface water – groundwater flux at Casino is used to constrain the groundwater model results. Only parameter combinations that are considered to meet all of these three criteria are accepted as behavioural parameter combinations that are used to make predictions. This set of behavioural parameter combinations is different for each hydrological response variable.

The quantitative uncertainty analysis is followed by a qualitative assessment of the effect of model assumptions on the prediction. The largest sources of uncertainty not captured in the quantitative uncertainty analysis are considered to be the availability of calibration catchments, the selection of objective functions for the uncertainty analysis and the interaction with the groundwater model.

2.6.1.5.1 Quantitative uncertainty analysis

The aim of the quantitative uncertainty analysis is to provide a probabilistic estimate of the change in the hydrological response variables due to coal resource development at the model nodes. A large number of parameter combinations are evaluated and, in line with the Approximate Bayesian Computation outlined in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016), only those parameter combinations that result in acceptable model behaviour are accepted in the parameter ensemble used to make predictions.

Acceptable model behaviour is defined for each hydrological response variable based on the capability of the model to reproduce historical, observed time series of the hydrological response variable. For each hydrological response variable, a goodness of fit between model simulated and observed annual hydrological response variable is defined and an acceptance threshold defined.

The ensemble of predictions are the changes in hydrological response variable simulated with the parameter combinations for which the goodness of fit exceeds the acceptance threshold. The resulting ensembles are presented and discussed in Section 2.6.1.6.

2.6.1.5.1.1 Design of experiment

Table 5 lists the parameters used in the uncertainty analysis, the range and distribution type sampled in the design of experiment and the transformation of the parameter. These parameters and how they interact, is explained in detail the Australian Water Resources Assessment landscape model (AWRA-L) v4.5 documentation (Viney et al., 2015).

Table 5 AWRA-L parameters included in the quantitative uncertainty analysis

Parameter name	Units	Transformation	Minimum	Maximum	Prior distribution
cGsmax_hruDR	na	none	0.02	0.05	uniform
cGsmax_hruSR	na	none	0.001	0.05	uniform
ER_frac_ref_hruDR	na	none	0.04	0.25	uniform
FsoilEmax_hruDR	na	none	0.2	1	uniform
FsoilEmax_hruSR	na	none	0.2	1	uniform
K_gw_scale	na	$\log_{10}$	0.001	1	uniform
K0sat_scale	na	$\log_{10}$	0.1	10	uniform
Kdsat_scale	na	$\log_{10}$	0.01	1	uniform
Kssat_scale	na	$\log_{10}$	0.0001	0.1	uniform
Pref_gridscale	na	none	0.1	5	uniform
S0max_scale	na	none	0.5	5	uniform
Sdmax_scale	na	none	0.5	1	uniform
Ssmax_scale	na	none	0.5	3	uniform
Ud0_hruDR	mm/d	$\log_{10}$	0.001	10	uniform

AWRA-L = Australian Water Resources Assessment landscape model; na = data not applicable

Through a space-filling Latin Hypercube sampling (Santer et al., 2003), 10,000 parameter combinations are generated of the AWRA-L parameters, with the ranges and transformations shown in Table 5. These ranges and transforms are chosen by the modelling team based on previous experience in regional and continental calibration of AWRA-L (Viney et al., 2015). These mostly correspond to the upper and lower limits of each parameter during calibration.

Each of the 10,000 parameter sets is used to drive AWRA-L to generate streamflow time series at each 0.05 x 0.05 degrees grid cell (Jones et al., 2009). The results of these runs are combined with the change in surface water – groundwater flux simulated with the groundwater model (companion product 2.6.2, Cui et al., 2016), as outlined in Section 2.6.1.1, to create time series of total streamflow under baseflow and coal resource development pathway (CRDP) conditions. This resulted in a database of 3756 evaluated parameter combinations for which historical streamflow as well as streamflow in baseline and CRDP are available. While the coverage of parameter space is limited with less than 4000 simulations, visual inspection of the successfully evaluated parameters showed that there was adequate coverage of all parameters and no bias or gaps in the sampling of the parameter hyperspace.

2.6.1.5.1.2 Observations

For 10 of the 16 model nodes in the model domain, observations of streamflow are available. For these catchments the historical observations of streamflow are summarised into the nine hydrological response variables for all years with a full observational record. The equivalent historical simulated hydrological response variable values are computed from the design of experiment runs. The difference between these observed and simulated historical hydrological response variable values are used in the Approximate Bayesian Monte Carlo analysis to select behavioural parameter combinations.

The difference between simulated and observed historical hydrological response variables is summarised as the average of a modified index of agreement (Willmott, 1981):

$$SS = \frac{1}{N}\sum_{j}^{N}\left[1 + \frac{\sum_{i}^{n} HRV_{j,obs}(i) - HRV_{j,sim}(i)}{\sum_{i}^{n}\left|HRV_{j,sim}(i) - \overline{HRV_{j,obs}(i)}\right| + \left|HRV_{j,obs}(i) - \overline{HRV_{j,obs}(i)}\right|}\right]^{-1} \quad (1)$$

with $HRV_{j,obs}(i)$ the observed hydrological response variable in catchment j ($j \in 1, \dots, N$) for year i ($i \in 1, \dots, n$). $HRV_{j,sim}(i)$ is the equivalent simulated value. The summary statistic varies between 0.5 and 1, where 1 represents a perfect fit.

2.6.1.5.1.3 Predictions

A total of 3756 time series with a length of 90 years of hydrological response variable values are available for baseline, $HRV_{base}(t)$, and CRDP conditions, $HRV_{CRDP}(t)$.

These two time series are summarised through the maximum raw change, amax, the maximum percent change, pmax, and the year of maximum change, tmax. The percentage change is defined as:

$$pmax = \frac{amax}{HRV_{base}(tmax)} \quad (2)$$

In other words, it is the maximum change in hydrological response variable divided by the value of the hydrological response variable under baseline conditions in the year when the maximum change occurs. The *pmax* value is very useful to contextualise changes in flux estimates. It can lead to aberrant results, especially for hydrological response variables that are categorical (such as the number of low-flow days) or when the $HRV_{base}(tmax)$ is very small or zero.

2.6.1.5.1.4 Sensitivity analysis

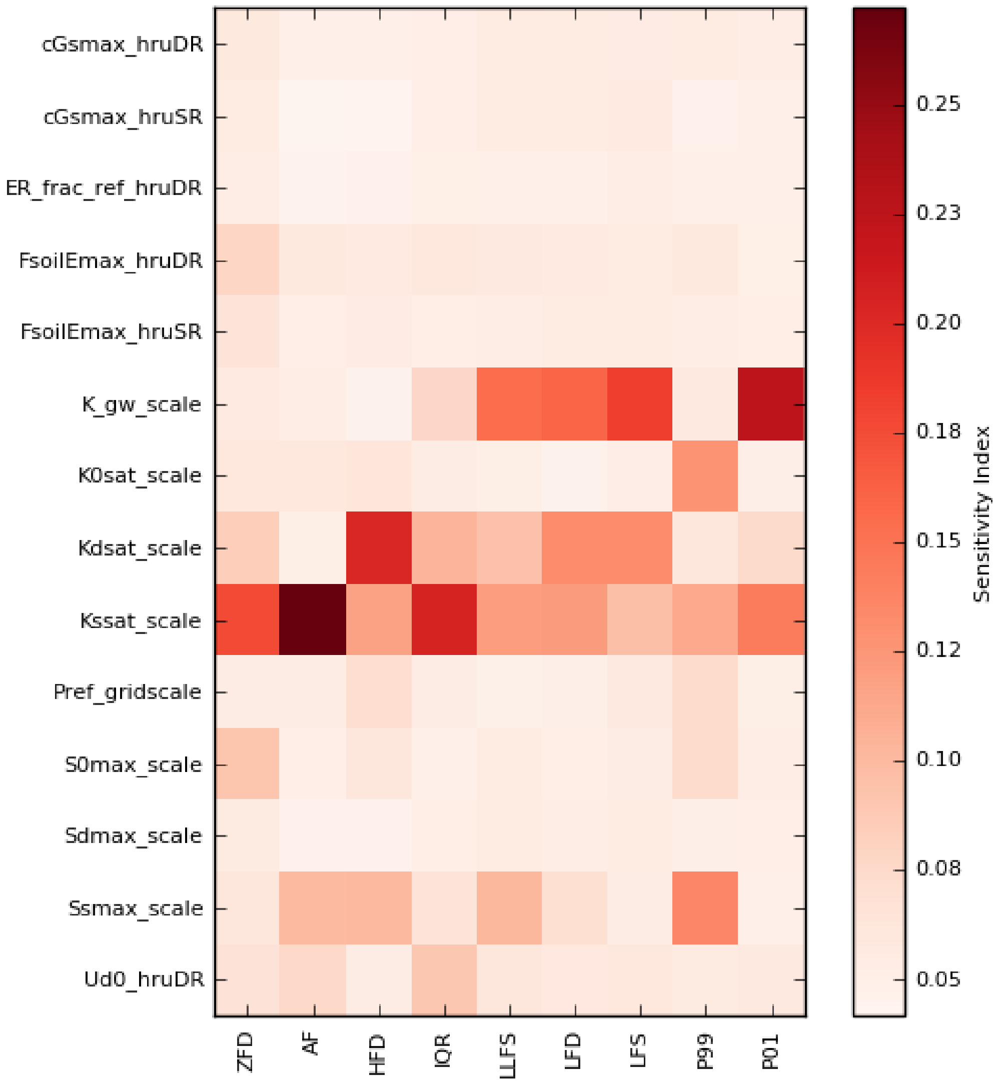

Figure 9 Sensitivity indices of hydrological response variable summary statistics to AWRA-L parameters

Sensitivity indices are a relative measure, darker colors indicate more sensitive hydrological response variable/parameter pairs

Figure 9 shows the sensitivity indices of the summary statistics for hydrological response variable to each parameter from Table 5, computed with the density-based sensitivity analysis methodology of Plischke et al. (2013).

From this sensitivity analysis it is clear that the hydrological response variables are sensitive to different parameters. For the metrics that are affected by high-streamflow, such as annual flow (AF), interquartile range (IQR), number of flood (high-flow) days (FD) and daily streamflow at the 99th percentile (P99), the most important parameters are those controlling the quick-flow and interflow components of the hydrograph (*K0sat_scale, Kssat_scale* and to a lesser extent *Ssmax_scale*, see Viney et al., 2015). For the hydrological response variables that are most sensitive to low-streamflow, daily streamflow at the the 1st percentile (P01), the number of low-flow days (LFD), the number of low-flow spells (LFS), the length of the longest low-flow spell

(LLFS), and the zero-flow days (ZFD), are most sensitive to *K_gw_scale*, which controls the slow-flow component of the simulated hydrograph (Viney et al., 2015).

The sensitivity analysis highlights the importance of constraining parameters with observations of the same type as the prediction. For instance, observations of annual flow will mainly constrain *Kssat_scale*, but will not be able to constrain *K_gw_scale*, which is the most important parameter for low-flow predictions.

2.6.1.5.1.5 Selection of behavioural parameter combinations

A central concept in the Approximate Bayesian Computation methodology, outlined in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016), is the summary statistic and corresponding rejection threshold. The summary statistic is a single number that quantifies the performance of the model with a given parameter combination. The rejection threshold is the minimum value this summary statistic needs to be for a proposed parameter combination to be accepted in the posterior parameter distribution for the hydrological response variable.

In the selection of behavioural parameter combinations for each hydrological response variable, three criteria and thresholds are used:

1. hydrological response variable specific summary statistic based on the average Nash–Sutcliffe efficiency (Eq. 1)
2. simulated rate of extraction for coal seam gas production by the groundwater model
3. average historical surface water – groundwater flux at Casino in September and October.

The first criterion constrains the AWRA-L parameters, while the second and third constrain the change in surface water groundwater flux from the groundwater model. These two criteria and acceptance thresholds are discussed in greater detail in companion product 2.6.2 (Cui et al., 2016).

The acceptance threshold for the first criterion is set to the 75th percentile of the design of experiment simulations. In other words, the 25% best parameter combinations for that hydrological response variable are accepted.

Only the parameter combinations that meet the thresholds for all three criteria are accepted. The predicted change in the hydrological response variables corresponding to the behavioural parameter combinations are presented in Section 2.6.1.6. Before presenting and discussing these results, the main assumptions and model choices underpinning the predictions are discussed in the qualitative uncertainty analysis.

2.6.1.5.2 Qualitative uncertainty analysis

The major assumptions and model choices underpinning the Richmond river basin surface water model are listed in Table 6. 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 will also assist in an open and transparent review of the modelling.

Each assumption is scored on four attributes as 'low', 'medium' or 'high'. The data column is the degree to which the question 'If more or different data were available, would this assumption/choice still have been made?' would be answered positively. A 'low' score means that the assumption is not influenced by data availability, while a 'high' score would indicate that this choice would be revisited if more data were available. Closely related is the resources attribute. This column captures the extent to which resources available for the modelling, such as computing resources, personnel and time, influenced this assumption or model choice. A 'low' score indicates the same assumption would have been made with unlimited resources, while a 'high' score indicates the assumption is driven by resource constraints. The third attribute deals with the technical and computational issues. 'High' is assigned to assumptions and model choices that are dominantly driven by computational or technical limitations of the model code. These include issues related to spatial and temporal resolution of the models. The final, and most important, column is the effect of the assumption or model choice on the predictions. This is a qualitative assessment of 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.

Assumptions are discussed in detail in the sections below Table 6, including the rationale for the scoring.

Table 6 Qualitative uncertainty analysis as used for the Richmond river basin surface water model

Number	Assumption/model choice	Data	Resources	Technical	Effect on predictions
1	Selection of calibration catchments	Medium	Low	Low	Medium
2	High-flow and low-flow objective function	Low	Low	High	Low
3	Selection of summary statistics for uncertainty analysis	Low	Low	Low	Low
4	Selection of acceptance threshold for uncertainty analysis	Medium	High	Low	Medium
5	Interaction with the groundwater model	Medium	Medium	High	Medium
6	No streamflow routing	Medium	Low	Low	Low

2.6.1.5.2.1 Selection of calibration catchments

The parameters that control the transformation of rainfall into streamflow are adjusted based on a comparison of observed and simulated historical streamflow. To calibrate the surface water model, a number of catchments are selected outside the Richmond river basin (e.g. Clarence river basin and Tweed river basin). The parameter combinations that result in objective function values above the predefined threshold are deemed suitable for all catchments in the bioregion.

The selection of calibration catchments is therefore almost solely based on data availability, which results in a 'medium' score for this criterion. As it is technically trivial to include more calibration catchments in the calibration procedure and as it would not appreciably change the computing time required, both the resources and technical columns have a 'low' score.

This regionalisation of parameters is a widely established technique internationally to predict flows at ungauged catchments (Bourgin et al., 2015). The regionalisation methodology is valid as long as the selected catchments for calibration are comparable in size, climate, land use, topography, geology and geomorphology. The majority of these assumptions can be considered valid (see Section 2.6.1.6) and the effect on predictions is therefore deemed small.

While the regionalisation assumption is valid, the availability of additional calibration catchments may further constrain the predictions. The overall effect of the choice of calibration catchments is therefore considered moderate, which is reflected in the 'medium' scoring.

2.6.1.5.2.2 High-flow and low-flow objective function

The AWRA-L model simulates daily streamflow. High-streamflow and low-streamflow conditions are governed by different aspects of the hydrological system. It has proven to be very difficult for any rainfall-runoff code to find parameter sets that are able to adequately simulate both extremes of the hydrograph. In recognition of this issue, two objective functions are chosen, one tailored to medium and high flows and another tailored to low flows.

Even with more calibration catchments and more time available for calibration, a high and low flow objective would still be necessary to find parameter sets suited to simulate different aspects of the hydrograph. Data and resources are therefore scored 'low', while the technical criterion is scored 'high'.

The high-streamflow objective function is a weighted sum of the Nash–Sutcliffe efficiency (E) and the bias. The former is most sensitive to differences in simulated and observed daily streamflow, while the latter is most affected by the discrepancy between long-term observed and simulated streamflow (Pushpalatha et al., 2012). The weighting of both components represents the trade-off between simulating daily and mean annual streamflow behaviour.

The low-streamflow objective is achieved by transforming the observed and simulated streamflow through a Box-Cox transformation (see Section 2.6.1.4). By this transformation, a small number of large discrepancies in high streamflow will have less prominence in the objective function than a large number of small discrepancies in low streamflow. Like the high-streamflow objective function, the low-streamflow objective function consists of two components, the E transformed by a Box-Cox power of 0.1 and bias, which again represent the trade-off between daily and mean annual accuracy.

The choice of the weights between both terms in both objective functions is based on the experience of the modelling team (Viney et al., 2009). The choice is not constrained by data, technical issues or available resources. While different choices of the weights will result in a different set of optimised parameter values, experience in the Water Information Research and Development Alliance (WIRADA) project in which the AWRA-L is calibrated on a continental scale has shown the calibration to be fairly robust against the weights in the objective function (Vaze et al., 2013).

Within the bioregional assessment the effect of this choice is further mitigated through the Approximate Bayesian Computation process in which hydrological response variable specific summary statistics are used to select behavioural posterior parameter distributions.

While the selection of objective functions and their weights is a crucial step in the surface water modelling process, the overall effect on the predictions is marginal through the uncertainty analysis, hence the 'low' scoring.

2.6.1.5.2.3 Selection of summary statistics for uncertainty analysis

The summary statistic in the Approximate Bayesian Computation process has a very similar role to the objective function in calibration. Where the calibration focuses on identifying a single parameter set that provides an overall good fit between observed and simulated values, the uncertainty analysis aims to select an ensemble of parameter combinations that is best suited to make the chosen prediction.

Within the context of the bioregional assessment, the calibration aims at providing a parameter set that performs well at a daily resolution, while the uncertainty analysis focuses on hydrological response variables that summarise specific aspects of the yearly hydrograph.

The summary statistic is the mean of the *E* of the observed versus simulated hydrological response variable values at the calibration catchments that contribute to flow in the Richmond river basin. This ensures parameter combinations are chosen that are able to simulate the specific part of the hydrograph relevant to the hydrological response variable, at a local scale. There are other ways to summarise the difference between observed and simulated values. The current summary statistic, based on the mean of Nash–Sutcliffe efficiencies across catchments, is chosen because it provides a fair, unbiased estimate of the model mismatch and is fairly robust against extreme outliers.

Like the objective function selection, the choice of summary statistic is primarily guided by the predictions and to a much lesser extent by the available data, technical issues or resources. This is the reason for the 'low' score.

2.6.1.5.2.4 Selection of acceptance threshold for uncertainty analysis

The acceptance threshold ideally is independently defined based on an analysis of the system (see companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016)). For the surface water hydrological response variables such an independent threshold definition can be based on the observation uncertainty, which depends on an analysis of the rating curves for each observation gauging station as well as at the model nodes. There is limited rating curve data available, hence the 'medium' score. Even if this information were to be available the operational constraints within the bioregional assessment prevents such a detailed analysis, although it is technically feasible. The resources column therefore receives a 'high' score while the technical column receives a 'low' score.

The choice of setting the acceptance threshold equal to the 75th percentile of the summary statistic for a particular hydrological response variable is a subjective decision made by the Assessment team. It does ensure, however, that the parameter combinations accepted in the posterior parameter distribution match the observed hydrological response variables at least as well as the top 25% of the design of experiment runs. By varying this threshold through a trial-and-error procedure in the testing phase of the uncertainty analysis methodology, the modelling team learned that this threshold is an acceptable trade-off between overfitting the observation and constraining the priors. While relaxing the threshold will lead to larger uncertainty intervals for the predictions, the median predicted values are considered robust to this change. A formal test of this hypothesis has not yet been carried out. The effect on predictions is therefore scored 'medium'.

2.6.1.5.2.5 Interaction with the groundwater model

The coupling between the results of the groundwater models and the surface water model, described in the model sequence section (Section 2.6.1.1), represents a pragmatic solution to account for surface water – groundwater interactions at a regional scale. Like the majority of rainfall-runoff models, the current version of AWRA-L does not allow an integrated exchange of groundwater-related fluxes during runtime. Even if this capability were available, the differences in spatial and temporal resolution would require non-trivial upscaling and downscaling processes of spatio-temporal distributions of fluxes. The choice of the coupling methodology is therefore mostly a technical choice, hence the 'high' score for this attribute. The data and resources columns are scored 'medium' as even when it is technically possible to couple both models in an integrated fashion, the implementation would be constrained by the available data and the operational constraints. This warrants the 'medium' score for both resources and data.

The integration of a change in baseflow from the groundwater model into AWRA-L does mean that the overall water balance is no longer closed in AWRA-L. This method of coupling both models is therefore only valid if the exchange flux is small compared to the other components of the water balance. The exchange flux (see companion product 2.5 for the Clarence-Moreton bioregion (Cui et al., 2016)) shows that for the Richmond river basin the change in baseflow under baseline and under the CRDP is much smaller than the other components of the surface water balance, and hence the overall effect on the predictions is assumed to be small. The effect on predictions is scored 'medium' as a change in hydrology is only possible via a change in the surface water – groundwater interaction.

2.6.1.5.2.6 No streamflow routing

Streamflow routing is not taken into account in the Richmond river basin as the surface water storages are relatively small (see companion product 1.5 for the Clarence-Moreton bioregion (Rassam et al., 2014)). Thus, the effects of regulation on the system are sufficiently small that lags in streamflow due to routing do not need to be taken into account. The effect of not incorporating routing is expected to be minimal on the prediction. Seeing the small potential for impact, resourcing the development of a river routing model for this region was not warranted.

Only the data column is scored 'medium' as there is limited information on dams in the bioregion. All other attributes are scored 'low' as it is technically feasible and within the operational constraints of the bioregional assessments to carry out streamflow routing. Doing so would only minimally affect the predictions, hence the 'low' score.

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2.6.1.6 Prediction

Summary

This section presents the predictive posterior distribution for each hydrological response variable. To guide the interpretation of the results, Table 7 summarises the location and catchment area of each model node.

As described in the uncertainty analysis (refer to Section 2.6.1.5), the maximum raw change (*amax*), maximum percent change (*pmax*) and year of maximum change (*tmax*) reported here are for the hydrological response variables for streamflow: annual flow (AF), interquartile range (IQR), daily streamflow at the 99th percentile (P99), number of flood (high-flow) days (FD), number of low-flow days (LFD), number of low-flow spells (LFS), longest low-flow spell (LLFS) and zero-flow days (ZFD).

The change in surface hydrology predicted due to the additional coal resource development in absolute terms is predicted to have a median decrease of less than 0.01 GL/y, which corresponds to a change of about 0.01%. These changes are several orders of magnitude smaller than the observed mean streamflow (Table 26, Section 2.1.4.1 of companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016)). Their effect on mean and high-streamflow hydrological response variables will therefore be minimal. Even the effect on low-streamflow hydrological response variables will be very small, especially in the perennial streams.

The maximum change in surface water – groundwater flux simulated by the groundwater model is several orders of magnitude less than the observed or simulated historical streamflow. The simulated increases in low-flow metrics are considered to be an erroneous overestimate due to artefacts in the simulation of low flow and the definition of the hydrological response variables. Accurately measuring and simulating low-flow conditions is very challenging and requires further efforts.

This section presents the predictive posterior distribution for each hydrological response variable. To guide the interpretation of the results, Table 7 summarises the location and catchment area of each model node, which are also shown in Figure 5 in Section 2.6.1.3.1. In Table 7 and the figures in this section, the model nodes are grouped per catchment and ordered from upstream to downstream.

Table 7 Summary of model nodes with their upstream contribution area

Model node	Easting	Northing	River	Area (km^2)
CLM_011	489500	6855400	Findon Creek at Terrace Creek	136
CLM_009	496657	6846680	Richmond River at Wiangaree	712
CLM_014	499528	6833860	Richmond River at Kyogle	903
CLM_001	497683	6814311	Richmond River above Eden confluence	1071
CLM_010	480200	6833566	Ironpot Creek at Toonumbar	97
CLM_013	490300	6829100	Ironpot Creek at Ettrick	185
CLM_012	492425	6818675	Eden Creek at Doubtful	582
CLM_002	497684	6813757	Eden Creek above Richmond confluence	696
CLM_003	499147	6808771	Richmond River downstream of West Casino Gas Project	1816
CLM_008	505285	6806928	Richmond River at Casino	1874
CLM_004	497685	6799908	Shannon Brook at Middle Creek confluence	241
CLM_005	497685	6799354	Middle Creek at Shannon Brook confluence	214
CLM_007	506213	6798245	Shannon Brook at Yorklea	498
CLM_006	514499	6800453	Shannon Brook at tidal limit	543
CLM_015	516017	6821200	Leycester Creek at Rock Valley	178
CLM_016	499946	6779831	Myrtle Creek at Rappville	392

Data: NSW Office of Water (Dataset 1)

The streamflow in the prediction catchments is only likely to change due to coal resource development in this bioregion via a change in the surface water – groundwater flux. As described in the uncertainty section (refer to Section 2.6.1.5), the maximum raw change (*amax*), maximum percent change (*pmax*) and year of maximum change (*tmax*) reported here are for hydrological response variables for streamflow: annual flow (AF), interquartile range (IQR), daily streamflow at the 99th percentile (P99), daily streamflow at the 1st percentile (P01), number of flood (high-flow) days (FD), number of low-flow days (LFD), number of low-flow spells (LFS), the longest low-flow spell (LLFS) and number of zero-flow days (ZFD). Zero streamflow is identified using the minimum detectable flow. For ease of applicability, a threshold of 0.01 ML/day is set for determining the number of ZFD for all surface water nodes (see companion submethodology M06 for surface water modelling (Viney, 2016)).

It is important to reiterate that both the calibration and uncertainty analysis indicate that the Australian Water Resources Assessment landscape model (AWRA-L) predictive capability is adequate for high-flow aspects of the hydrograph, while the predictive capability is not as good for low-flow metrics in the Clarence-Moreton bioregion. In addition to this, such low changes in flow are extremely hard to observe as the largest uncertainties in the rating curves used to transfer measured stage heights to flows are associated with low-flow measurements (Tomkins, 2014).

2.6.1.6.1 Annual flow (AF)

Figure 10 shows very small declines in AF, with median changes not in excess of 0.01 GL/y. The largest predicted range of change is at model nodes CLM_003 and CLM_008, which are the main channel of the Richmond River itself. The 95th percentile of change in AF does not exceed 0.1 GL/y. In percentage terms, the 95th percentile of reduction in AF is less than 0.1% for all nodes. For the nodes where the median absolute change in AF is not zero, the median of the year of maximum change is between 2055 and 2065.

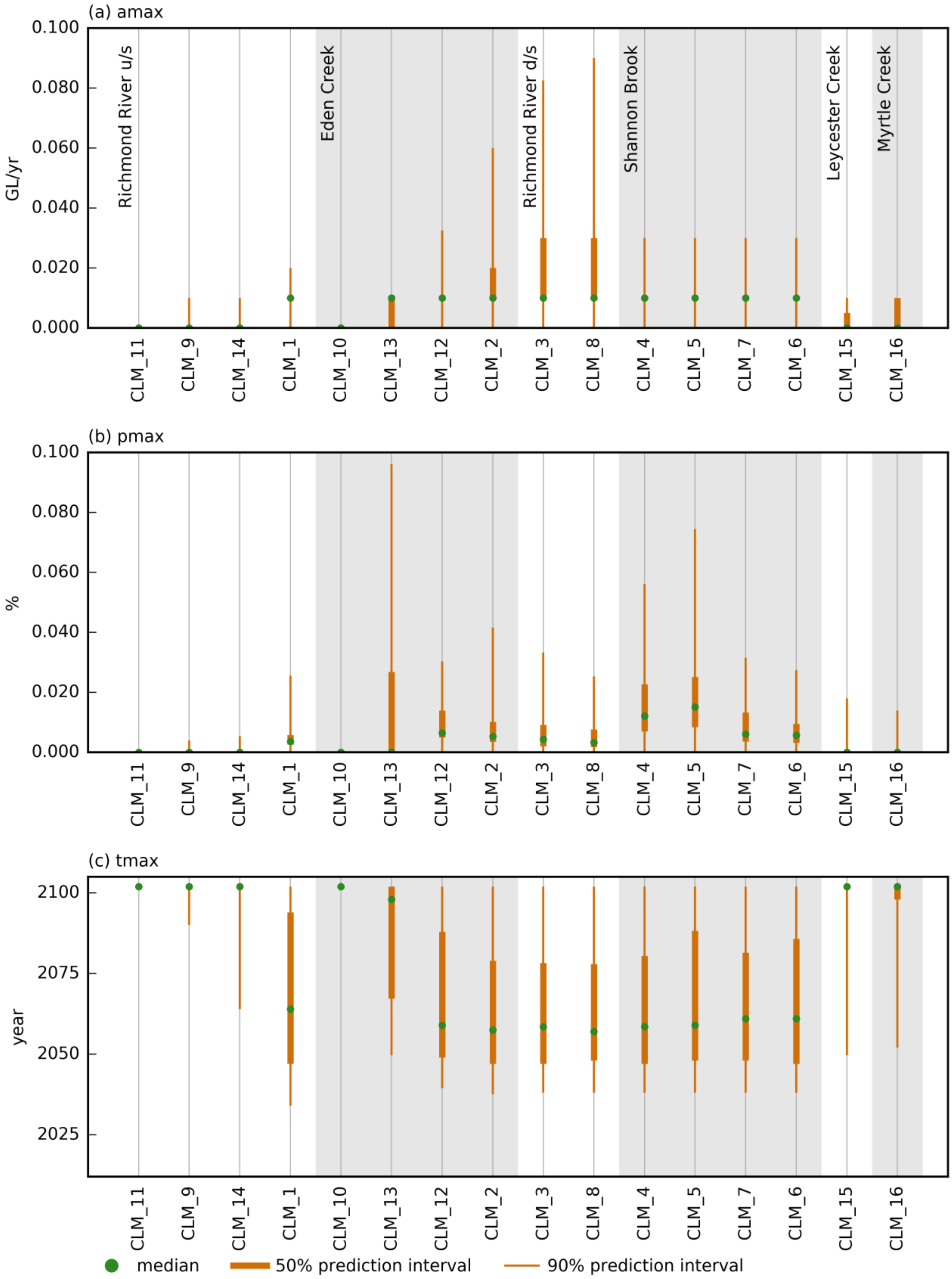

Figure 10 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for annual flow (AF)

d/s = downstream of; u/s = upstream of
The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.2 Interquartile range (IQR)

A pattern very similar to AF can be seen in Figure 11, showing very small reductions in interquartile flow, with median change values not exceeding 0.01 ML/day. Percentage changes are close to zero with the 95th percentile not exceeding 2%. The largest percentage change occurs in CLM_006, the most downstream node of Shannon Brook. Due to the comparable small contributing area of this catchment, a reduction of 0.01 ML/day is a relatively large change.

The maximum change in IQR occurs in the second half of the simulation period, with median values close to the end of the simulation period.

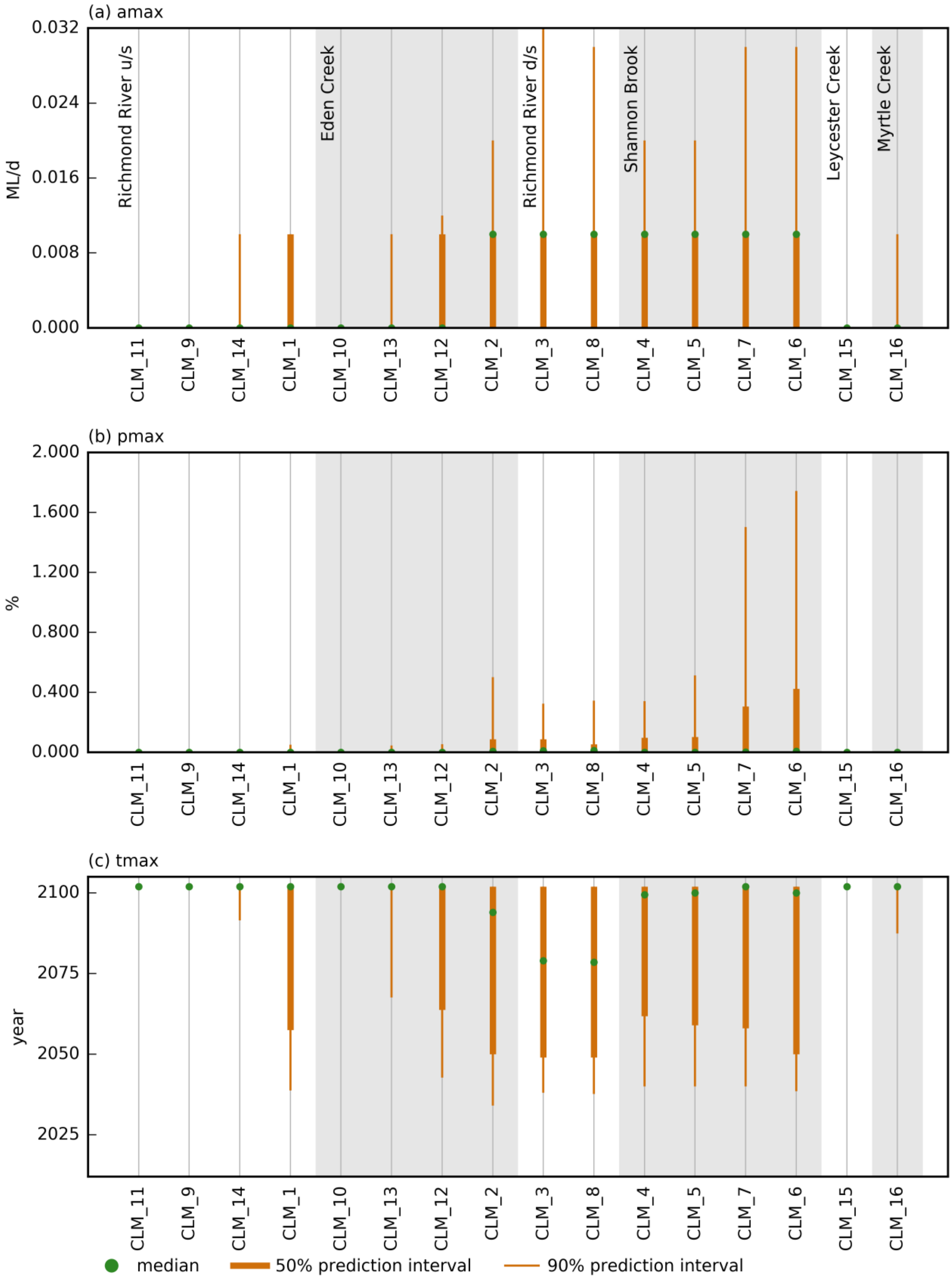

Figure 11 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for interquartile range (IQR)

d/s = downstream of; u/s = upstream of

The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.

Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.3 Daily streamflow at the 99th percentile (P99)

Figure 12 shows a small decrease in the P99 at all 16 model nodes. The 95th percentile of change in P99 does not exceed 0.35 ML/day. The median values of percentage change are all less than 0.001%. The median year of maximum change in the catchments with non-zero median absolute changes is close to 2050.

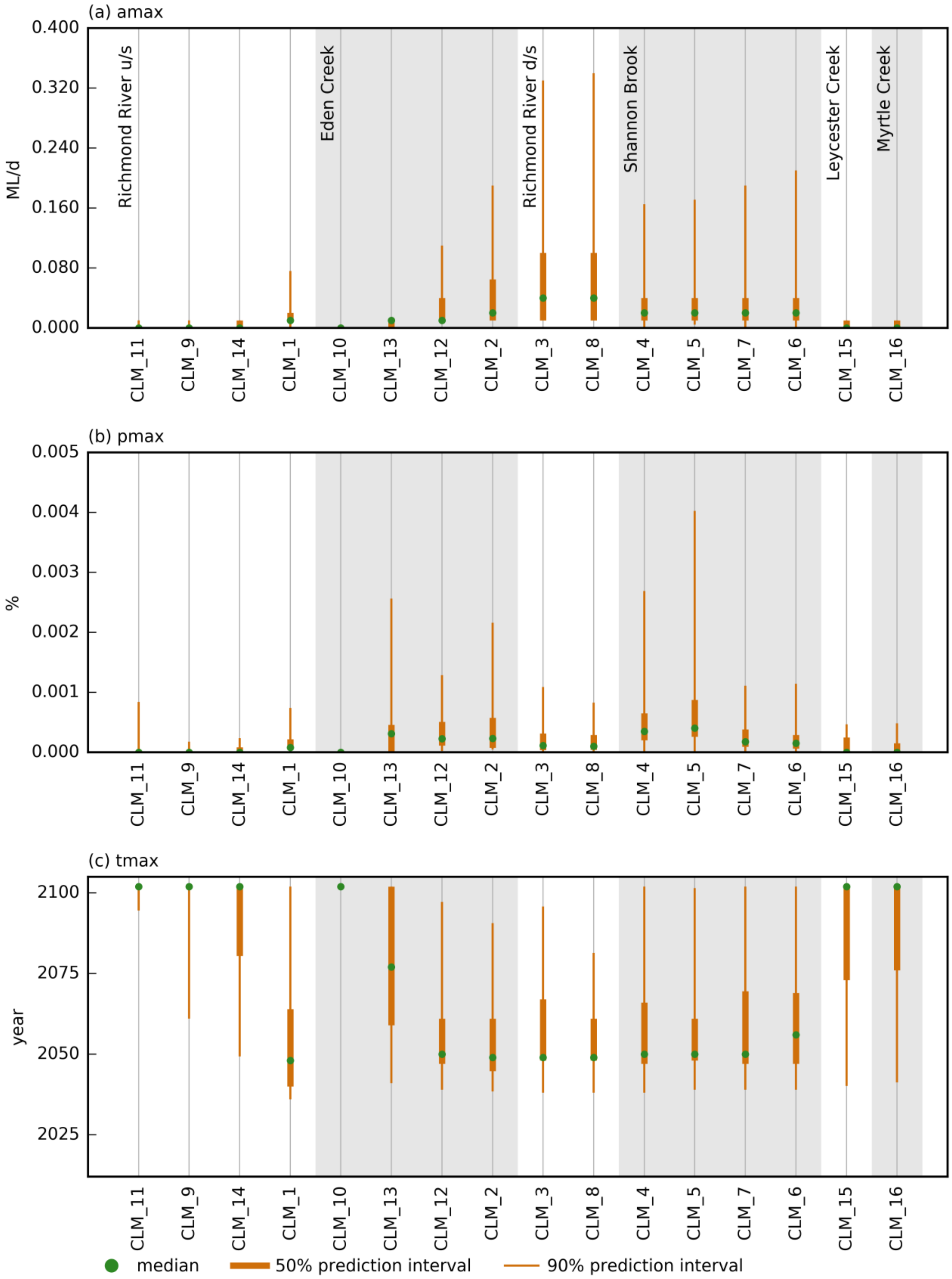

Figure 12 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for daily streamflow at the 99th percentile (P99)

d/s = downstream of; u/s = upstream of
The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.4 Flood (high-flow) days (FD)

There is almost no change in the number of days with flows above the long-term 90th percentile (Figure 13). The 95th percentile of absolute change is at most a reduction of 1 day of high-flow conditions.

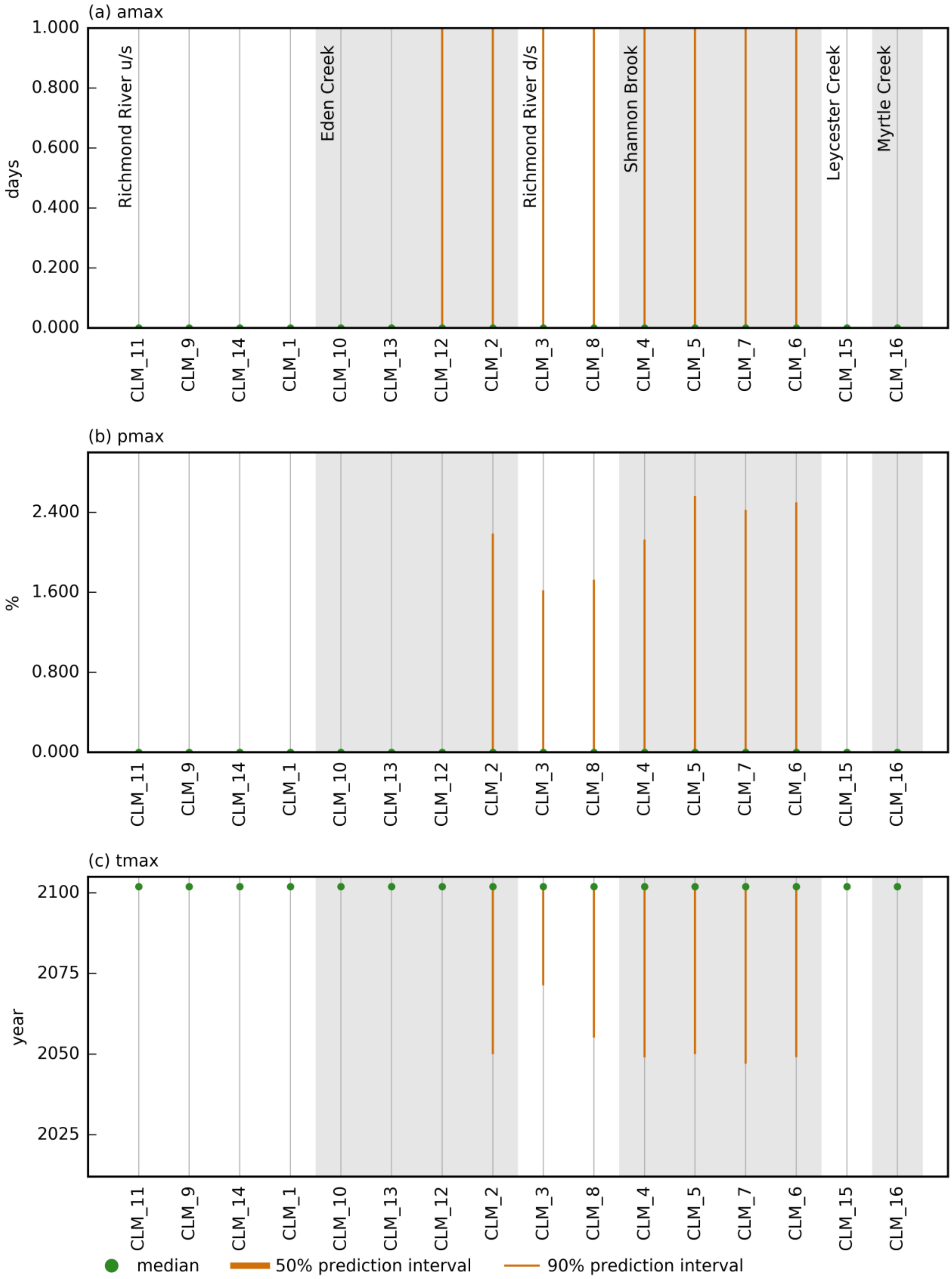

Figure 13 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of flood (high-flow) days (FD)

d/s = downstream of; u/s = upstream of
The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.5 Daily streamflow at the 1st percentile (P01)

Figure 14 indicates that the median change in P01 will be less than 0.02 ML/day. These changes are very close to the threshold of 0.01 ML/day, below which simulated flow is considered zero in the calculation of ZFD.

In CLM_003 and CLM_008, the section of the Richmond River downstream of the confluence with Eden Creek, the 95th percentile of change can be as high as 0.13 ML/day. In the Richmond River and Shannon Brook, the relative change is up to 80% (95th percentile in CLM_008). The 90th percentile prediction intervals do however indicate that P01 will not decrease by 100% at any of the simulation nodes; that is, under coal resource development pathway (CRDP) conditions P01 will be non-zero at all simulation nodes.

The maximum changes in low flow are simulated to occur in the second half of the simulation period.

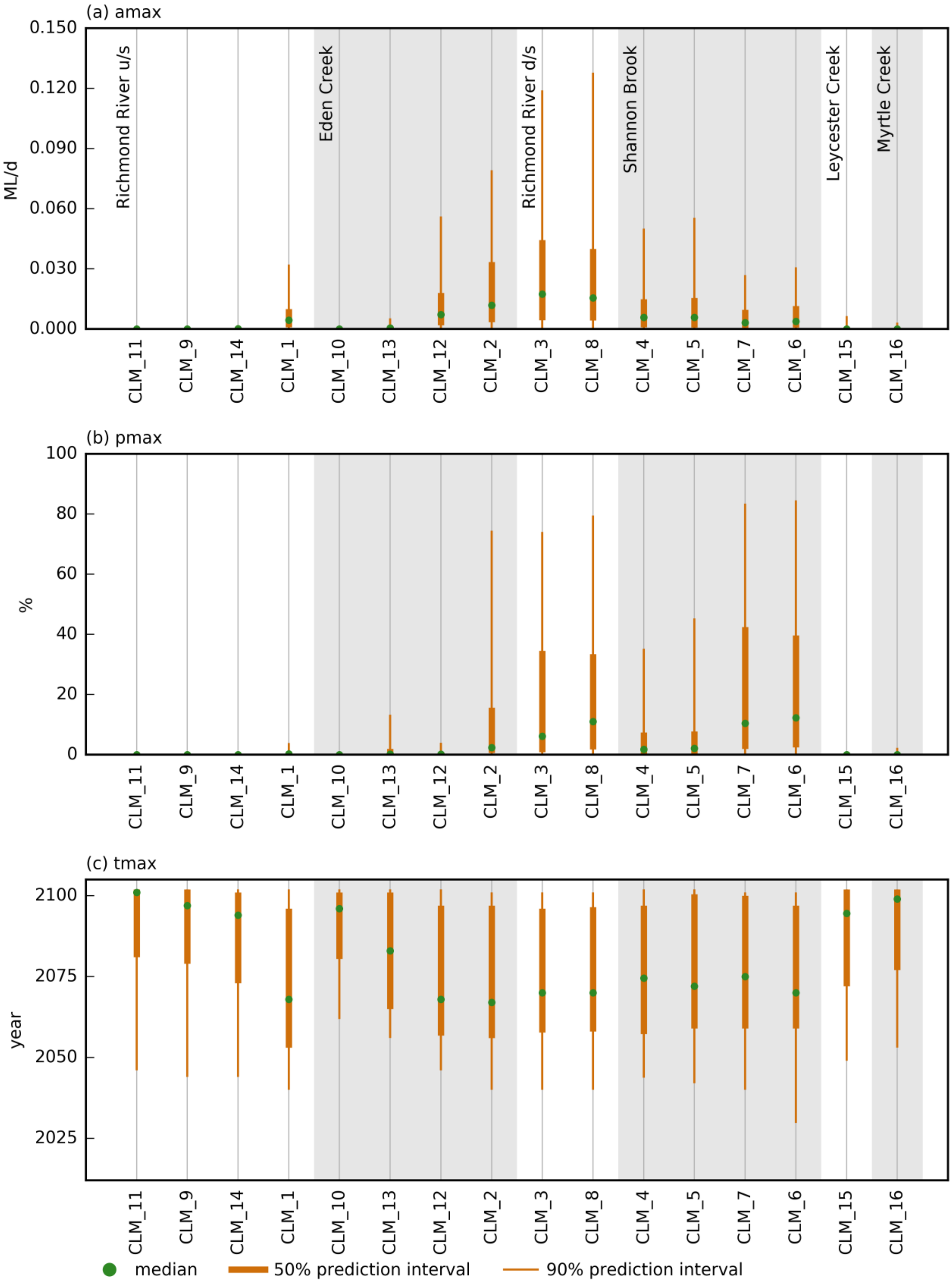

Figure 14 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for daily streamflow at the 1st percentile (P01)

d/s = downstream of; u/s = upstream of

The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.

Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.6 Low-flow days (LFD)

Figure 15 shows that the number of LFD (the number of days per year the flow is less than the long-term 10th percentile of flow) increases in several of the catchments that overlap the CRDP in its contribution area, and that the median increase is generally between zero and 20 days. This would de facto mean that low-flow conditions increase up to 3 weeks per year.

This relatively large change is partly an artefact of the way the hydrological response variable is defined. For days in the future with a streamflow that is equal to or slightly above the long-term 10th percentile of flow, a very small change in streamflow may often be sufficient to cause the daily flow event to be classified as a LFD. As it generally is very likely to have several days in succession with low flow, small changes in streamflow can cause large changes in LFD as formally defined in this hydrological response variable.

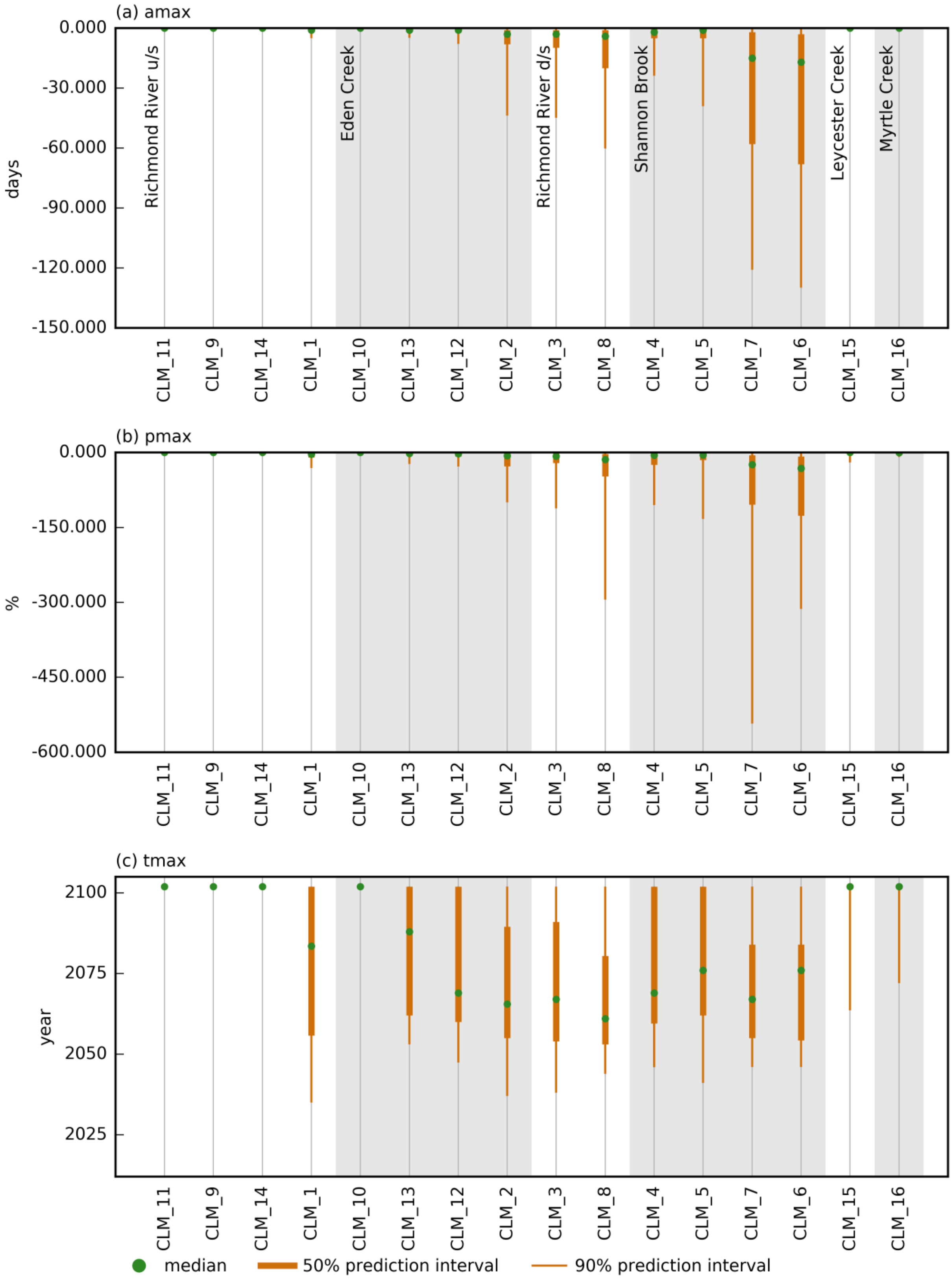

Figure 15 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of low-flow days (LFD)

d/s = downstream of; u/s = upstream of
The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.7 Low-flow spells (LFS)

The median change in the number of LFS in Figure 16 indicates that the number of LFS across the bioregion is simulated to increase by up to three events. In the smaller Shannon Brook catchment (CLM_004 to CLM_007) the 95th percentile indicates an increase of up to 16 LFS. In this catchment a small change in flow rate (less than 0.03 ML/day decrease in P01, Figure 14) can result in large changes in the number of LFD and LFS.

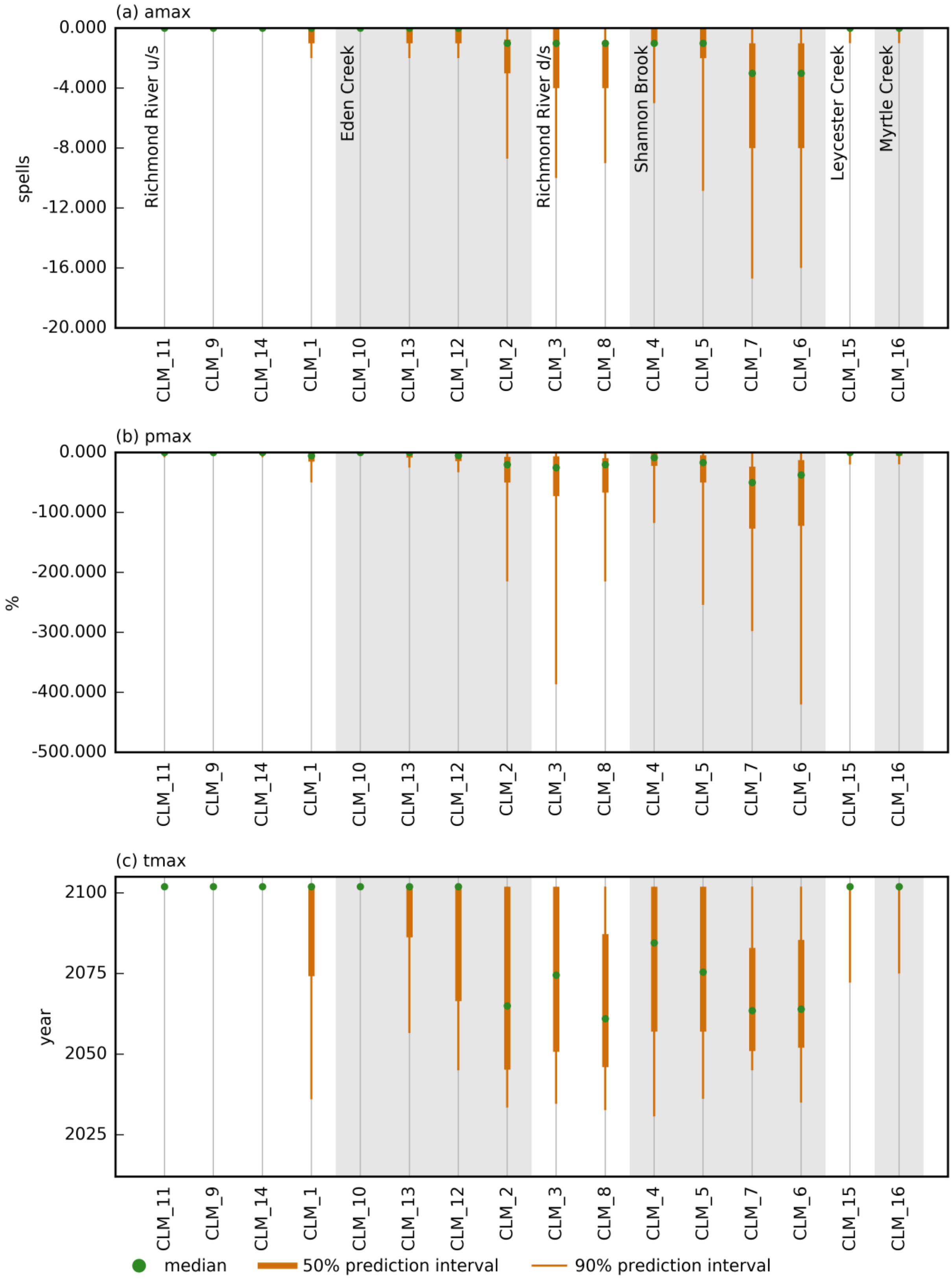

Figure 16 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of low-flow spells (LFS)

d/s = downstream of; u/s = upstream of
The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.8 Longest low-flow spell (LLFS)

The medians of absolute maximum change in Figure 17 indicate that the LLFS across the region is to increase by up to 8 days. As for the changes in LFS and LFD, this occurs at the downstream nodes of Shannon Brook.

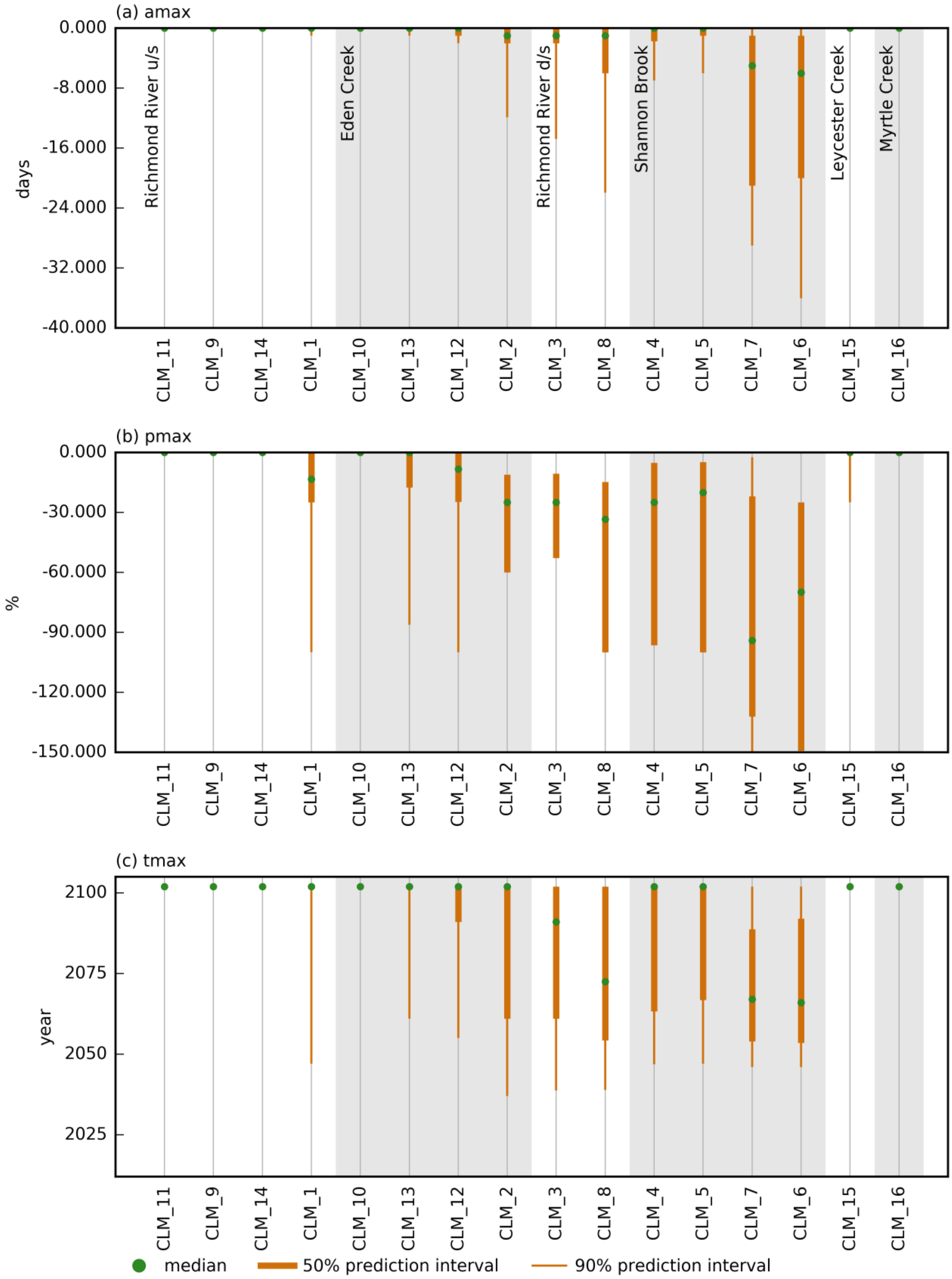

Figure 17 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of longest low-flow spells (LLFS)

d/s = downstream of; u/s = upstream of
The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.9 Zero-flow days (ZFD)

The median absolute change in Figure 18 indicates that the number of ZFD across the region will not increase, with the exception of nodes CLM_007 and CLM_006 at the downstream end of Shannon Brook where the median change in the number of ZFD is 3 days. The 95th percentile of change in ZFD is 120 days. As noted earlier, small changes in simulated flow can result in large changes in the number of ZFD, as ZFD are defined as days with streamflow less than 0.01 ML/day.

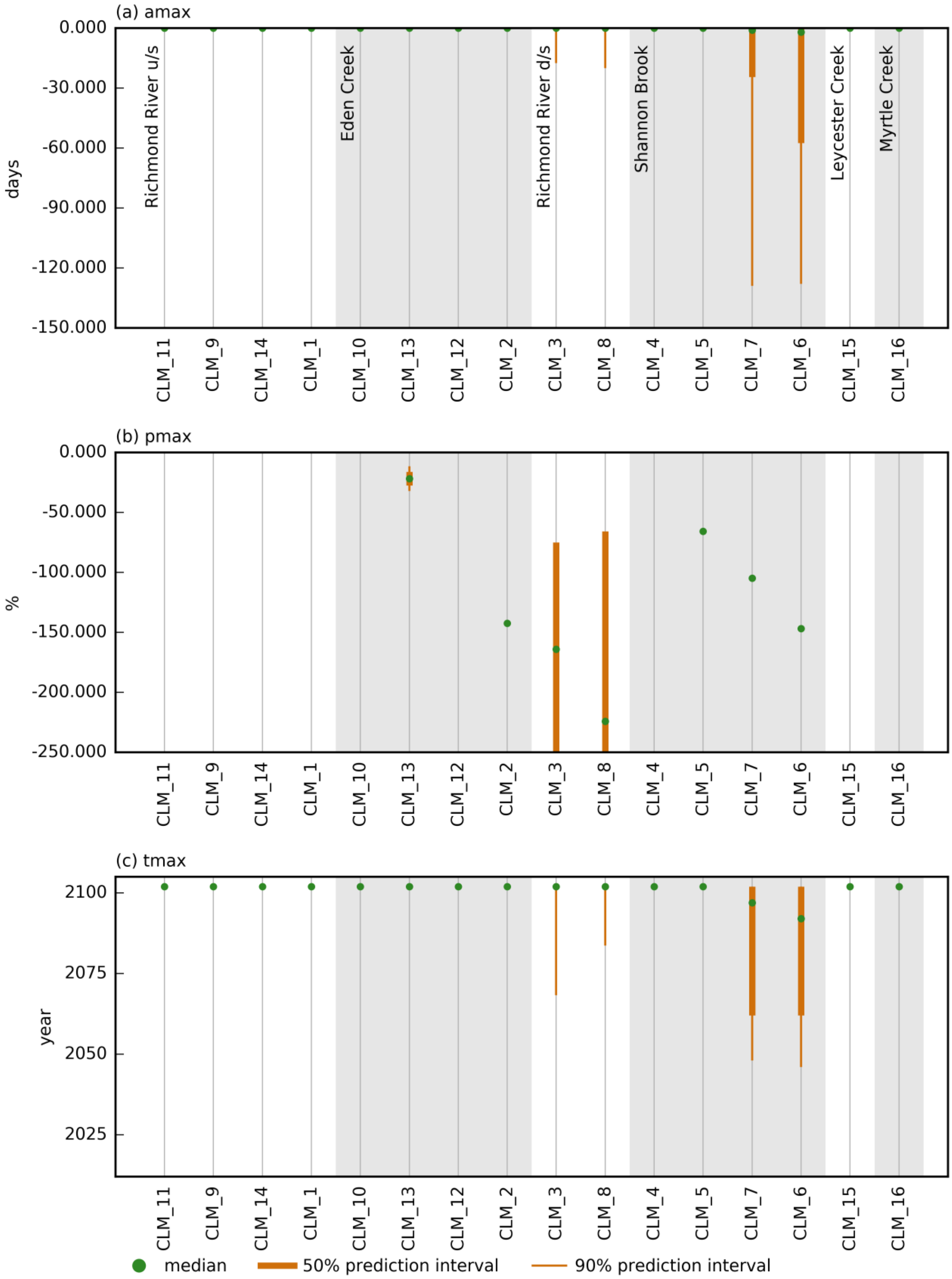

Figure 18 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of zero-flow days (ZFD)

d/s = downstream of; u/s = upstream of
The circle indicates the median of the posterior predictive distribution, the length of the thick vertical line spans the interquartile range (or 50th percentile prediction interval), and the thin vertical line spans the 90th percentile prediction interval. Nodes are grouped per catchment, ordered from upstream to downstream.
Data: Bioregional Assessment Programme (Dataset 2)

2.6.1.6.10 Summary and conclusions

The change in surface hydrology predicted due to the additional coal resource development in absolute terms is predicted to have a median decrease of less than 0.01 GL/y, which corresponds to a change of about 0.01%. These changes are several orders of magnitude smaller than the observed mean streamflow (Table 26, Section 2.1.4.1 of companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016)). Their effect on mean and high-flow hydrological response variables will therefore be minimal. Even the effect on low-flow hydrological response variables will be very small, especially in the perennial streams.

In addition to this, such low changes in flow are extremely hard to observe as the largest uncertainties in the rating curves used to transfer measured stage heights to flows are associated with low-flow measurements (Tomkins, 2014).

For some model nodes, notably CLM_003 and CLM_008, the 95th prediction interval of change in surface water – groundwater flux is of the same order of magnitude as the 1st percentile of historical observed or simulated flow.

The simulated increases in low-flow metrics are considered to be an erroneous overestimate due to artefacts in the simulation of low flow and the definition of the hydrological response variables. Accurately measuring and simulating low-flow conditions is very challenging and requires further efforts.

References

Raiber M, Cui T, Pagendam D, Rassam D, Gilfedder, M, Crosbie, R, Marvanek, S, and Hartcher, M (2016) Observations analysis, statistical analysis and interpolation for the Clarence-Moreton bioregion. Product 2.1-2.2 from the Clarence-Moreton Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/CLM/CLM/2.1-2.2.

Tomkins KM (2014) Uncertainty in streamflow rating curves: methods, controls and consequences Hydrological Processes 28, 464–481.

Viney N (2016) Surface water modelling. Submethodology M06 from the Bioregional Assessment Technical Programme. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/submethodology/M06.

Datasets

Dataset 1 NSW Office of Water (2015) CLM - Richmond river Gauging station summaries. Bioregional Assessment Source Dataset. Viewed 01 September 2016, http://data.bioregionalassessments.gov.au/dataset/9e435b5d-0702-4f5f-b29b-897db026ddf0.

Dataset 2 Bioregional Assessment Programme (2016) CLM AWRA HRVs Uncertainty Analysis. Bioregional Assessment Derived Dataset. Viewed 01 September 2016, http://data.bioregionalassessments.gov.au/dataset/e51a513d-fde7-44ba-830c-07563a7b2402.

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.

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

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.

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

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

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).

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

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

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

Geofabric: a nationally consistent series of interrelated spatial datasets defining hierarchically-nested river basins, stream segments, hydrological networks and associated cartography

groundwater system: see water system

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.

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).

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

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.

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

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

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

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

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

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

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

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

water 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.

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

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’.

www.bioregionalassessments.gov.au

Australian Government

Department of the Environment and Energy

Bureau of Meteorology

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