Australian Government

BIOREGIONAL ASSESSMENTS

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

Surface water numerical modelling for the Namoi subregion

Product 2.6.1 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment

2018

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

The Bioregional Assessment Programme

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

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

Department of the Environment and Energy

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.

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Authorship is listed in relative order of contribution.

Cover photograph

Gulligal Lagoon, which is located about halfway between Gunnedah and Boggabri on the western side of the Namoi River, NSW, 2005

Credit: Neal Foster

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Department of the Environment and Energy

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CSIRO

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Executive summary

Coal resource development can potentially affect water-dependent assets through impacts on surface water hydrology. This product presents the surface water modelling approach, assumptions that underpin the models and modelled hydrological changes in response to likely coal resource development in the Namoi subregion after December 2012.

To quantify impacts of coal resource development in the Namoi subregion, two potential futures are considered in a bioregional assessment (BA):

- *baseline coal resource development (baseline)*: a future that includes all coal mines and coal seam gas (CSG) fields that are in commercial production 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 in the Namoi subregion, including expansions of baseline operations, that are expected to begin commercial production after December 2012.

Baseline coal mines and additional coal resource development are defined in Section 2.3.4 of companion product 2.3 (conceptual modelling) for the Namoi subregion. The baseline includes six coal mines: five open-cut coal mines – Boggabri, Rocglen, Sunnyside, Tarrawonga and Werris Creek; and one underground longwall mine – Narrabri North. The ten additional coal resource developments include nine coal mines and one CSG development: Boggabri Coal Expansion Project, Caroona Coal Project, Gunnedah Precinct, Maules Creek Mine, Narrabri South, Tarrawonga Coal Expansion Project, Vickery Coal Project, Vickery South Coal Project, Watermark Coal Project and Narrabri Gas Project. Due to insufficient information regarding the location and depth of mining, two mines, Vickery South Coal Project (open-cut coal mine) and the Gunnedah Precinct (open-cut and underground), are not being modelled. Analysis of the potential impacts and risks of these two developments will be restricted to commentary in companion product 3-4 (impact and risk analysis).

Modelling of the Namoi subregion follows the companion submethodology M06 for surface water modelling. The key features of surface water modelling are as follows:

- The modelling domain includes all of the Namoi river basin including the Peel River.
- The modelling includes rainfall-runoff modelling using the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and river modelling using the AWRA river model (AWRA-R).
- Streamflow inputs are obtained from the output of the AWRA-L model for input into the AWRA-R model.

- Changes in baseflow due to the modelled coal resource developments from the Namoi subregion groundwater model as outlined in companion product 2.6.2 (groundwater numerical modelling) are also incorporated into the AWRA-R model along the river network.
- The mine footprint data are obtained from mine layout maps in environmental impact statements for respective mines in order to calculate effects of mine development on runoff.
- Daily streamflow predictions are produced at 54 model nodes for the simulation period from 2013 to 2102 using future climate input data.

Evaluation of the effects of the model assumptions on predictions shows that most assumptions are unlikely to have a significant effect on predictions. However, predictions are sensitive to the implementation of the CRDP – particularly in catchments where the mine footprint is a large fraction of the total catchment area. Predictions may also be affected by the criteria for choosing the most appropriate parameter combinations and representation of river regulation in the river model.

AWRA-L and AWRA-R are both regionally calibrated using two calibration schemes: one biased towards high streamflow, and another biased towards low streamflow. There are variations in the models' ability to predict certain hydrological response variables such as low-flow days, zero-flow days and low-flow spells. The AWRA-R model captures relevant aspects of river management (including water resources assessment and allocations, dam storage volumes and dam releases). Recharge and other output from AWRA-R are used in the groundwater model and changes in the baseflow predicted by the groundwater model are then used to rerun AWRA-R.

The prediction results show that additional coal resource development in the Namoi subregion can cause significant changes across the flow regime. This is particularly evident for the hydrological response variables that characterise high-streamflow conditions at model nodes where the footprint forms a large proportion of the catchment.

In general, the hydrological changes attributable to the additional coal resource development are greater in the small tributaries of the Namoi River than in the model nodes along the river itself. The biggest hydrological changes (flow reductions of up to 23%) occur in the Namoi River tributaries Merrygowen Creek (downstream of the Boggabri and Tarrawonga mines) and Back Creek (downstream of the Maules Creek Mine), and in the Mooki River tributary Watermark Creek (which is affected by the Watermark Coal Project). There is no direct effect of the coal seam gas developments on surface water as the amount of water the Narrabri Gas Project proposed to release to the surface water courses is minimal at the regional scale.

The percentage changes due to additional coal resource development in the low-streamflow hydrological response variables are greater than those in the high-streamflow hydrological response variables. This especially applies to the streams with near-zero or very small baseline low-flow (e.g. for Back, Merrygowen and Bollol creeks). This is because changes to low-streamflow characteristics are caused by a combination of the instantaneous impact of interception from the additional mine footprints and the cumulative impact on baseflow over time caused by groundwater drawdown, while the changes to high-streamflow characteristics are dominated by direct interception of runoff. It is expected that there is considerable uncertainty in predicting baseflow changes due to the scale of groundwater modelling, lack of finer scale processes in riparian zones and difficulty in modelling low streamflows. As a result, the uncertainty in changes in the predicted low-streamflow hydrological response variables is also greater than that in the high-streamflow hydrological response variables.

Overall, large potential hydrological changes due to coal resource development are in catchments that are close to the developments themselves and this effect propagates to downstream locations, where the relative impact (a % of streamflow) becomes smaller because of dilution from downstream tributaries. These modelling results are used to define a zone of potential hydrological change for surface water in the Namoi subregion. The zone is used to 'rule out' potential impacts on landscape classes and water-dependent assets within the Namoi assessment extent. This zone includes locations where the projected change in at least one of the nine hydrological response variables has a 5% chance or greater of exceeding a specified threshold. The resulting zone of potential hydrological change for surface water includes those parts of the Namoi River and its tributaries downstream of, and including, the Mooki River in the east. Baradine Creek and the uppermost nodes of Bohena Creek and the Mooki River are outside the zone of potential hydrological change.

The surface water numerical modelling described in this product should be considered in conjunction with the groundwater numerical modelling (product 2.6.2). Together they provide key inputs to receptor impact modelling (product 2.7) and underpin the analysis of impacts on, and risks to, landscape classes and assets in product 3-4 (impact and risk analysis).

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This technical product was reviewed by several groups:

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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.

Currency of scientific results

The modelling results contained in this product were completed in November 2016 using the best available data, models and approaches available at that time. The product content was completed in February 2018.

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

Introduction

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

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

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

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

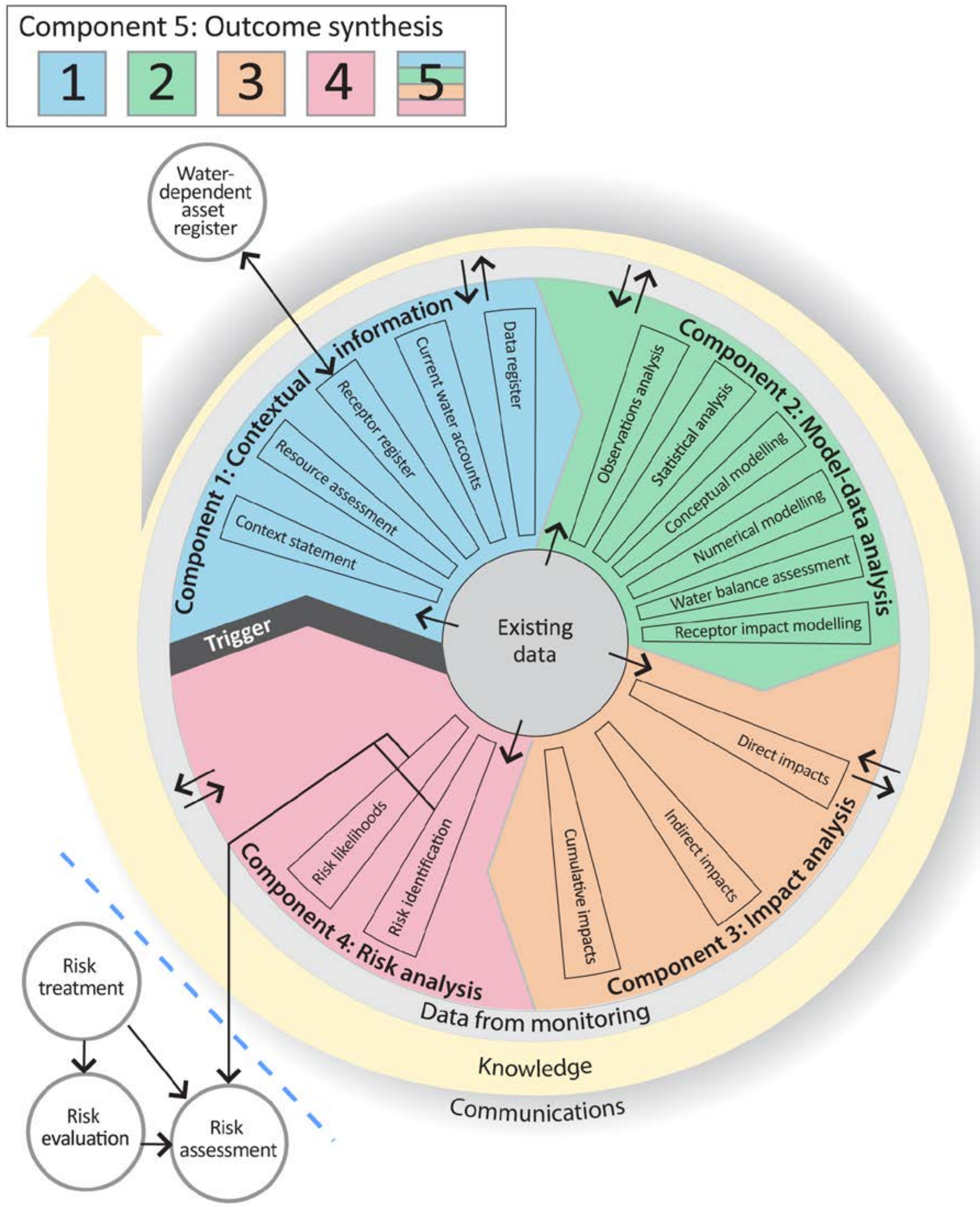

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

The overall scientific and intellectual basis of the BAs is provided in the BA methodology (Barrett et al., 2013). Additional guidance is required, however, about how to apply the BA methodology to a range of subregions and bioregions. To this end, the teams undertaking the BAs have developed and documented detailed scientific submethodologies (Table 1), in the first instance, to support the consistency of their work across the BAs and, secondly, to open the approach to scrutiny, criticism and improvement through review and publication. In some instances, methodologies applied in a particular BA may differ from what is documented in the submethodologies.

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

Table 1 Methodologies

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

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

Technical products

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

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

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

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

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

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

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

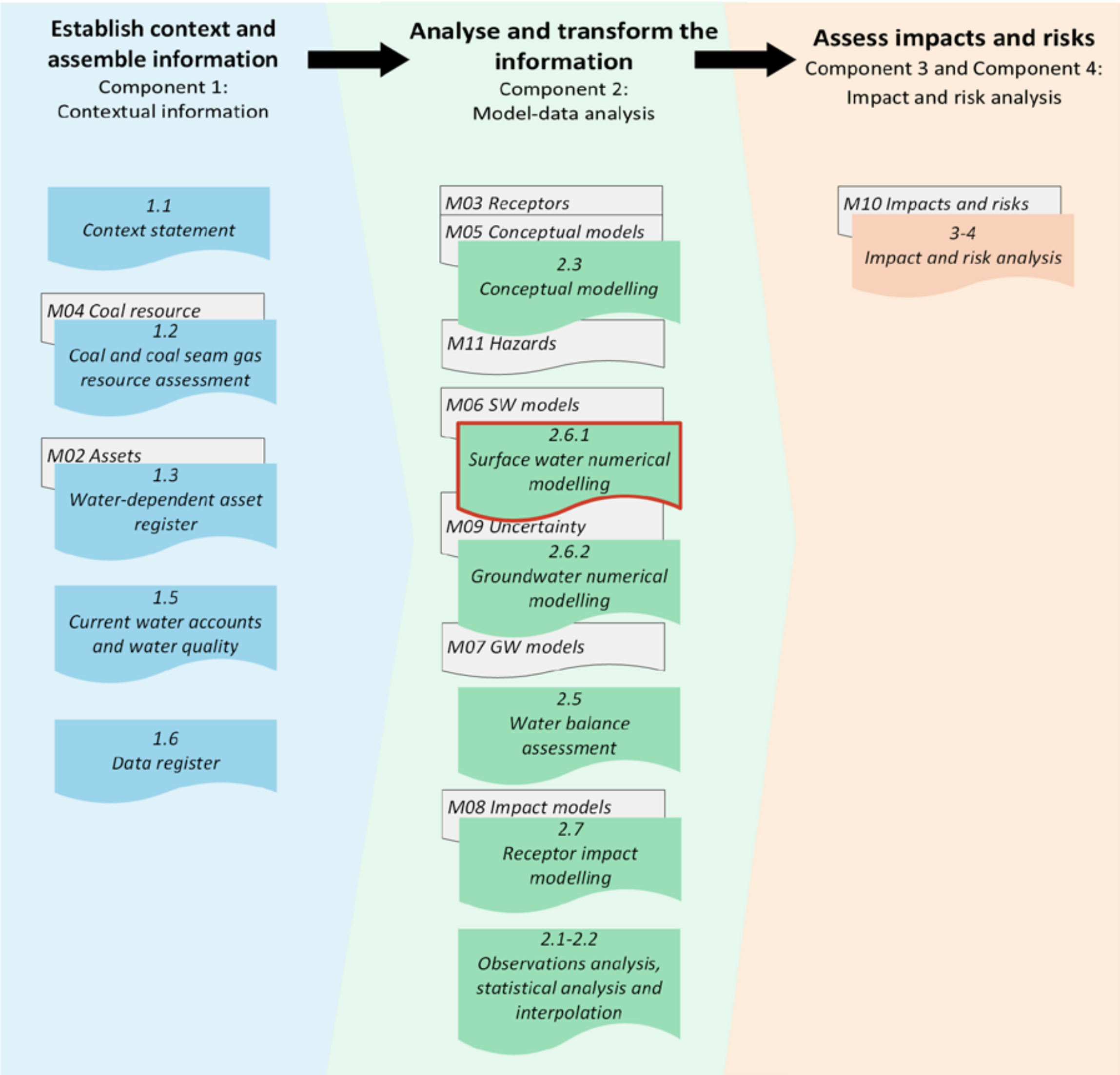

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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

Table 2 Technical products delivered for the Namoi subregion

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

Component	Product code	Title	Section in the BA methodology[b]	Type[a]
Component 1: Contextual information for the Namoi subregion	1.1	Context statement	2.5.1.1, 3.2	PDF, HTML
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3	PDF, HTML
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4	PDF, HTML, register
	1.5	Current water accounts and water quality	2.5.1.5	PDF, HTML
	1.6	Data register	2.5.1.6	Register
Component 2: Model-data analysis for the Namoi subregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2	PDF, HTML
	2.3	Conceptual modelling	2.5.2.3, 4.3	PDF, HTML
	2.5	Water balance assessment	2.5.2.4	PDF, HTML
	2.6.1	Surface water numerical modelling	4.4	PDF, HTML
	2.6.2	Groundwater numerical modelling	4.4	PDF, HTML
	2.7	Receptor impact modelling	2.5.2.6, 4.5	PDF, HTML
Component 3 and Component 4: Impact and risk analysis for the Namoi subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Namoi subregion	5	Outcome synthesis	2.5.5	PDF, HTML

[a]The types of products are as follows:

- 'PDF' indicates a PDF document that is developed by the Northern Inland Catchments Bioregional Assessment using the structure, standards and format specified by the Programme.
- 'HTML' indicates the same content as in the PDF document, but delivered as webpages.
- 'Register' indicates controlled lists that are delivered using a variety of formats as appropriate.

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

About this technical product

The following notes are relevant only for this technical product.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Northern Inland Catchments bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://www.bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived Datasets, the created date is used.

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 26 June 2018, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 26 June 2018, 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 Namoi subregion

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

First, the methods are summarised and existing models reviewed, followed by details regarding the development and calibration of the model. The product concludes with predictions of hydrological response variables, including uncertainty.

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). Product 3-4 (impact and risk analysis) then reports impacts on landscape classes and water-dependent assets arising from these hydrological changes.

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

2.6.1.1 Methods

Summary

A generic methodology for surface water numerical modelling in the Bioregional Assessment Programme appears in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). This section describes the departures from that generic methodology that have been applied in the Namoi subregion.

Surface water modelling of the Namoi subregion includes landscape water balance modelling and river modelling. Streamflow inputs are obtained by accumulating output from the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) for input into the AWRA river model (AWRA-R). Baseflow contributions from the Namoi subregion groundwater model are also fed into the AWRA-R model at points along the river network. Thus, the river model integrates the impacts of mining development on groundwater and surface water systems.

2.6.1.1.1 Background and context

The surface water numerical modelling in bioregional assessments (BAs) has a specific objective: to probabilistically evaluate potential hydrological change caused by the coal resource development pathway (CRDP) relative to the baseline at specified locations in the subregion. Outputs from the surface water modelling are used to inform both the impact and risk analysis (reported in product 3-4) and receptor impact modelling (product 2.7) to facilitate evaluation of the cumulative impacts of coal resource development on water-dependent assets (including ecological, economic and sociocultural assets).

To evaluate these impacts probabilistically large ensembles of predictions are generated using a range of model parameter sets. The range of parameters reflects the natural variability of the system thus covering uncertainty in the understanding of the system. During the uncertainty analysis, these parameter combinations are filtered in such a way that only those that are consistent with the available observations and the understanding of the system are used to generate the ensemble of predictions. The details are documented in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016).

It is not possible to capture all uncertainty of the understanding of the system in the parameterisation of the numerical models, so it is inevitable that there will be a number of assumptions. These assumptions are introduced and briefly discussed in Section 2.6.1.3 on model development. The uncertainty analysis in Section 2.6.1.5 further provides a systematic and comprehensive discussion of these assumptions. This discussion focuses on the rationale behind the assumptions and the effect on the predictions. The latter is crucial in justifying assumptions.

2.6.1.1.2 Surface water numerical modelling

Surface water modelling in the Namoi subregion is achieved using a combination of rainfall-runoff modelling and river system modelling. The rainfall-runoff model is the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) (Viney et al., 2015). This model is applied using the regional calibration scheme described in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). The choice of the AWRA set of models is also described in M06.

The simulation of river management or routing of streamflow through the river network with a river model is necessary as the river system has large stream stretches and regulation relating to reservoir operation and consumptive use such as irrigation demand (see companion submethodology M06 for surface water modelling (Viney, 2016)). Therefore, a routing model, the AWRA river model (AWRA-R, Dutta et al., 2015) is used to model surface water resources in the Namoi subregion.

2.6.1.1.3 Model sequencing

For the numerical simulation of the hydrological changes due to additional coal resource development on the identified model nodes, a model or model sequence is needed that can simulate the impact on the regional groundwater system, the alluvial groundwater system and the stream network. Developing a single, coupled and integrated surface water and groundwater model is beyond the operational constraints and data available in this assessment. Therefore, for the surface water modelling of the Namoi subregion, a loosely coupled model sequence of three models was developed, consisting of a groundwater model MODFLOW-USG (see companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)) to simulate the resource development induced changes on the groundwater systems, and a rainfall-runoff model and a river routing and management model to simulate those changes on the surface water systems of the subregion.

Figure 3 shows in more detail the sequencing of the different models. The modelling is focused on the change in surface water statistics as a result of additional coal resource development, rather than on predicting future surface water flow under a given development pathway. The calibrated AWRA-L and AWRA-R models are used to determine the AWRA-L baseline and CRDP responses, respectively (see Section 2.6.1.3 on model development for further details). The AWRA-R baseline and CRDP simulations are run using the results of the AWRA-L baseline and CRDP, respectively. The AWRA-R baseline run simulates streamflow at surface water model nodes incorporating the effects of commercially producing (as of 2012) open-cut coal mines. The AWRA-R CRDP run simulates streamflow at the surface water model nodes incorporating the effect of baseline coal mines plus the identified additional coal resource development.

Results of AWRA-R baseline are modified by the changes in baseflow caused by baseline coal mines in the groundwater model, whilst the results of AWRA-R CRDP are modified by the changes in baseflow by CRDP mines. The baseline and CRDP surface runoff results are used to calculate a number of hydrological response variables for both the baseline and CRDP. The change in hydrological response variables between the baseline and CRDP (due to the additional coal resource development) will inform where the receptor impact modelling is necessary for the surface water model nodes. A description of the surface water hydrological response variables (see Table 8) is provided in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

The technical detail of the conceptualisation, parameterisation and implementation, together with the uncertainty analysis of the simulated impacts, are documented in this product for the AWRA-L and AWRA-R models. Companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018) describes the groundwater modelling methods.

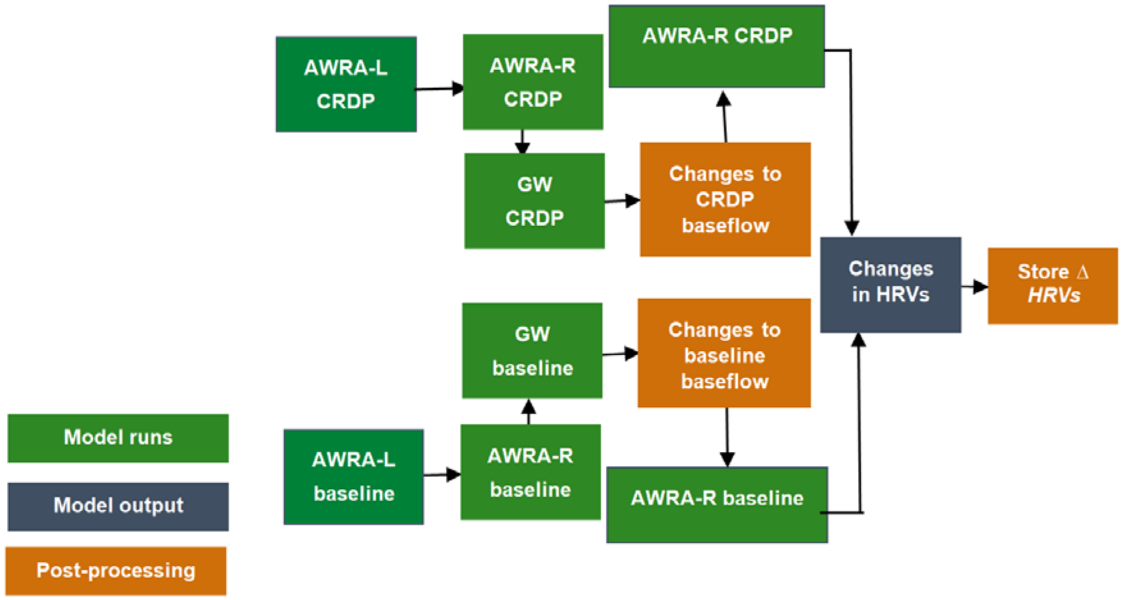

Figure 3 Model sequence for the Namoi subregion

GW is the groundwater model as described in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018). AWRA-L = Australian Water Resources Assessment landscape model; AWRA-R = AWRA river model; baseline = baseline coal resource development; CRDP = coal resource development pathway (the coal resource developments in the CRDP equal those in the baseline plus additional coal resource development); HRV = hydrological response variable; store Δ HRVs = storing of the changes in hydrological response variables

2.6.1.1.4 Integration with uncertainty analysis workflow

Companion submethodology M09 (Peeters et al., 2016) discusses in detail the propagation of uncertainty through the numerical models in the BAs. The uncertainty analysis is carried out to provide an ensemble of the predicted maximum absolute and relative change and time to this change of each hydrological response variable at each model node.

To generate these ensembles, 3000 parameter combinations of the combined groundwater and surface water model are evaluated. For each hydrological response variable, only those parameter combinations for which the goodness of fit between observed annual hydrological response variables and their simulated equivalent meet a predefined threshold are accepted in the posterior ensemble of parameter combinations. In the case of Namoi, a pragmatic choice is made to set the acceptance threshold to the 90th percentile of goodness of fit for model evaluations. The ensemble of predictions for each hydrological response variable is thus based on the top 10% (i.e. 300) of parameter combinations for that hydrological response variable to allow robust estimates of the 5th, 50th and 95th percentiles of the prediction ensemble. Tests of this assumption suggest that this number is large enough to estimate the 5th, 50th and 95th percentiles robustly. The reasons for and implications of this assumption are discussed in Section 2.6.1.5.

Except for the number of model replicates, in all other respects, the surface water modelling in the Namoi subregion follows the methodology set out in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

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2.6.1.2 Review of existing models

Summary

This section presents a review of previous surface water models used in the Namoi river basin. Five modelling studies within the Namoi river basin were identified. Except for the Schlumberger Namoi Catchment Water Study, none of these studies includes the impacts of coal resource development in its modelling. Predicted differences in average streamflow between two modelling scenarios that are similar to the baseline and coal resource development pathway (CRDP) futures in the bioregional assessment (BA) are no more than 0.2% at key locations along the Mooki and Namoi rivers. All of the previously used surface water models are unsuitable for use in the BA for various reasons.

2.6.1.2.1 Review of surface water models used in the Namoi subregion

This section presents a review of surface water models previously used in the Namoi river basin and discusses the relevance of those to the surface water modelling undertaken for the BA for the Namoi subregion.

Table 3 lists the five surface water modelling studies carried out in the Namoi river basin using four different models. The Namoi subregion, which forms part of the Namoi river basin, is included in all of these studies.

Table 3 Surface water models previously used in the Namoi river basin

Study	Model used	Reference
Murray-Darling Basin Sustainable Yields	SIMHYD, IQQM	CSIRO (2007)
Namoi Catchment Water Study	LASCAM	Schlumberger (2012)
Namoi river basin modelling	IHACRES	Croke et al. (2006)
NSW surface water modelling for water sharing and management	IQQM (Sacramento)	NSW Department of Water and Energy (2008)
Murray–Darling Basin Plan	Namoi IQQM	MDBA (2012)

Table 4 gives a summary of surface water modelling studies within the Namoi river basin. The right to publish the modelling data (as required in the Bioregional Assessment Programme) from these studies is either unavailable or uncertain in all except those from the Namoi Catchment Water Study and CSIRO’s Murray-Darling Basin Sustainable Yields Project. Except for the Namoi Catchment Water Study, none of the earlier studies assesses the impacts of coal resource development. Consequently, only the LASCAM model used in the Namoi Catchment Water Study is further reviewed in this section.

Table 4 Summary of Namoi surface water modelling studies and suitability of their use in the bioregional assessment

Study	Domain covered?	Coal resource development assessed?	Modelled streamflow data available?	Data publication right?*	Simulation time span (years)	Location density of flow nodes (model nodes)	River system modelling?	Use of climate trend
Murray-Darling Basin Sustainable Yields	Yes	No	Yes	Yes	112 (from 2007)	5 x 5 km grid (~1600 grids)	Yes	Yes
Namoi Catchment Water Study	Yes	Yes	Yes	Yes	90 (from 2011)	99	No[a]	Yes[b]
Namoi river basin modelling	Yes	No	No	na	No future scenario modelled	17	No[c]	No
NSW surface water modelling for water sharing and management	Yes	No	Unsure	Partially	114 (from 2006)	Unsure	Yes	Yes
Murray–Darling Basin Plan	Yes	No	Unsure	Unsure	114 (from 2009)	Unsure	Yes	Yes

[a]River routing was done.
[b]Detailed climate trends not described in Schlumberger (2012).
[c]River modelling using inflow to the reach (no consumptive use and regulation modelled).
na = not available
*right to publish modelled data

Namoi Catchment Water Study

Schlumberger Water Services (SWS) used the LASCAM hydrological model (Viney et al., 2000; Sivapalan et al., 2002) for surface water modelling in the Namoi Catchment Water Study. The modelling domain covers eastern and central surface water catchments above a location approximately 6 km upstream of Narrabri comprising the Peel River catchment and areas upstream of Keepit Dam (Schlumberger, 2012). Thus, SWS's domain covers all coal mine development sites and most of the area of coal seam gas (CSG) future development sites identified in the CRDP for the Namoi subregion.

Data and model calibration

LASCAM was used on a series of 99 linked subcatchments, which were characterised in terms of land use and vegetation characteristics, and stream channel geometry. The input data used were rainfall, evaporation, vegetation cover, land use and soil type. A daily time step was used in calibrating the model using input data from 1996 to 2010. Among other observed variables the daily streamflow and flow duration curves were used to compare the modelled and observed results in calibration. A reference climate was derived from repeating 20 years of data from 1990 to 2009 and simulations were run for 90 years from 2010 to 2100 using the reference climate. No mention of river system modelling or river routing is found in Schlumberger (2012), though routing is an integral component of LASCAM.

Scenarios used

Eight different development scenarios were modelled in the Namoi Catchment Water Study (Table 5). Of these, the scenario most comparable to the baseline future for the BA for the Namoi subregion is scenario 1, which considers six approved open-cut coal mines and one underground coal mine (Table 5). The difference between scenario 1 and the BA baseline is that the former includes the Canyon Coal Mine, which, since it closed in 2009, is not included in the latter.

The scenario in the Namoi Catchment Water Study that most closely approximates the CRDP future in BAs is scenario 2 which augments scenario 1 with two new open-cut coal mines, two expanded open-cut coal mines, one underground coal mine and two CSG developments. Scenario 2 includes one CSG field (Santos' Bando CSG field) as well as the Canyon Mine which are not in the CRDP. Conversely, scenario 2 does not include the Vickery Coal Project or the Narrabri South underground coal mine, both of which are in the CRDP.

The Namoi Catchment Water Study reports that the main impacts to surface water will be derived from open-cut mining with little impact predicted from CSG or underground mine development. Predicted differences in long-term (2010–2100) average streamflow between scenario 1 and scenario 2 are reductions of approximately 0.1% at three locations in the Namoi River (approximately at Gunnedah, Boggabri and Narrabri) and approximately 0.0% and 0.2% at two locations in the Mooki River (Breeza and Ruvigne).

Table 5 Development scenarios used in Schlumberger's modelling study

Scenario number	Description	Number of open-cut mines	Number of underground mines	Number of CSG fields
0	No current or future mining or CSG	0	0	0
1	Approved mines and CSG production	6	1	Pilot holes only
2	Approved and planned mines and CSG	10	2	2
3	Extensive and widespread mining and CSG	24	7	8
4	Extensive and widespread mining only	24	7	Pilot holes only
5	Extensive and widespread CSG only	6	1	8
6	Half underground mines beneath alluvium	24	7	8
7	More rapid development of coal and gas resources than in scenario 3	24	15	8

CSG = coal seam gas
Data: Schlumberger (2012)

2.6.1.2.2 Conclusion

Five modelling studies within the Namoi river basin were identified using four surface water models. Of these studies, only the Namoi Catchment Water Study considered coal mine and CSG development scenarios. Of the eight scenarios in the Namoi Catchment Water Study, scenario 1 has the coal mine and CSG development configuration closest to those considered for the baseline future for the Namoi subregion, while scenario 2 is closest to the CRDP future. Predicted differences in average streamflow between the two scenarios are no more than 0.2% at key locations along the Mooki and Namoi rivers.

As identified in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016), there are many generic surface water models that have been applied in Australia for a multitude of purposes. However, there are no surface water models fully suitable for use in BAs that have been applied previously in the Namoi subregion. For a discussion of the reasons for the choice of the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and river model (AWRA-R) in the Bioregional Assessment Programme, refer to companion submethodology M06 (Viney, 2016).

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2.6.1.3 Model development

Summary

This section describes the key steps taken to develop and implement surface water models for predicting hydrological changes arising from coal resource development in the Namoi subregion. 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 development of time series of open-cut and underground coal mine footprints.

The modelling domain comprises the catchment of the Namoi River above Walgett (38,500 km^2) including the Peel river basin. Within this domain, 54 model nodes have been identified at which daily streamflow predictions are produced. The model simulation period is from 2013 to 2102.

Seasonal climate scaling factors from the Institute of Atmospheric Physics, China (IAP) global climate model 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 1.9% per degree of global warming.

2.6.1.3.1 Spatial and temporal dimensions

In the Namoi subregion the modelling domain consists of the catchment of the Namoi River above Walgett (Figure 4) which covers an area of about 38,500 km^2. Almost one-third of the modelling domain is outside the subregion, mostly to the east of the Hunter-Mooki Thrust Fault System and including the Peel and Manilla river basins. Conversely, some parts of the western extremities of the subregion are outside the modelling domain because they are not part of the Namoi river basin.

Both the baseline and coal resource development pathway (CRDP) include simulations from 2013 to 2102. However, for both, the period from 1983 to 2012 is also modelled and acts as an extended model spin-up period.

Both surface water models, the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and the AWRA river model (AWRA-R), operate on a daily time step. AWRA-L uses a spatial grid resolution of 0.05 x 0.05 degrees (approximately 5 x 5 km), while the smallest spatial unit in AWRA-R is the subcatchment, with size dictated by the location of model nodes. Unless indicated otherwise in this section, surface water modelling in the Namoi subregion follows the methodology set out in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

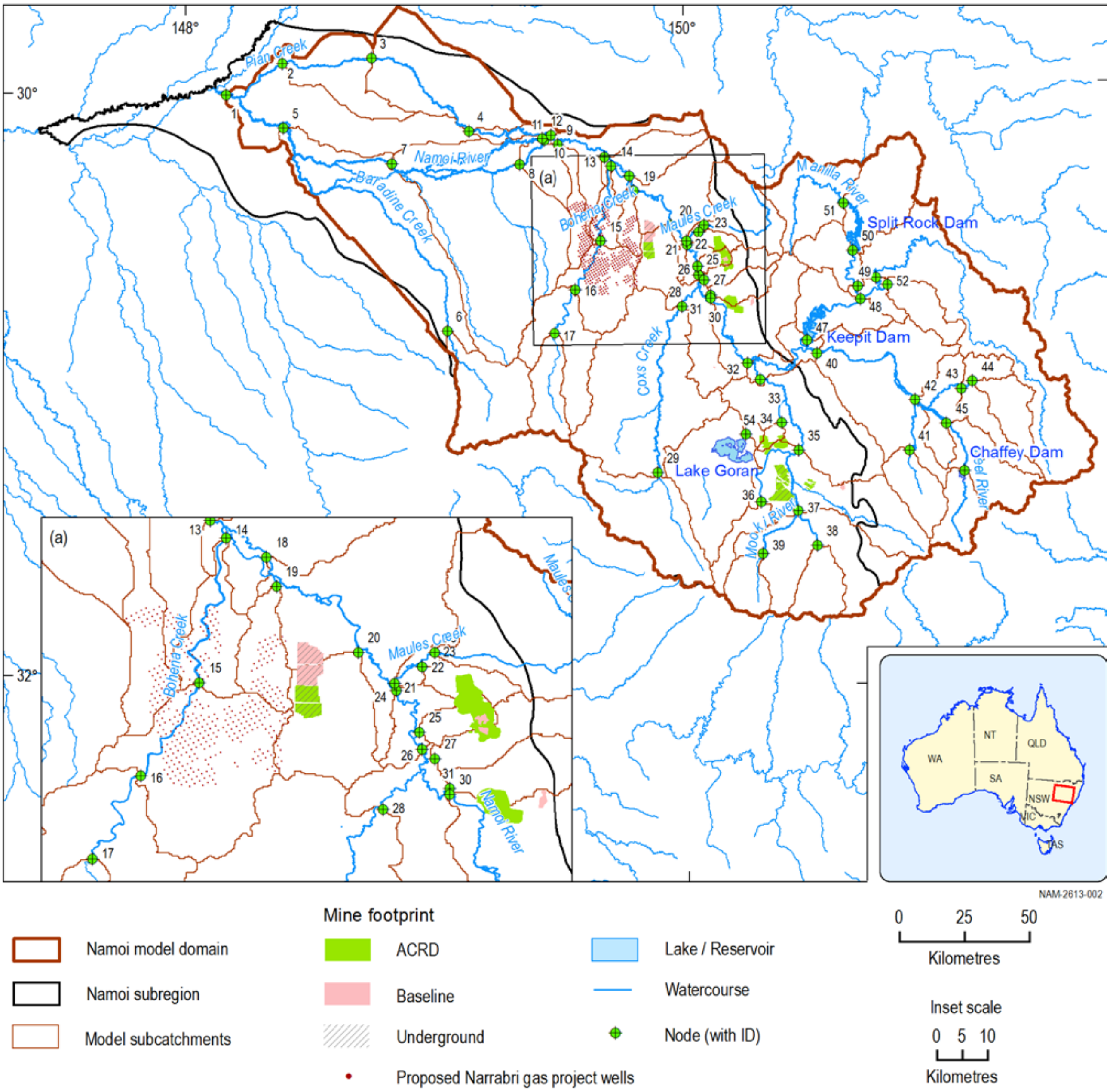

Figure 4 Location of surface water model nodes in the Namoi subregion and modelling domain

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bureau of Meteorology (Dataset 1); Bioregional Assessment Programme (Dataset 2, Dataset 3)

2.6.1.3.2 Location of model nodes for flow prediction

The surface water model nodes are the locations where streamflow predictions are made. In general, these nodes are located either:

- at streamflow gauges
- above major confluences
- immediately below proposed coal mine and coal seam gas (CSG) developments
- at locations required for receptor impact modelling.

In the Namoi subregion there are 54 model nodes based on the above criteria (Figure 4).

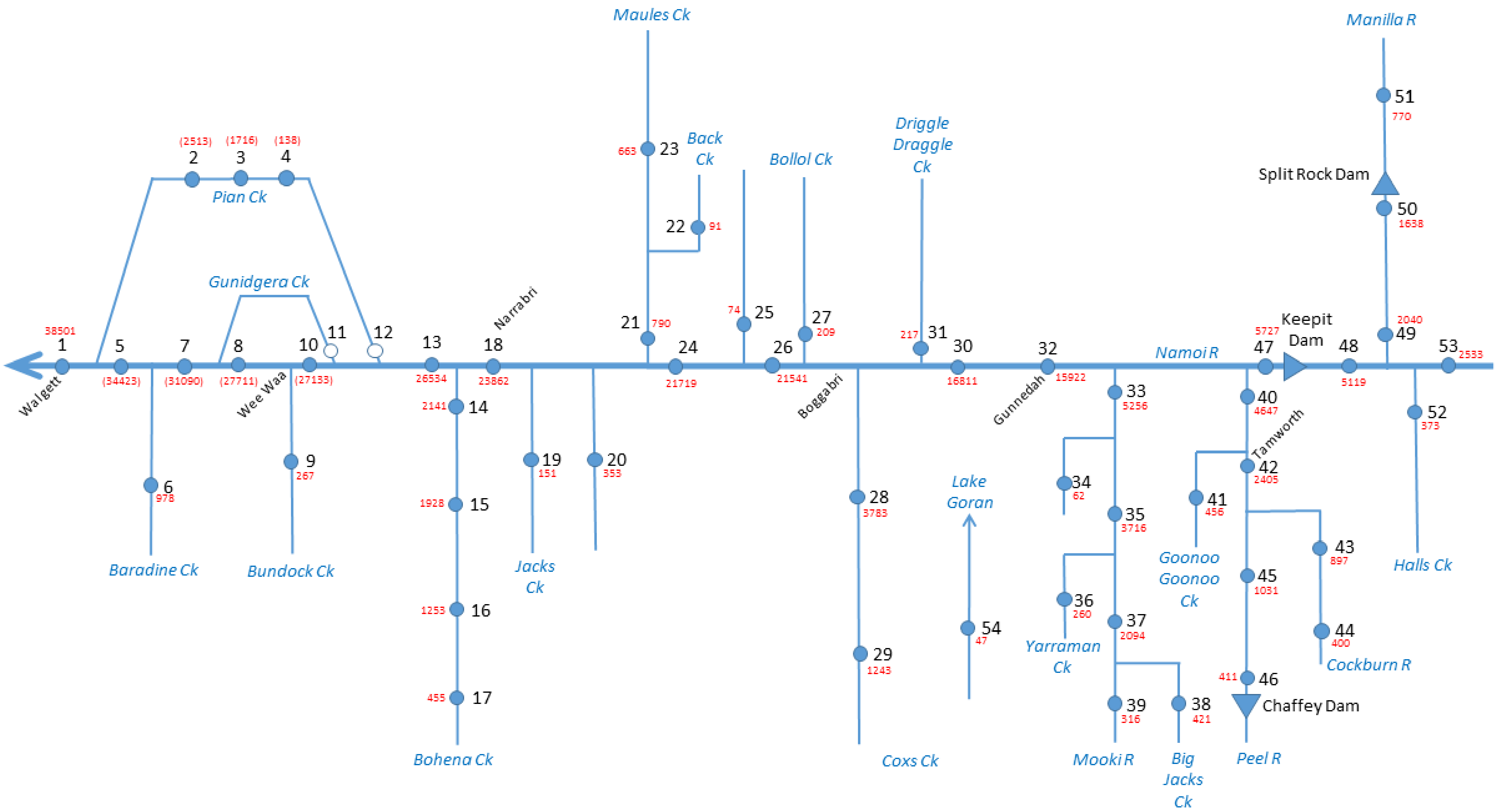

Figure 5 Schematic representation of the node-link network for the surface water modelling for the Namoi subregion

Numbers in red show the contributing area in km^2.
Data: Bioregional Assessment Programme (Dataset 2)

More nodes would have helped get a better interpolation, but the aim is to position them strategically to determine maximum cumulative impacts at critical locations.

For ease of reporting (see Section 2.6.1.6), model nodes have been numbered from the most downstream node upstream, commencing with node 1 on the Namoi River at Walgett. Numbers progress along the main river channel and up each tributary with a node in the order that tributaries meet the main river channel (Figure 5).

2.6.1.3.3 Choice of seasonal scaling factors for climate trend

In developing a future series of climate input, 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 Namoi subregion. There are 15 available GCMs (as presented in Table 6) with 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 Namoi subregion are shown in Table 6 for each GCM. The 15 GCMs predict changes in mean annual precipitation ranging from +8.3% (i.e. an increase in mean annual precipitation) to –6.5%. The GCM with median change is IAP from the Institute of Atmospheric Physics, China. The corresponding projected change in mean annual precipitation per degree of global warming is a reduction of 1.9%, or about 10 mm. The seasonal scaling factors for IAP are +0.27%, –4.32%, –3.87% and –0.49% for summer, autumn, winter and spring, respectively. In other words, projected increases in precipitation in the wettest season, summer, are offset by projected decreases in the other three seasons.

Table 6 List of 15 global climate models and their predicted change in mean annual precipitation for the Namoi subregion per degree of global warming

Global climate model	Modelling group and country	Change in mean annual precipitation (%)
CCCMA T47	Canadian Climate Centre, Canada	8.3%
MIUB	Meteorological Institute of the University of Bonn, Germany Meteorological Research Institute of KMA, Korea	4.8%
MIROC3	Centre for Climate Research, Japan	4.2%
NCAR-PCM	National Center for Atmospheric Research, USA	3.1%
CCCMA T63	Canadian Climate Centre, Canada	3.0%
NCAR-CCSM	National Center for Atmospheric Research, USA	1.2%
INMCM	Institute of Numerical Mathematics, Russia	0.7%
IAP	**LASG/Institute of Atmospheric Physics, China**	**–1.9%**
IPSL	Institut Pierre Simon Laplace, France	–2.1%
GFDL2.0	Geophysical Fluid, Dynamics Lab, USA	–2.1%
MRI	Meteorological Research Institute, Japan	–2.2%
CSIRO-MK3.0	CSIRO, Australia	–2.3%
MPI-ECHAM5	Max Planck Institute for Meteorology DKRZ, Germany	–3.7%
GISS-AOM	NASA/Goddard Institute for Space Studies, USA	–5.2%
CNRM	Meteo-France, France	–6.5%

Data: Bioregional Assessment Programme (Dataset 4)

The seasonal scaling factors associated with IAP 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. The global warming for 2073 to 2102 is assumed to be 2 °C.

The scaling factors are applied to scale the daily precipitation in the climate input series that is generated for 2013 to 2102. The resulting annual precipitation time series for the Namoi subregion is shown in Figure 6. It depicts a 30-year cycle of 1983 to 2012 climate that is repeated a further three times but with increasingly trended climate change scalars.

In order to create the 90 years of climate inputs needed for the modelling, the last 30 years (1983-2012) of climate data were repeated 3 times with a climate change signal added on top of it. While this misses some of the extremes of historical variability, this will not affect the results since the timing of the coal resource developments would need to align exactly with an extreme year in order for its impacts to be felt. Also, as the difference between two futures each with exactly the same climate inputs is considered, any differences will largely cancel out. Finally, a 30 year repeating sequence was needed in order to assess ecological impacts since they are assessed over 30 year periods, and a climate sequence which differed between periods would make it impossible to disentangle the impacts of coal resource development from the impacts of climate variability.

Figure 6 shows that the decrease in precipitation from 2013 to 2102 is less than the typical inter-annual variability. Furthermore, it reduces average annual precipitation to levels that remain much higher than were typically encountered before the 1950s. Potential evaporation data from the 30-year cycle of 1983 to 2012 was repeated without scaling to generate potential evaporation for 2013 to 2102.

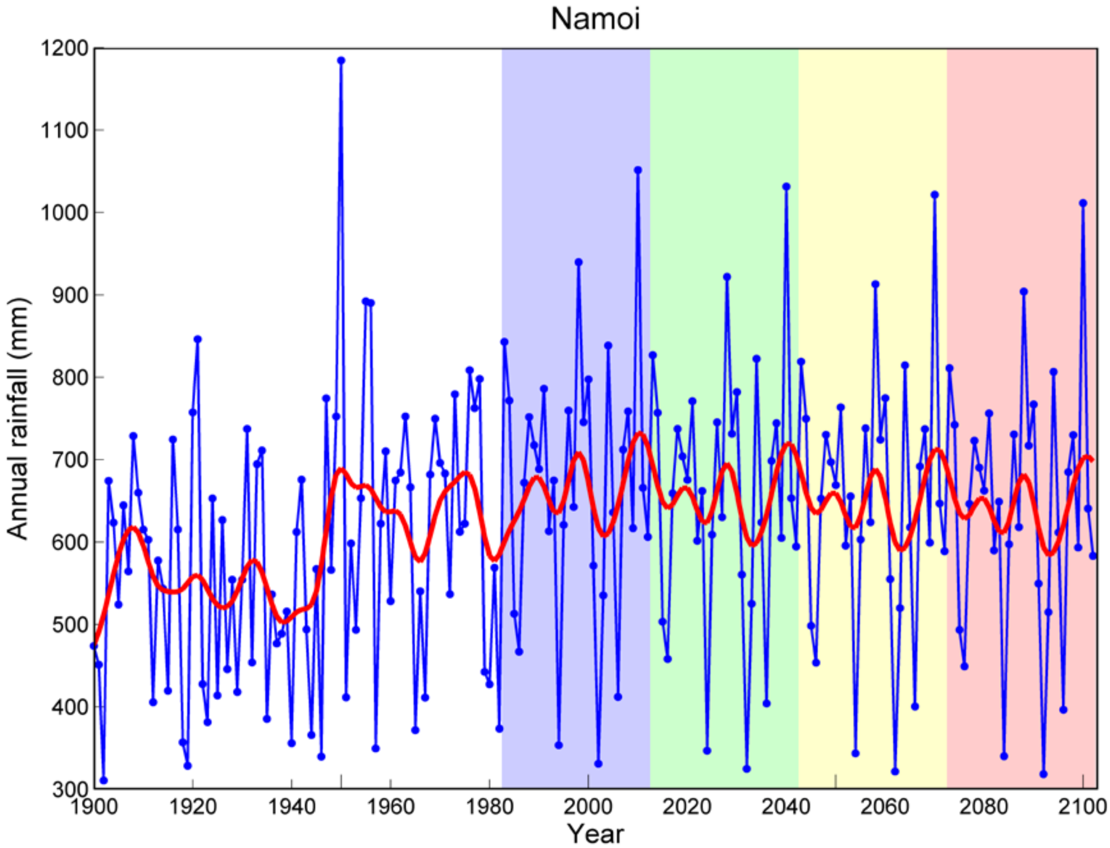

Figure 6 Time series of observed (1900 to 2012) and projected (2013 to 2102) annual precipitation averaged over the Namoi subregion (blue line)

The blue line shows the time series. The red line is a 23-year centrally weighted moving average. The colour bands show each 30 year prediction periods.
Data: Bioregional Assessment Programme (Dataset 5)

2.6.1.3.4 Representing the hydrological changes from coal development

Mine footprints

One important impact of coal mines is the interception (and on-site retention) of surface runoff that would otherwise flow to the stream network (see Section 2.3.5.3.3 in companion product 2.3 for the Namoi subregion (Herr et al., 2018)). It is important, therefore, to determine the areas where surface runoff will be intercepted. This area is termed the surface water footprint of the mine, and it can differ from the groundwater footprint. For the purposes of bioregional assessments (BAs), the surface water footprint covers the entire area disturbed by coal mine operations, including pits, road, spoil dumps, water storages and infrastructure. It may also include otherwise undisturbed parts of the landscape from which natural runoff is retained in reservoirs.

The footprint does not include established rehabilitated areas from which surface runoff can enter the stream network. Nor does it include catchment areas upstream of drainage channels that divert water around a mine site and do not retain it.

Mine footprint areas change over the lifetime of a mine's operations. As new parts of the lease are opened up for active use, the footprint increases. As mined parts of the lease are rehabilitated and their runoff returned to natural drainage, the footprint decreases although not necessarily to pre-mining condition. As well as the area of any final voids, the final mine footprint may also include the area covered by any infrastructure (e.g. dams, levee banks, roads) that is intended to remain on the site after final rehabilitation.

Mine footprint time series

Time series of mine footprints for baseline and CRDP mines were compiled from spatial data supplied by mining companies and the NSW Department of Trade and Investment, or extracted by the Assessment team from environmental impact statements and related documents, Landsat TM and Google Earth imagery. The full detail of mine footprint time series is given in Section 2.1.6.12.4 of companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018), therefore only an example of the plot is shown here.

Figure 7 shows the growth of mine footprint areas for Tarrawonga Mine for both the baseline and CRDP. The baseline mine starts in 2006 with its footprint reaching to a maximum of 5.0 km^2 in 2014. The total CRDP footprint reaches its maximum of 7.2 km^2 in 2016.

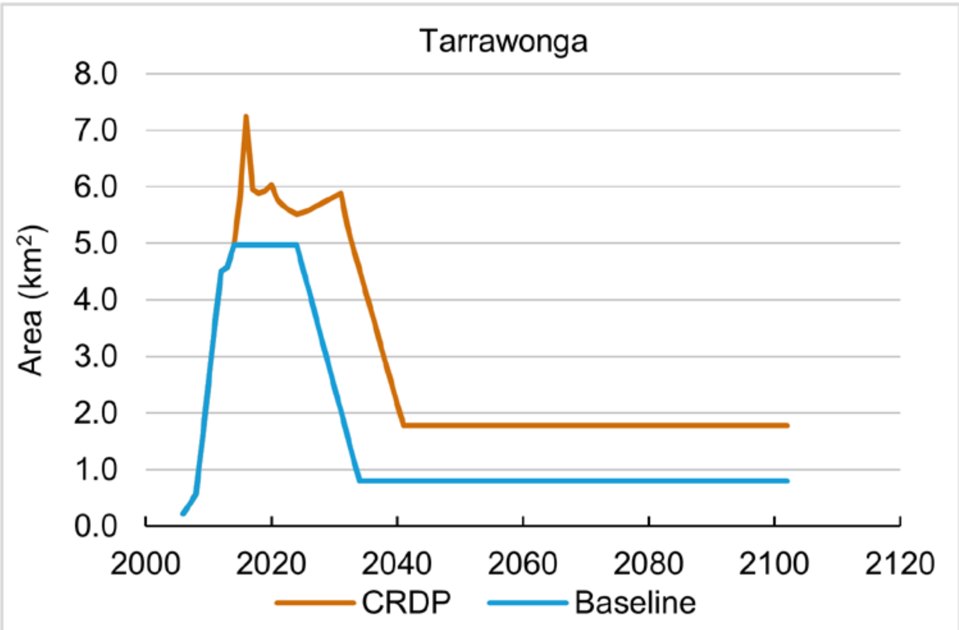

Figure 7 Temporal variation of footprint areas under the baseline and CRDP for Tarrawonga Mine

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 3)

Impacts of mine footprints

The primary ways in which coal mining affects streamflow are through interception of direct runoff and groundwater-mediated changes in baseflow. For an open-cut mine, interception of runoff is assumed to occur in the area covered by the mine's surface water footprint. Within this area, 100% of the streamflow that would have been generated in the absence of the mine is assumed to be retained on site and does not contribute to predicted streamflow.

For an underground mine, surface subsidence associated with the collapse of the longwall panels is expected to lead to increased ponding at the surface. This increased ponding is likely to result in a decrease in natural flow to the streams. A 5% reduction in runoff in areas covered by an underground mine footprint is conservatively (i.e. impact is likely to be smaller) assumed, which factors in regulatory requirements on mining companies to minimise the impacts from mine subsidence through such steps as appropriate longwall orientation and drainage management (see Section 2.1.6.12 in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018)).

The surface water footprints are not used to estimate the changes in baseflow. These are estimated by the groundwater model using the groundwater footprints, which are described in detail in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018). The 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 change in baseflow, and is then equally partitioned to obtain the daily changes.

2.6.1.3.5 Modelling river management

The river model, AWRA-R, is used to simulate some aspects of the management and regulation of the Namoi River, but this is undertaken differently to the Namoi and Peel Integrated Quantity-Quality Models (IQQM) (Simons et al., 1996), used by state agencies to set and assess river management rules, water sharing plans and allocations. This reflects the different purposes for which these models have been developed. The implementation of AWRA-R in the BA for the Namoi subregion is not specifically developed for river operations planning and management and, without further development, should not be used for this purpose.

Streamflow in the Namoi river basin is regulated by three major dams, Split Rock, Keepit and Chaffey dams (Figure 5). These dams supply water to downstream irrigation, industry and town water. Since reliable data on dam releases are not readily available, an irrigation module (which has as a constraint the regulated licensed irrigation volume) is used that is separate to the AWRA-R model to determine dam release values (Hughes et al., 2014). The data on water for domestic, industrial (e.g. mine) and other purposes (e.g. environmental release) are taken from the relevant agencies such as NSW Department of Primary Industries. Other variables required for AWRA-R are largely based on existing management rules.

A water resource assessment component (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) for a detailed description) was developed to estimate the allocation, which is the fraction of the licensed irrigation volume allowed to be extracted in the regulated section of the river system in a water year. This differs from the IQQM resource assessment, which includes all general security licences, whereas all irrigation licences are lumped in AWRA-R. This is a reasonable assumption since licences for irrigation comprise a large proportion of the general security licence volume. Within a year, allocations cannot go below the level estimated at the previous resource assessment.

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2.6.1.4 Calibration

Summary

This section describes the calibration of the two components of surface water modelling in the Namoi subregion. These components are the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and the AWRA river model (AWRA-R).

AWRA-L is regionally calibrated at 11 unregulated catchments using two calibration schemes: one biased towards high streamflow, and another biased towards low streamflow. The high-streamflow and low-streamflow calibrations perform reasonably well for predicting daily runoff for a wide range of streamflow conditions. For the nine hydrological response variables predicted by the model (Section 2.6.1.6), the high-streamflow calibration outperforms the low-streamflow calibration for predicting annual flow (AF) only. The low-streamflow calibration provides better predictions for the other eight hydrological response variables. Both calibrations tend to over estimate the daily flow rate at the 1st percentile (P01). Conversely, both calibrations under estimate zero-flow days (ZFD), low-flow days (LFD), low-flow spells (LFS) and length of low-flow spell (LLFS). Neither calibration predicts ZFD well, although the low-streamflow calibration slightly outperforms the high-streamflow calibration on a catchment-by-catchment basis.

AWRA-R is calibrated for 23 streamflow gauging sites of the Namoi River and tributaries. Using runoff from both AWRA-L calibrations, two concurrent AWRA-R calibrations are conducted: a high-streamflow calibration and a low-streamflow calibration. Both variants perform well overall, with the high-streamflow calibration outperforming the low-streamflow calibration. However, the AWRA-R low-streamflow calibration is markedly better than the high-streamflow calibration, with smaller model biases and similar interquartile ranges compared to the AWRA-R high-streamflow calibration for the low-streamflow metrics, except for ZFD and LFD, which are poorly simulated in both calibrations.

This section also assesses the AWRA-R model components representing river management (including water resources assessment and allocations, dam storage volumes and dam releases) that were calibrated using simulated or modelled outputs (Section 2.6.1.3). Results show that these components of the model capture relevant aspects of river management for a wide range of climate conditions.

Detailed model calibration was undertaken as part of the surface water modelling in the BA for the Namoi subregion (consistent with the overall BA approach outlined in companion submethodology M06 for surface water modelling (Viney, 2016)). This reflects that the focus of the BA modelling is on the difference between two possible futures (baseline and CRDP), rather than on making an absolute prediction, as well as on the presentation of results within an uncertainty framework. The probabilistic focus means that the model parameters are varied over a wide range of plausible values (i.e. several orders of magnitude) in order to capture the uncertainty inherent in the system. The purpose of model calibration is therefore restricted to ensuring that the model is able to adequately represent the surface water system with optimal parameter values. However, these optimal parameter values are not used further in the modelling, so a detailed and time-consuming optimisation procedure (as commonly undertaken for deterministic modelling) is not followed in the BA. Instead, this calibration methodology means that results are reported for thousands of model runs that cover the range of plausible input parameter values (see Viney, 2016 for further details). This approach, which is not yet widely reported in relevant technical or scientific literature, is different from typical calibration methods used in surface water models which only report results for one optimal model run.

2.6.1.4.1 Australian Water Resources Assessment landscape model

Data

Data needed for calibration of the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) include climate data and streamflow. The calibration period used for AWRA-L model development is from 1983 to 2012, which includes both wet and dry periods.

AWRA-L is run using gridded data of maximum temperature, minimum temperature, incoming solar radiation and precipitation. Daily grids (cell resolution of 0.05 x 0.05 degrees; ~5 x 5 km) of these variables are generated for the Australian continent by the Bureau of Meteorology (Dataset 1). Details of this dataset are provided in Section 2.1.1 of companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018).

Daily stage and streamflow data from 11 streamflow gauging stations with unregulated catchments located in and near the Namoi subregion were used to calibrate AWRA-L. These gauging stations and the catchment boundaries are shown in Figure 8. Of the 11 stations, six are located within the modelling domain (Section 2.6.1.3) and five are located in the adjacent basins. Site details are summarised in Section 2.1.4 of companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018). Observed daily mean streamflow data for the above gauges for 1983 to 2012 were obtained from the NSW Office of Water (Dataset 3).

Criteria for selecting the calibration catchments include that they:

- have catchment areas greater than 50 km^2
- have long-term measurements (more than 20 years from 1983)
- are currently not impacted by coal mining or coal seam gas (CSG) extraction or other major extractive industries
- have no significant flow regulation (e.g. dams)
- are not nested (i.e. not directly upstream or downstream of another selected gauge)
- are located within or close to the Namoi subregion and have similar catchment sizes and climate regimes.

Catchment boundaries for the 11 calibration catchments were delineated using the Australian Hydrological Geospatial Fabric (Geofabric) (Bureau of Meteorology, Dataset 1).

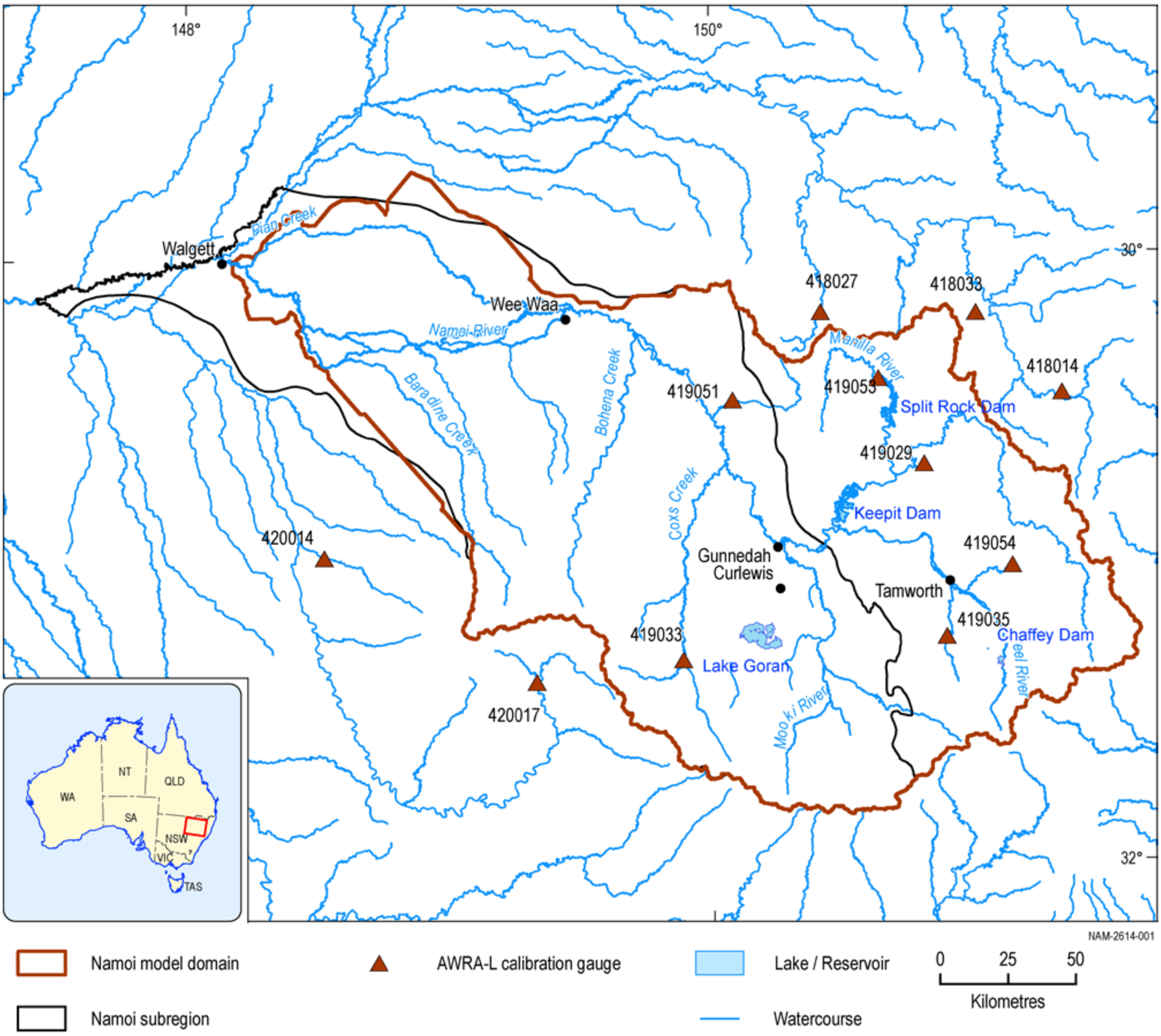

Figure 8 Location of the 11 catchments used in AWRA-L model calibration for the Namoi subregion

AWRA-L = Australian Water Resources Assessment landscape model
Data: Bureau of Meteorology (Dataset 1), Bioregional Assessment Programme (Dataset 2)

Calibration evaluation metrics

As per companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016), two regional model calibrations were undertaken: one biased towards predicting high-streamflow behaviour, and the second towards predicting low-streamflow behaviour. Three metrics were used to evaluate model performance:

- **Daily efficiency (E_d)**, also referred to as the Nash–Sutcliffe efficiency, which compares daily model predictions against daily observation data. Efficiency values range from 1 (which indicates perfect agreement between prediction and observation) to minus infinity.
- **Model bias (B)**, the cumulative prediction error divided by the sum of observations, which gives an indication of the model's overall tendency towards underprediction or overprediction. Bias ranges from –1 (negative values indicate underprediction) to plus

infinity (overprediction). The closer the model bias is to zero, the better the model is at estimating the observed volume of streamflow.

- **F value**, which seeks to combine efficiency and bias into a single metric. The high-streamflow calibration uses a version of F given by $F_1 = (E_d(1.0) + E_m)/2 – 5|\ln(1 + B)|^{2.5}$, where $E_d(1.0)$ is the efficiency of daily streamflow (without transformation, or with a Box-Cox lambda value of 1.0) (Box and Cox, 1964), E_m is the efficiency of the monthly predictions assessed against monthly observations, and B is the bias. The low-streamflow calibration uses a version of F given by $F_2 = E_d(0.1) – 5|\ln(1 + B)|^{2.5}$, where $E_d(0.1)$ is the efficiency of daily streamflow transformed with a Box-Cox lambda value of 0.1.

Model calibration results

Figure 9 and Table 7 summarise results of the two model calibrations for the 11 calibration catchments in terms of the three performance metrics. The high-streamflow calibration yields a reasonable Nash–Sutcliffe efficiency of daily streamflow, indicated by a median $E_d(1.0)$ of 0.59 and 25th and 75th percentile values of 0.54 to 0.65, respectively. Overall model bias is low with a median bias of 0.04, but the interquartile range from negative to positive values indicates variability across the 11 catchments with considerable overestimation in some catchments. The high-streamflow calibration yields a median F_1 of 0.66. The $E_d(1.0)$ value is greater than 0.3 for 9 of the 11 catchments, with negative values (suggesting poor simulation) for one catchment: –0.73 at gauging station 419029 on Halls Creek (tributary of the Namoi River), with a prediction bias of 0.65.

The low-streamflow calibration is evaluated against the daily streamflow data transformed with a Box-Cox lambda value of 0.1. The low-streamflow calibration yields a lower efficiency than the high-streamflow calibration, indicated by a median $E_d(0.1)$ of 0.36. The $E_d(0.1)$ is greater than 0.3 for 7 of the 11 catchments and there are three gauging stations with negative $E_d(0.1)$ values. The median bias of –0.09 indicates an overall tendency for underprediction by the low-streamflow calibration, although the interquartile range (–0.26 to 0.16) indicates less variability than for the high-streamflow calibration.

The 11 calibration catchments cover a wide range of climate and topographic conditions, with mean annual streamflow ranging from 11.2 GL/year at catchment 418033 (Bakers Creek at Bundarra) to 50.7 GL/year at catchment 420017 (Castlereagh River at Hidden Valley) (Table 7). This suggests that AWRA-L can predict streamflow variability reasonably in the Namoi subregion where climate conditions vary widely.

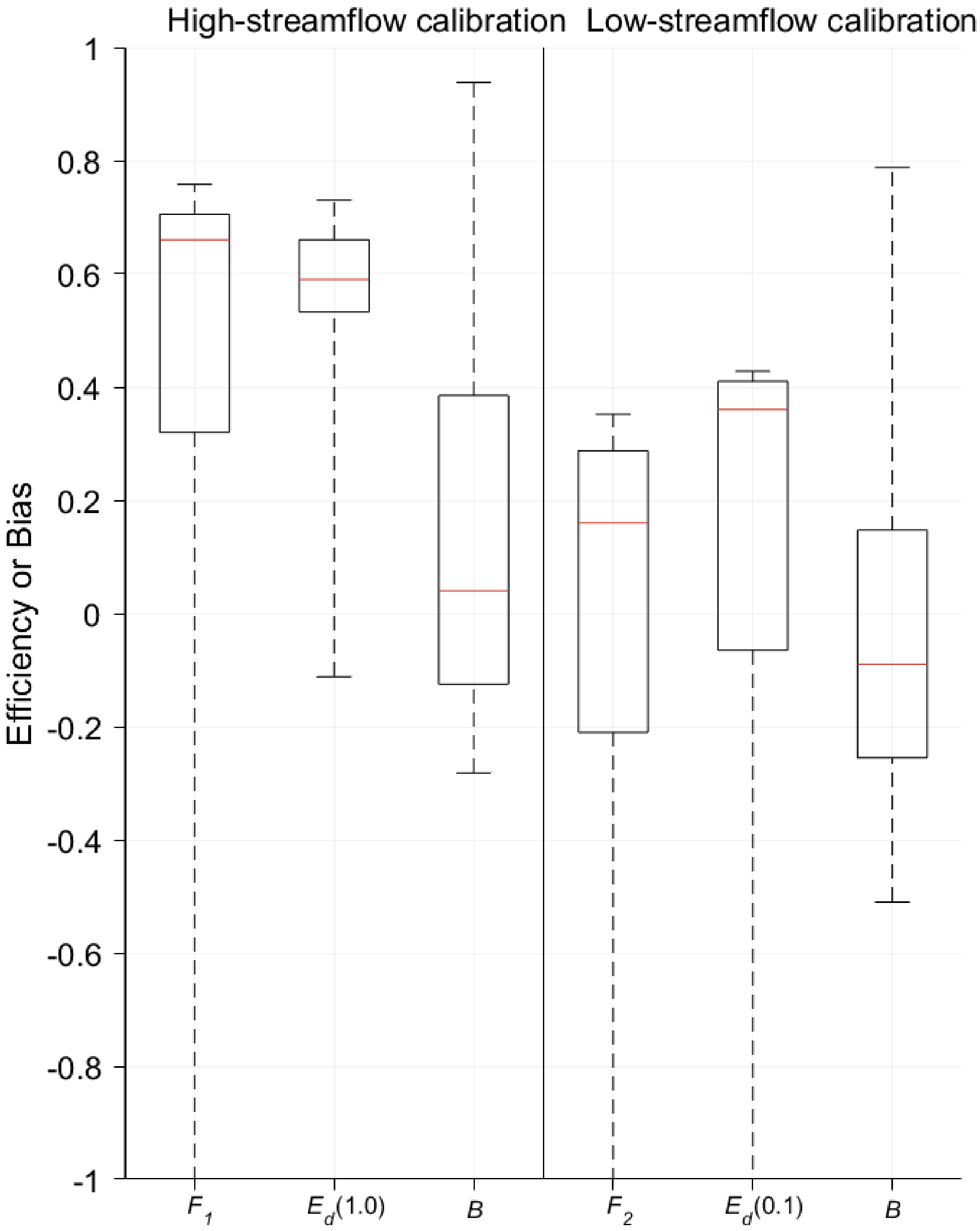

Figure 9 Summary of two AWRA-L model calibrations using 11 catchments for the Namoi subregion

AWRA-L = Australian Water Resources Assessment landscape model
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. F_1 is the F value for high-streamflow calibration; F_2 is the F value for the low-streamflow calibration; $E_d(1.0)$ is the daily efficiency with a Box-Cox lambda value of 1.0; $E_d(0.1)$ is the daily efficiency with a Box-Cox lambda value of 0.1; *B* is model bias.
Data: Bioregional Assessment Programme (Dataset 2)

Table 7 Calibration statistics for the 11 AWRA-L calibration catchments

Streamflow gauge ID	Mean annual streamflow (GL/y)	F_1	E_d(1.0)	Bias (F_1)	F_2	E_d(0.1)	Bias (F_2)
418033	11.2	0.69	0.67	-0.11	0.16	0.41	-0.26
420014	11.4	0.32	0.52	-0.27	-14.06	-2.44	-0.75
419029	15.3	-1.22	-0.73	0.65	-0.21	0.41	0.54
419051	21.5	-3.09	0.3	1.37	-2.84	-0.23	1.16
419035	22.1	0.83	0.76	-0.06	0.3	0.42	-0.21
419054	26.7	0.66	0.57	0.1	0.25	0.25	-0.02
419033	32.7	0.32	0.59	0.43	-0.21	-0.17	0.16
419053	33.3	0.66	0.71	0.25	0.3	0.31	0.11
418027	36.4	0.32	0.62	-0.3	-0.18	0.41	-0.35
418014	50.5	0.71	0.63	-0.13	0.16	0.36	-0.24
420017	50.7	0.71	0.58	0.04	0.43	0.44	-0.09
Median	**26.7**	**0.66**	**0.59**	**0.04**	**0.16**	**0.36**	**-0.09**

AWRA-L = Australian Water Resources Assessment landscape model; F_1 = F value for high-streamflow calibration; F_2 = F value for low-streamflow calibration (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)); E_d(1.0) = daily efficiency with a Box-Cox lambda value of 1.0; E_d(0.1) = daily efficiency with a Box-Cox lambda value of 0.1
Data: Bioregional Assessment Programme (Dataset 2)

Nine hydrological response variables (Table 8) have been chosen to characterise the hydrological changes of coal resource development on water resources. Figure 10 shows the model bias in the prediction of the hydrological response variables based on the high-streamflow and low-streamflow calibrations. Overall, the low-streamflow calibration outperforms the high-streamflow calibration across eight of the nine hydrological response variables with smaller median model biases and narrower interquartile ranges for the 11 catchments. Only for annual flow (AF) is the median bias of high-streamflow calibration marginally better than the low-streamflow calibration. Both calibrations tend to over estimate the interquartile range in daily flow (IQR). As many of the calibration catchments are intermittent or ephemeral, the metric describing the 1st percentile of daily flow rate (P01) is typically zero and is therefore difficult to predict with both calibration schemes tending to over predict. Similarly, neither calibration predicts zero-flow days (ZFD) well, although the low-streamflow calibration slightly outperforms the high-streamflow calibration on a catchment-by-catchment basis. Box plots of both these hydrological response variables are truncated in Figure 10. The high-streamflow calibration generally over estimates the daily flow rate at the 99th percentile (P99), whereas the low-streamflow calibration generally under estimates P99, but the latter has an overall smaller bias. Both calibrations under estimate the low-streamflow metrics, low-flow days (LFD), low-flow spells (LFS) and length of low-flow spell (LLFS) similarly. Overall the biases of hydrological response variables are less for low-streamflow calibration than for the high-streamflow calibration.

Table 8 Details of the nine hydrological response variables

Hydrological response variable	Definition	Unit
P01	The daily flow rate at the 1st percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	ML/day
zero-flow days (ZFD)	The number of zero-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	Days
low-flow days (LFD)	The number of low-flow days per year. This is the maximum value of the 90-year period (from 2013 to 2102). The threshold for low-flow days is the 10th percentile from the simulated 90-year period (2013 to 2102).	Days
low-flow spells (LFS)	The number of low-flow spells per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	Times/year
length of low-flow spell (LLFS)	The length (days) of the longest low-flow spell each year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	Days
P99	The daily flow rate at the 99th percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	ML/day
high-flow days (FD)	The number of high-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). The threshold for high-flow days is the 90th percentile from the simulated 90-year period (2013 to 2102). In some early products, this was referred to as ‘flood days’.	Days
annual flow (AF)	The volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year.. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	GL/year
interquartile range (IQR)	The interquartile range in daily flow (ML/day); that is, the difference between the daily flow rate at the 75th percentile and at the 25th percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	ML/day

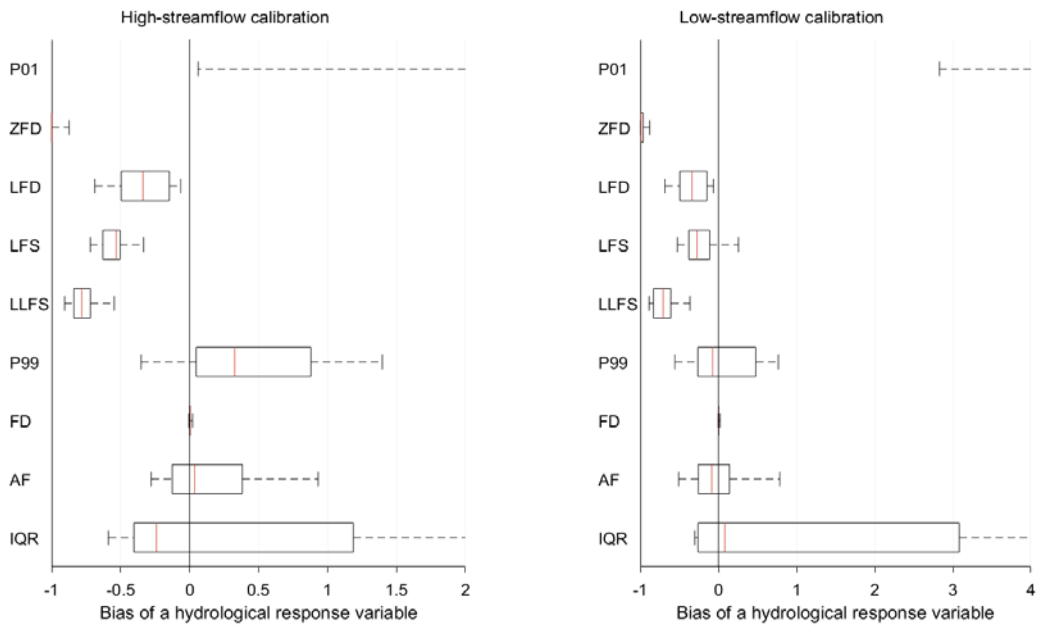

Figure 10 Summary of model bias for the nine simulated hydrological response variables for high-streamflow (left) and low-streamflow (right) calibrations

In each boxplot, the left, middle and right of the box are the 25th, 50th and 75th percentiles, and the left and right whiskers are the 10th and 90th percentiles.
Shortened forms of hydrological response variables are defined in Table 8.
Data: Bioregional Assessment Programme (Dataset 2)

It is noted that the parameter sets consisting of a single value for each parameter obtained from the regional model calibrations are not applied directly to the simulation and uncertainty analysis. However, the 3000 stochastic parameter sets used in simulation are drawn from distributions that are biased towards the values obtained in the two calibrations. The calibration parameter sets are also taken as reference values to evaluate performance of the best 10% of parameter sets (i.e. 300 model runs) selected for each hydrological response variable.

Implications for model predictions

Results from the regional model calibrations (Table 7 and Figure 9) suggest that AWRA-L performs reasonably well in estimating high streamflow and low streamflow in the Namoi subregion.

It is noted that when the model is calibrated against observations from 11 streamflow gauges it does not generate a uniform model performance. Though the model performs well overall, it performs poorly in some catchments and does not estimate the suite of hydrological response variables equally effectively. Both the high-streamflow and low-streamflow model calibrations generate a poor overall model performance for gauge 419029 (Halls Creek) and gauge 420014 (Magometon Creek), both with $E_d(1.0)$ lower than zero and large absolute biases (Table 7). Gauge 419029 has the largest percentage of daily streamflow data tagged as unverified implying a less reliable data. Gauge 419051 (Maules Creek) lies on the subregion boundary with the Hunter-Mooki Thrust Fault System passing through its catchment (Figure 8). This fault-line may be interfering with the surface flow, causing leakage through it which may result in the model highly over estimating streamflow in both calibrations. Note that distribution of observed runoff coefficients showed that the median runoff coefficient of gauge 419051 lies close to the 10th percentile indicating a comparatively very low runoff coefficient. Also, the annual runoff depth of gauge 419051 is much less than nearby gauges, especially 418027 (Table 7).

A key characteristic of a regional model calibration approach (i.e. a single simultaneous calibration against observations from multiple catchments) is that, unlike with local calibration (i.e. separate calibration for each individual catchment), there is little degradation from model calibration to model prediction (Viney et al., 2014). Except for the gauges discussed above which are affected by data quality or geography, the biases at the majority of individual stream gauging sites are in the range of –30% to +40%. Given the regionalisation methodology applied here, it is reasonable to assume that prediction biases in ungauged parts of the subregion will be similar. This provides confidence when applying AWRA-L to each model node where there are no streamflow observations.

Although not directly calibrated towards any of the hydrological response variables, an assessment of how well the two calibration sets predict the hydrological response variables serves as a further assessment of model performance. In general, one or other of the two calibration sets provides predictions of the high-streamflow hydrological response variables with little bias, although (apart from P01) both tend to under predict the low-streamflow hydrological response variables. This suggests that less confidence may be ascribed to the prediction of the low-streamflow hydrological response variables in Section 2.6.1.6 than to the prediction of the other variables.

2.6.1.4.2 Australian Water Resources Assessment river model

Data

Input data to drive the AWRA river model (AWRA-R) calibration include climate, potential evaporation, catchment runoff (from AWRA-L), groundwater depth and town water supply diversions. Calibration datasets against which performance of AWRA-R and the various modules were evaluated are daily streamflow, dam storage volumes, water allocations, dam releases and irrigation diversions. The calibration period for the different AWRA-R components covers 1 January 1981 to 30 June 2006.

The only direct climate input into AWRA-R is daily precipitation, which is used to calculate precipitation directly onto the open water surfaces (the river channels and storages). Daily gridded precipitation data from the Bureau of Meteorology (Dataset 1) have been used in the calibration of AWRA-R. The gridded data were clipped and aggregated (spatially averaged) using reach subcatchment boundaries defined in the Namoi river system AWRA-R node-link network (Bioregional Assessment Programme, Dataset 4).

Daily estimates of potential evaporation and catchment runoff were obtained from the calibrated AWRA-L simulation (Bioregional Assessment Programme, Dataset 2) and aggregated to the reach scale defined by the Namoi river system node-link network (Bioregional Assessment Programme, Dataset 4) for input into AWRA-R.

Town water supply diversions are not calibrated and are used as inputs in AWRA-R (Bioregional Assessment Programme, Dataset 5).

The AWRA-R model used for calibration comprises 45 nodes and their contributing areas, shown in Figure 11. These include the 32 gauging stations with stage and streamflow data used in assessing the model's performance in calibration (NSW Office of Water, Dataset 3), and one dummy node located close to the Pian Creek offtake. Twenty-three of the gauging stations are non-headwater gauges: they include ten on the Namoi River, three on the Peel River, three on Pian Creek, two on the Manilla River, and one each in Coxs Creek, Mooki River, Narrabri Creek, Cockburn River and Gunidgera Creek (red triangles in Figure 11). The other calibration model nodes (black dots in Figure 11) comprise nine gauging stations on headwater streams, plus 12 model nodes (see Section 2.6.1.3.2), located on ungauged headwater streams. Daily streamflows at the 12 ungauged nodes are simulated by AWRA-L (Bioregional Assessment Programme, Dataset 2) and stages obtained from idealised cross-sections at each location (see companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018); Bioregional Assessment Programme, Dataset 4). Eight model nodes, defining an additional eight ungauged reaches, located downstream of other model nodes, are not used in the calibration but are needed for the AWRA-R model simulations.

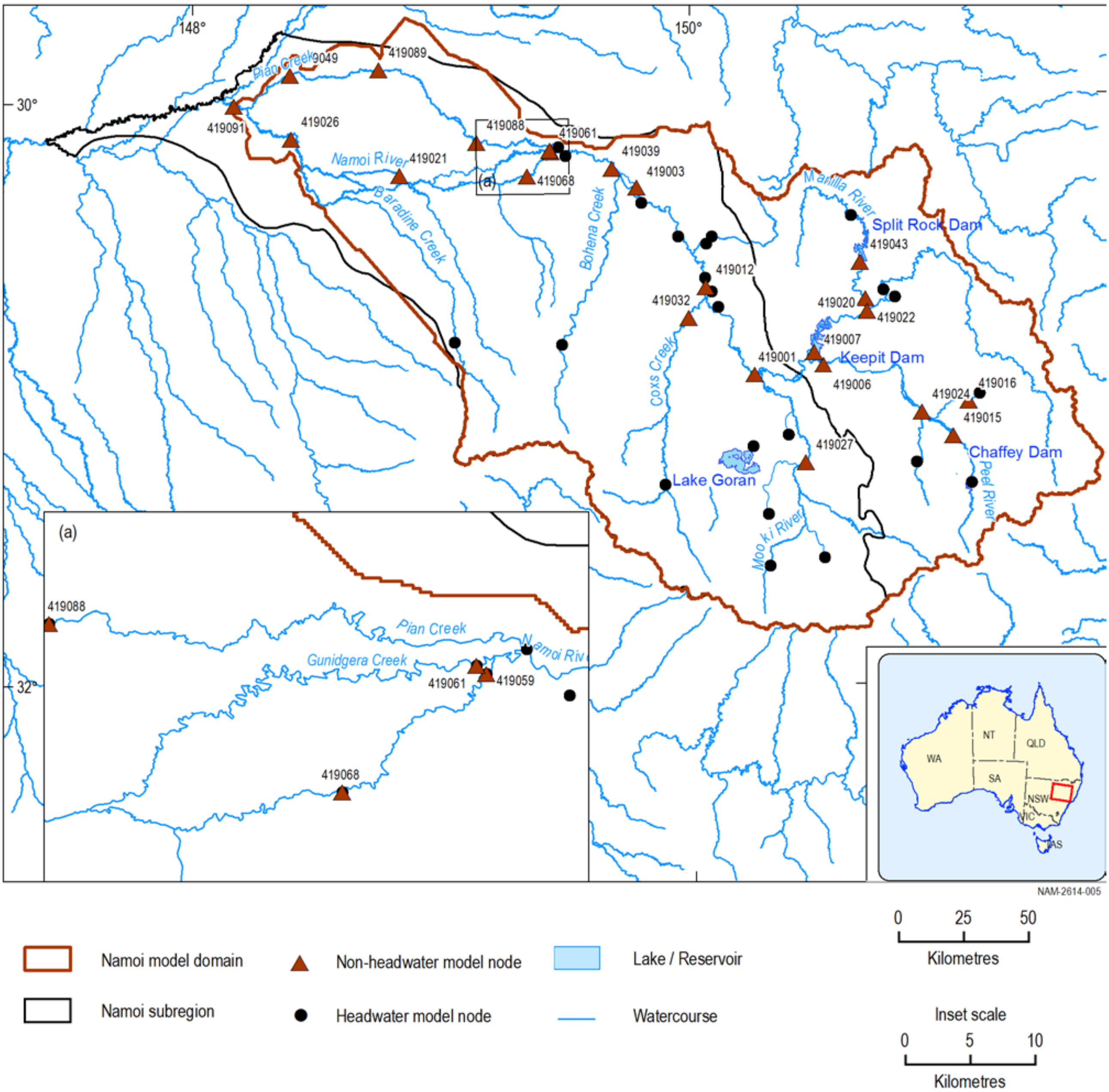

Figure 11 The 45 streamflow gauging stations used for AWRA-R model calibration

AWRA-R = Australian Water Resources Assessment river model
Data: Bureau of Meteorology (Dataset 1), Bioregional Assessment Programme (Dataset 4)

Daily irrigation diversions, dam storage volumes, daily dam releases and allocations were sourced from the Namoi and Peel Integrated Quantity-Quality Model (IQQM) (Bioregional Assessment Programme, Dataset 5) for the period 1 January 1981 to 30 June 2006. These were used to calibrate the AWRA-R irrigation and dam storage and releases modules.

Model calibration results

Streamflow routing and reach water balance

AWRA-R was calibrated using 23 streamflow gauges defining a concurrent number of modelling reaches. Two variants of the model were calibrated using AWRA-L high-streamflow and low-streamflow calibration outputs, respectively (Bioregional Assessment Programme, Dataset 2).

The agreement of both high-streamflow and low-streamflow AWRA-R calibrations were assessed using the Nash–Sutcliffe efficiency (E_d) for daily streamflow (E_d(1.0)) and for daily streamflow transformed with a Box-Cox lambda value of 0.1 (E_d(0.1)) as well as both F_1 and F_2 values (see Section 1.1.1.4.1). The bias generally remains very low as each reach is individually calibrated and parameterised, as opposed to the regional calibration implemented for AWRA-L (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

The performance is reported for the 23 non-headwater gauges depicted as triangles in Figure 11 and where routing and reach water balance processes (including runoff from catchments between the two nodes, river water diversions, groundwater fluxes, overbank flow) take place.

Figure 12 shows boxplots summarising the performance of the AWRA-R high-streamflow and AWRA-R low-streamflow calibrations in the 23 gauges. Table 9 presents a summary of the goodness-of-fit metrics used to evaluate the two model variants. In terms of E_d(1.0) (emphasis on high flows), the AWRA-R high-streamflow calibration agrees reasonably well with observations, indicated by a median E_d(1.0) of 0.77 (interquartile range 0.40 to 0.84) and a median bias of 0.001. Fourteen of the 23 gauges have an E_d(1.0) greater than 0.6, while four gauges (419007, 419061, 419088 and 419089 corresponding to model nodes 47, 11, 4 and 3, respectively) have a negative E_d(1.0).

It is noted that the IQQM data used to calibrate irrigation diversions was based on a fixed irrigation development (year 2000), hence it would tend to over estimate irrigation diversion during the 1980s and 1990s when agricultural development was less. However, calibration of the irrigation module was performed prior to the reach-by-reach calibration in AWRA-R, therefore any undue impacts on streamflow arising from a fixed irrigation development were reduced through calibration.

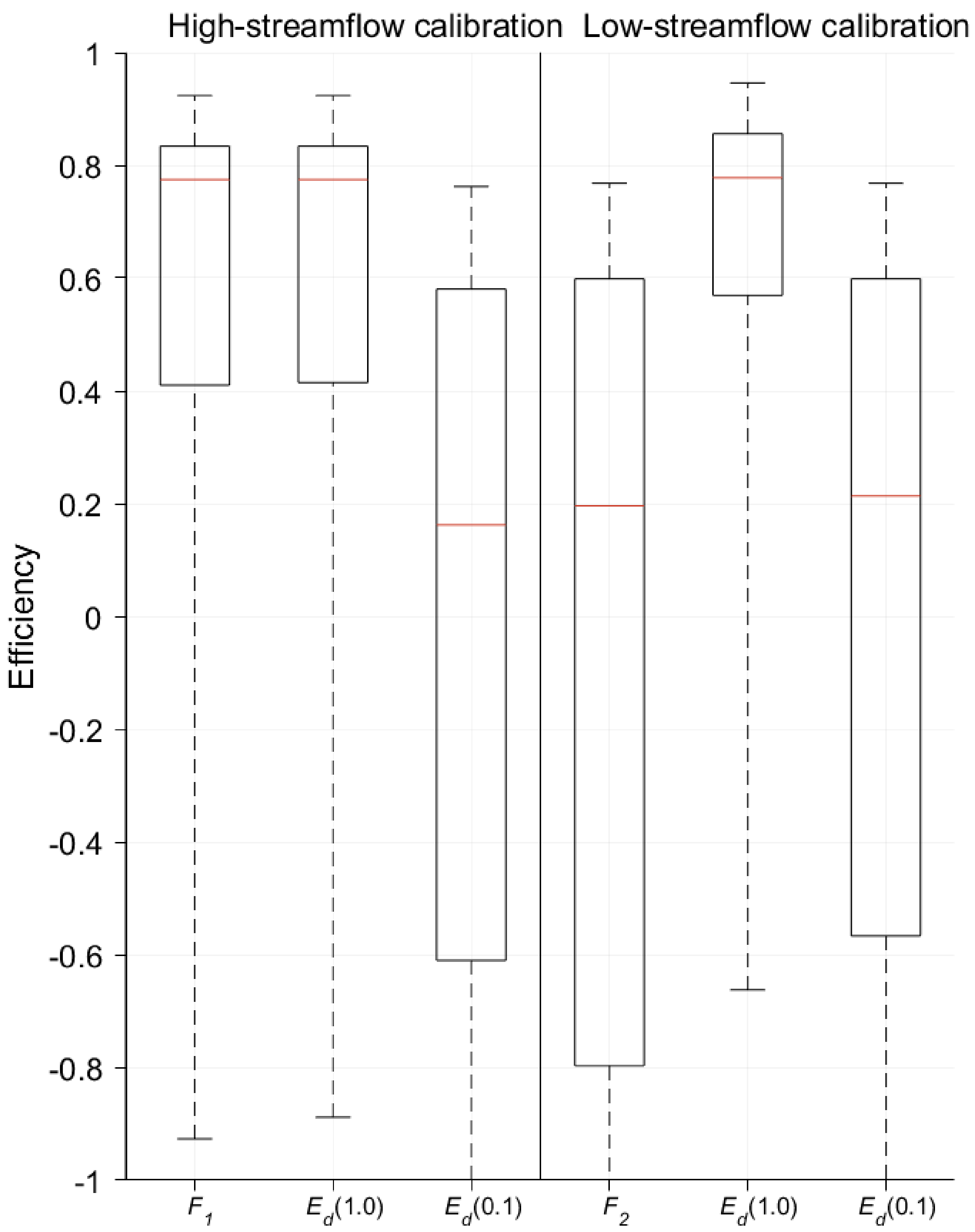

Figure 12 Summary of two model calibrations for the 23 gauges represented in the Namoi River AWRA-R model

AWRA-R = Australian Water Resources Assessment river model
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. F_1 is the F value for high-streamflow calibration; F_2 is the F value for the low-streamflow calibration; $E_d(1.0)$ is the daily efficiency with a Box-Cox lambda value of 1.0; $E_d(0.1)$ is the daily efficiency with a Box-Cox lambda value of 0.1.
Data: Bioregional Assessment Programme (Dataset 4)

Overall agreement in terms of $E_d(0.1)$ (emphasis on medium to low flows) for the AWRA-R high-streamflow calibration is much poorer than $E_d(1.0)$, with a median value of 0.16 (interquartile range –0.65 to 0.58). Seven of the 23 gauges have an $E_d(0.1)$ greater than 0.5, while ten have negative $E_d(0.1)$ values. The high-streamflow calibration yields a median F_1 of 0.77 and the median bias is about 0.002.

Table 9 Summary of AWRA-R calibration for the 23 calibration gauges in the Namoi subregion

Streamflow gauge ID	Model nodes	Mean annual streamflow (GL/y)	High-streamflow calibration			Low-streamflow calibration		
			F_1	$E_d(1.0)$	$E_d(0.1)$	F_2	$E_d(1.0)$	$E_d(0.1)$
419091	1	511	0.41	0.41	0.37	0.36	0.74	0.38
419049	2	101	0.52	0.57	–0.10	–0.12	0.60	–0.11
419089	3	71	–0.50	–0.50	–9.69	–9.15	–0.22	–9.15
419088	4	55	–31.49	–26.67	–0.30	–2.07	–10.46	–0.33
419026	5	522	0.87	0.87	0.40	0.41	0.87	0.41
419021	7	496	0.84	0.84	0.34	0.33	0.78	0.33
419068	8	394	0.70	0.72	0.58	0.20	0.70	0.21
419059	10	468	0.77	0.77	–0.66	–0.60	0.92	–0.60
419061	11	152	–0.73	–0.68	0.09	0.07	–0.40	0.09
419039	13	681	0.92	0.92	0.81	0.82	0.94	0.82
419003	18	670	0.92	0.92	0.75	0.75	0.96	0.75
419012	26	658	0.95	0.95	0.75	0.75	0.96	0.75
419032	28	217	0.41	0.43	–0.83	–1.07	0.56	–1.06
419001	32	579	0.92	0.92	0.64	0.64	0.92	0.64
419027	35	159	0.45	0.45	–0.28	–0.36	0.58	–0.36
419006	40	199	0.81	0.81	–0.91	–0.86	0.82	–0.86
419024	42	146	0.80	0.80	0.58	0.61	0.79	0.61
419016	43	68	0.79	0.79	0.39	0.40	0.73	0.40
419015	45	82	0.69	0.69	0.16	0.55	0.81	0.55
419007	47	250	–1.72	–1.72	–3.67	–3.67	–1.72	–3.67
419022	48	267	0.80	0.80	0.94	0.95	0.80	0.95
419020	49	63	0.80	0.80	–0.47	–0.46	0.78	–0.46
419043	50	53	0.13	0.13	–8.51	–9.30	0.29	–9.30
Median		217	0.77	0.77	0.16	0.20	0.78	0.21

AWRA-R = Australian Water Resources Assessment river model; F_1 = F value for high-streamflow calibration; F_2 = F value for low-streamflow calibration (see Viney, 2016); $E_d(1.0)$ = daily efficiency with a Box-Cox lambda value of 1.0; $E_d(0.1)$ = daily efficiency with a Box-Cox lambda value of 0.1
Data: Bioregional Assessment Programme (Dataset 4)

The AWRA-R low-streamflow calibration has a median of $E_d(1.0)$ of 0.78 (interquartile range 0.56 to 0.87). Sixteen out of the 23 gauges have an $E_d(1.0)$ greater than 0.6, and the same four gauges have a negative $E_d(1.0)$. In terms of $E_d(0.1)$ for AWRA-R low-streamflow calibration, model performance is marginally better than for the AWRA-R high-streamflow calibration, with a median value of 0.21 (interquartile range –0.60 to 0.61). Only seven gauges have an $E_d(0.1)$ greater than 0.5. The low-streamflow calibration has a median F_2 value of 0.20 and a median bias of 0.001.

Overall, the low-streamflow calibration was deemed better in terms of E_d(1.0) and bias than the high-streamflow calibration, and marginally better in terms of E_d(0.1).

The impact of including eight additional ungauged nodes (where simulations are required) between gauges nodes (thus defining new reaches) marginally degrades agreement with observations compared to the original calibration of AWRA-R. For example, the median E_d(1.0) using the low-streamflow calibration with the additional gauges is 0.77 (range 0.53 to 0.86). The largest degradation is for gauge 419027 (Node 35 in the Mooki River), where E_d(1.0) decreases from 0.58 to 0.53, followed by gauge 419001 (Node 32 in the Namoi River) from 0.92 to 0.89. Changes in E_d(1.0) are marginal (<0.02) in the rest of the gauging stations. Again, median bias is less than 0.002.

Boxplots in Figure 13 show the bias of the two calibration schemes (AWRA-R high-streamflow and AWRA-R low-streamflow calibration) in predicting the nine hydrological response variables that characterise the impacts of coal resource development on water resources (see Section 1.1.1.4.1). Similar to the AWRA-L results, these boxplots show that generally the AWRA-R low-streamflow calibration has smaller model biases and similar interquartile ranges compared to the AWRA-R high-streamflow calibration for the low-streamflow metrics (LFD, LFS, LLFS and P01). ZFD and P01 remain poorly simulated. The median biases in the high-streamflow metrics are generally marginally smaller in the high-streamflow calibration, and the interquartile ranges for high-streamflow metrics from both calibrations are narrower than their low-streamflow counterparts, highlighting less variability among the hydrological response variables in the calibrated Namoi reaches.

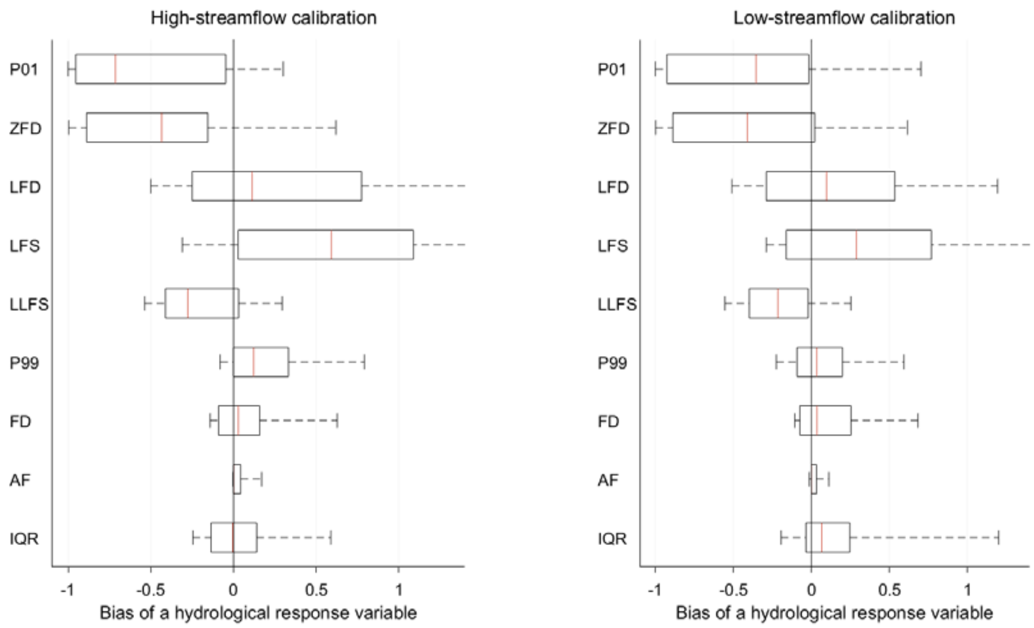

Figure 13 Summary of performance of the nine simulated hydrological response variables obtained using the two AWRA-R model calibrations

AWRA-R = Australian Water Resources Assessment river model
In each boxplot, the left, middle and right of the box are the 25th, 50th and 75th percentiles, and the left and right whiskers are the 10th and 90th percentiles for the 23 AWRA-R calibration reaches.
Shortened forms of hydrological response variables are defined in Table 8.
Data: Bioregional Assessment Programme (Dataset 4)

Irrigation module

The irrigation module in AWRA-R was calibrated in 14 reaches along the Namoi River and three reaches along the Peel River. In the absence of observed irrigation diversion and allocation data, calibration of AWRA-R was performed against monthly IQQM-simulated diversions and allocation data for the period 1981 to 2006 (Bioregional Assessment Programme, Dataset 5) using AWRA-R simulated streamflow (Bioregional Assessment Programme, Dataset 4). Crop types and crop proportions used in the calibration were also obtained from the Namoi and Peel IQQM models and adjusted during calibration if needed.

Table 10 presents a summary of goodness-of-fit metrics used to evaluate the performance of calibration. Simulated and observed irrigation diversions were compared using (i) the coefficient of determination (r^2), which indicates the agreement in temporal patterns, (ii) the monthly Nash–Sutcliffe efficiency (E_m), which indicates the calibration accuracy, and (iii) bias (B), which indicates the overall tendency of the model towards overestimation or underestimation. Overall, AWRA-R calibrated diversions are satisfactory, with a median r^2 of 0.4 and interquartile range from 0.25 to 0.47. The median Nash–Sutcliffe efficiency is 0.35 (interquartile range from 0.14 to 0.47). Diversions are under estimated in ten reaches, with three reaches with nodes 49, 3 and 45 having a negative bias of more than 20%, whereas overestimation occurs in the remaining reaches and only one reach (node 15) has a positive bias greater than 20%. The median bias is 10%.

Table 10 Summary of AWRA-R irrigation calibration for 17 reaches in the Namoi river basin

Streamflow gauge ID	Model node	Mean annual irrigation diversion (ML/y)	r^2	E_m	B
419091	1	16175	0.20	0.15	–0.04
419089	3	91691	0.04	–0.17	–0.35
419088	4	27225	0.40	0.34	0.04
419026	5	20250	0.32	0.21	0.31
419021	7	39909	0.23	–0.09	0.12
419068	8	27275	0.27	0.13	0.14
419059	10	129739	0.49	0.48	–0.03
419039	13	4727	0.05	–0.52	–0.06
419003	18	8934	0.39	0.35	0.09
419012	26	5543	0.29	0.21	0.11
419001	32	3166	0.43	0.41	–0.03
419006	40	10722	0.48	0.48	–0.05
419024	42	2221	0.47	0.47	–0.03
419015	45	3521	0.48	0.46	–0.23
419007	47	2301	0.70	0.70	–0.10
419022	48	328	0.47	0.40	0.03
419020	49	2444	0.45	0.41	–0.37
Median		8934	0.40	0.41	0.10

r^2 = coefficient of determination; E_m = monthly Nash–Sutcliffe efficiency; B = bias; AWRA-R = Australian Water Resources Assessment river model
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

Figure 14 shows examples of time series of observed and simulated diversions and mean monthly diversions for three reaches located on the Namoi River.

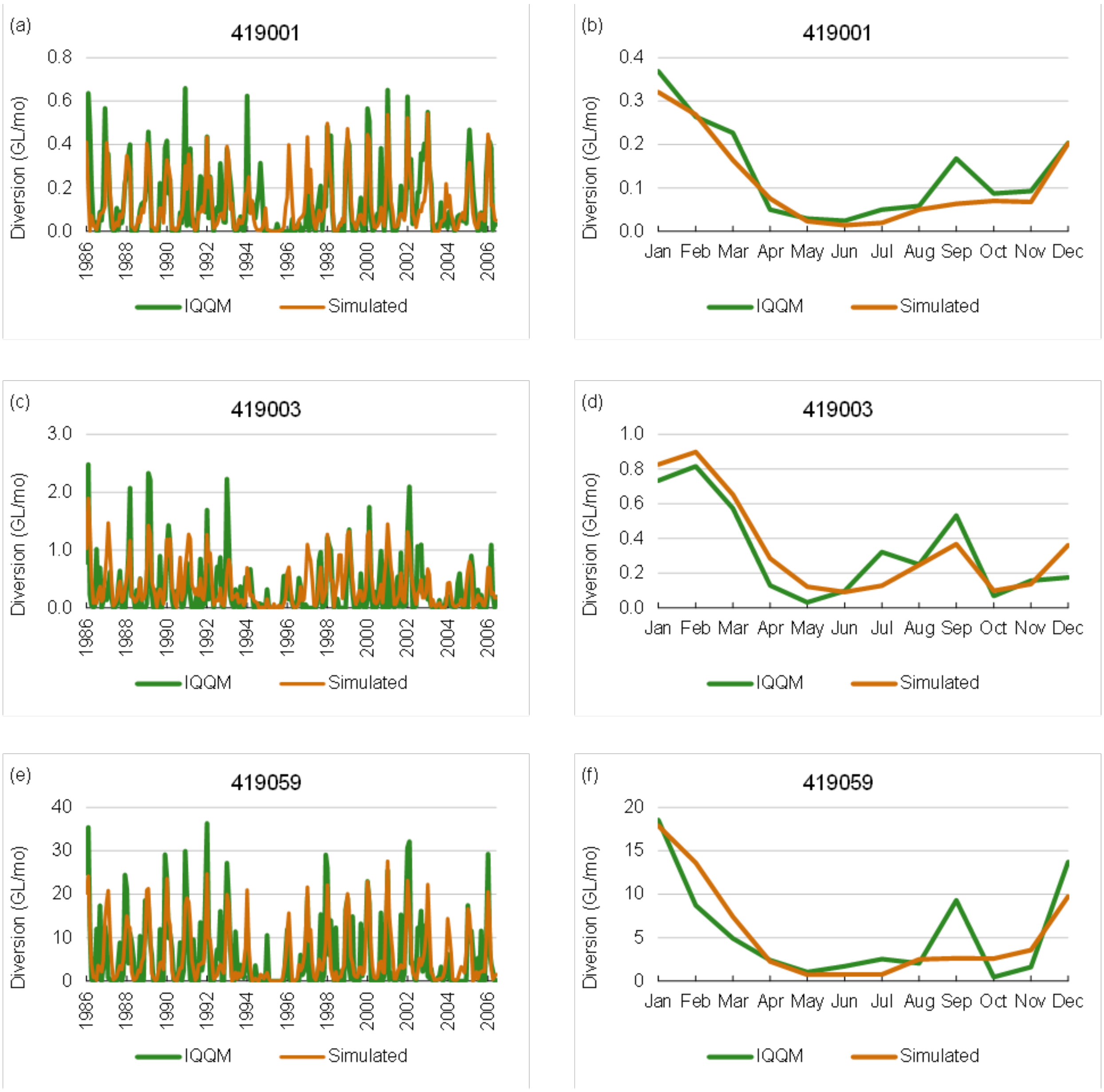

Figure 14 Example of IQQM and simulated monthly and mean monthly irrigation diversions for three reaches in the Namoi River

IQQM = Integrated Quantity-Quality Model
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

Generally, diversion peaks during the summer months (December to February) are under estimated, particularly prior to 1996 though less so in the remainder of the calibration period. Mean monthly diversions are simulated reasonably well, with most of the diversions occurring during the summer months and little or no diversion occurring during the winter months, when irrigation demand is low. IQQM diversions increase in many reaches during September, perhaps for irrigation of winter pasture during the last growing stage or for filling of on-farm storages before the start of the cotton irrigation season. Large peaks and increase in diversions in September were difficult to replicate in AWRA-R, even with the modifications (off-allocation diversion) implemented in the model (see Section 2.6.1.3) since these occurrences do not happen in most years.

Dam storage volumes, releases and allocations

Two systems are considered to estimate allocations in the Namoi subregion: (i) the Namoi River system, which includes Split Rock Dam and Keepit Dam and the downstream reaches that order water from these two dams; and (ii) the Peel River system, which includes Chaffey Dam and the downstream reaches that order water from this dam. Storage volumes for Split Rock Dam and Keepit Dam were calibrated as a single dam with combined storage against IQQM-simulated combined daily storage volumes (Bioregional Assessment Programme, Dataset 5), referred hereafter as Namoi Dams. Only releases from Keepit Dam were calibrated, with Split Rock transferring water to Keepit Dam when downstream demand is higher than the volume of water stored in Keepit. Transfers do not exceed 1500 ML/day. Storage volumes for Chaffey Dam releases were calibrated against IQQM-simulated daily storage volumes, releases and allocations (Bioregional Assessment Programme, Dataset 5), rather than against true observed data as the latter are too patchy and incomplete. The general calibration methodology and justification is described in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). Allocations in the Namoi River and Peel River systems are determined by the volume of water held in the systems' dams.

Goodness-of-fit metrics used to evaluate the performance on calibrated storage volumes and dam releases include the monthly Nash–Sutcliffe efficiency (E_m), the coefficient of determination (r^2) and the root-mean-square error (RMSE) to assess the overall accuracy.

For illustrative purposes, time series of monthly storage volumes are shown in Figure 15a and Figure 15b. Temporal patterns agree well with observations, with r^2 values of 0.84 and 0.89 for Namoi Dams and Chaffey Dam, respectively. In contrast, modelled volumes are satisfactory for Namoi Dams (E_m = 0.57) and good for Chaffey Dam (E_m = 0.71). The RMSE is 113 GL and 5 GL for Namoi Dams and Chaffey Dam, respectively. It can be seen in Figure 15 that the Namoi AWRA-R dam model generally under estimates storage volumes between 1981 and 1993, but over estimates them during the dry period between 2003 and 2006.

Time series of monthly dam releases are shown in Figure 15c and Figure 15d. Temporal patterns agree well with observations, with r^2 values of 0.74 and 0.85 for Namoi Dams and Chaffey Dam, respectively. Simulated releases are good for both the Keepit Dam (E_m = 0.53) and Chaffey Dam (E_m = 0.71). The releases RMSE for the calibration period (1 January 1986 to 30 June 2006) are 156 GL and 24 GL for Keepit Dam and Chaffey Dam, respectively.

Figure 16 summarises the monthly percentage error in storage volume for Namoi Dams and Chaffey Dam, computed as the percentage of the difference between the volumes simulated and observed divided by the simulated volume. The error is generally between –20% and +20%. It is likely that the modelled storages will generally be within a similar margin of error.

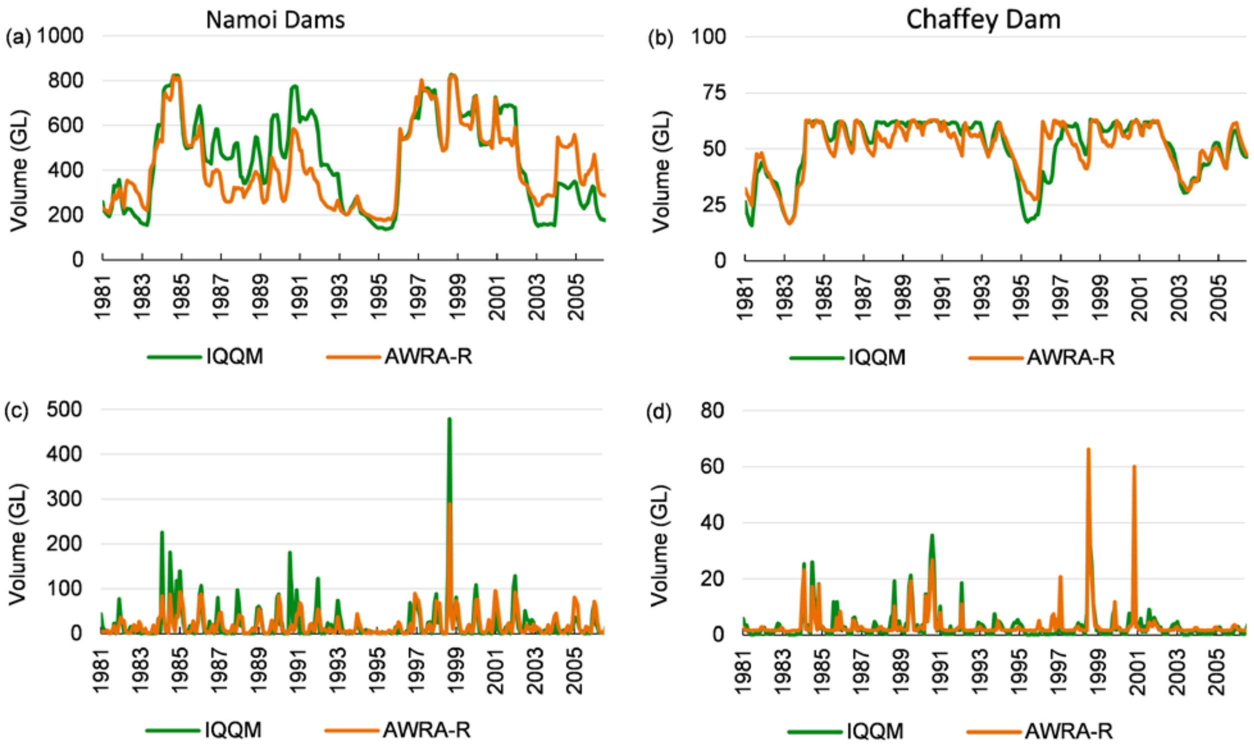

Figure 15 IQQM and AWRA-R simulated monthly dam storage volume for (a) combined Split Rock and Keepit dams and (b) Chaffey Dam, and IQQM and AWRA-R simulated monthly releases for (c) Keepit Dam and (d) Chaffey Dam

AWRA-R = Australian Water Resources Assessment river model; IQQM = Integrated Quantity-Quality Model
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

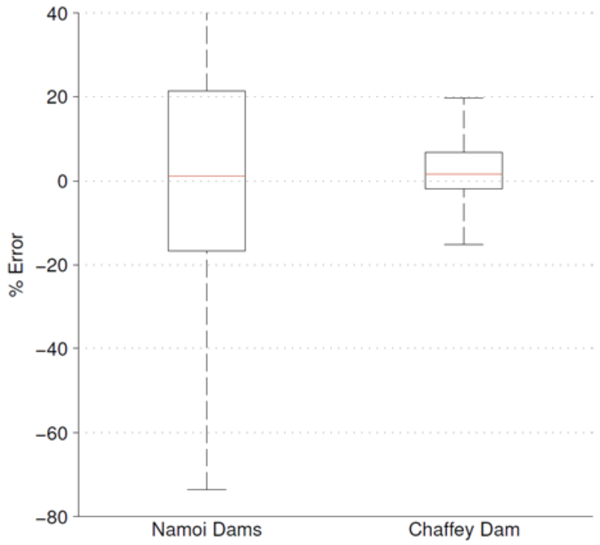

Figure 16 Summary of percentage error for monthly dam storage volumes for Namoi Dams and Chaffey Dam

In each boxplot, the bottom, middle and top of the box are the 25th, 50th and 75th percentiles, and the bottom and top end of whiskers are the 10th and 90th percentiles.
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

The poor daily efficiencies for the simulated releases from Keepit Dam can be largely attributed to the under estimation of a number of peak releases, particularly during the period 1981 to 1993, but also a large spill release in September 1998. In the case of Chaffey Dam releases, the model conceptualisation captures well the downstream irrigation and town water supply demand.

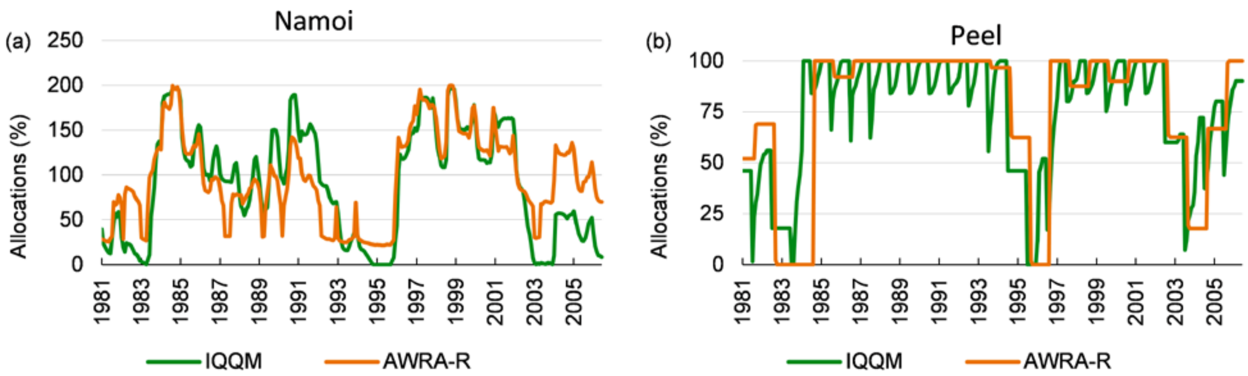

Figure 17 IQQM and AWRA-R simulated allocations for the Namoi River and Peel River systems

AWRA-R = Australian Water Resources Assessment river model; IQQM = Integrated Quantity-Quality Model
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

Time series of observed and estimated allocations are shown in Figure 17. Simulated allocations for the Namoi River (Figure 17a) reflect the amount of storage in both modelled dams and the continuous accounting system, which allows users to have more than 100% of their entitled licence. As is the case for dam storage volumes in the Namoi River system, AWRA-R generally under estimates allocations between 1981 and 1993, but over estimates them during the dry period between 2003 and 2006. AWRA-R simulated allocations in the Peel River generally show higher allocations in years when water volumes in the dam are high (greater than 50 GL) and do not show the inter-annual variability present in IQQM. This is because IQQM computes allocations on 1 July (defined as the beginning of the water year in the Peel River, Green et al., 2011) and allocation increments may occur during the year if available resources increase. Conversely, AWRA-R computes an annual allocation on 31 August (preceding the beginning of the irrigation season), when about 33% of the annual average inflow has reached the dam. Overall, AWRA-R shows reasonable allocation patterns both in dry and wet periods.

Implications for model predictions

Overall, AWRA-R streamflow is reasonably well simulated using both high-streamflow and low-streamflow calibrations. As expected, the low-streamflow calibration performs better when the evaluation is focused on the low flows, particularly in intermittent streams. The better performance of the low-streamflow calibration is also observed in terms of the hydrological response variables used to quantify the hydrological changes due to additional coal resource development, particularly for the variables characterising low streamflow, although the performance for the variables characterising high flows is typically only marginally worse. Generally, the hydrological response variables characterising low-flow conditions are under estimated, whereas those characterising high-flow conditions are over estimated. The number of zero-flow days remains poorly simulated with either model variant, though is slightly better for the low-streamflow calibration.

Similar to AWRA-L calibrations, the parameter sets obtained for AWRA-R high-streamflow and low-streamflow calibration show large uncertainty in predicting the nine hydrological response variables. The outputs from simulations that use the 3000 parameter sets for both AWRA-L and AWRA-R are expected to provide suitable uncertainty bounds for predicting the hydrological changes due to additional coal resource development on the nine hydrological response variables in each model node in the Namoi subregion.

A wide range of dam operating conditions are represented in the model as a result of choosing a 26-year calibration period that includes significant dry and wet periods. This ensures that the model can be used in some of the extreme conditions imposed by modelling of additional coal resource development.

The irrigation demand routine that computes releases for irrigation performs reasonably well. This is highlighted in the reasonably good representation of monthly patterns (r^2 greater than 0.7 in both Keepit Dam and Chaffey Dam) between simulated and IQQM-modelled releases. Releases are well simulated for Chaffey Dam (E_m = 0.71). Some peak releases from Keepit Dam are not well matched by AWRA-R, resulting in poor overall agreement with an E_m equal to 0.08.

AWRA-R simulated dam storage volumes, releases and allocations are reasonable and comparable to studies that simulated dam volumes and releases in multi-purpose reservoirs for scenario modelling (see Wu and Chen, 2012).

Overestimation of releases during the dry period between 2003 and 2006 can be partly explained by AWRA-L inflows to both dams, as AWRA-L tends to over estimate streamflow in the Namoi River during this drought period. Moreover, the calibration scheme uses one parameter per dam that linearly scales these inflows, thus it is difficult to solve this issue through calibration of the AWRA-R dam module only. Improvement of model performance can be achieved through better model conceptualisation and calibration strategies.

Finally, it should be noted that the hydrological modelling (in Section 2.6.1.6) presents the difference between the baseline and CRDP futures. As both futures use the same set of model parameters for simulation, any shortcomings in model performance will be common to both runs and would be largely eliminated on taking the difference.

2.6.1.4.3 Gaps

It is challenging for rainfall-runoff modelling to simulate low-streamflow metrics right (Nicolle et al., 2014). Firstly, since the daily flow rate at P01 can be many orders of magnitude smaller than the high daily flow rate at P99, it makes the AWRA-L model almost always over estimate the low-streamflow hydrological response variable P01 when it is calibrated using the Nash–Sutcliffe efficiency based objective function using normal streamflow or using the Box-Cox transformed streamflow. As a result of over estimation of low flows the duration hydrological response variables such as ZFD, LFD, LFS and LLFS are under estimated. There are no widely accepted rules to determine the degree of transformation needed to help eliminate this problem (Pushpalatha et al., 2012). Pushpalatha et al. (2012) used a number of flow transformation criteria and Nash–Sutcliffe efficiency to evaluate the efficiency of hydrological models and found that for most of the criteria high flows still make a significant contribution to the objective function value (see also Zhang et al. (2014)).

Secondly, the quality of the data gets degraded at the lower end of streamflow measurement due to uncertainty related to the rating curve as a result of frequent changes of channel bed geometry caused by floods and large flows. For example, Tomkins (2014) investigated the rating curve uncertainties from the Namoi river basin, and found that most gauges showed significant deviations at low stages, affecting the determination of low streamflow.

In the bioregional assessment (BA), the effects of over estimation of low streamflow are lessened by taking outputs from 3000 simulations using unique parameter sets applied to both AWRA-L and AWRA-R. As discussed in Section 2.6.1.5, the selected 300 best parameters are used for the prediction providing suitable uncertainty bounds for the changes in hydrological response variables caused by additional coal resource development.

Furthermore, the BA determines the effects of additional coal resource development on the water resources given by the difference between baseline and CRDP futures. As the errors introduced due to the uncertainty of model parameters are common to both baseline and CRDP, they cancel out when the net effect is calculated by taking the difference between the two pathways.

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Datasets

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2.6.1.5 Uncertainty

Summary

The uncertainty analysis includes a qualitative assessment of the effect of model assumptions on the predictions as well as a quantitative evaluation of the parameter uncertainty on the predictions.

For each hydrological response variable, an ensemble of parameter combinations is selected from a large range of parameter combinations that result in an acceptable match between historically observed hydrological response variables and simulated equivalents.

This ensemble of parameter combinations is used to calculate the maximum raw change, the corresponding relative change and the year of maximum change for each hydrological response variable at each model node.

In the qualitative uncertainty analysis, the rationale behind the major assumptions and their effect on predictions is discussed and scored. The assumption deemed to have the largest effect on predictions is the implementation of the coal resource development pathway (CRDP).

2.6.1.5.1 Quantitative uncertainty analysis

The aim of the quantitative uncertainty analysis is to provide probabilistic estimates of the changes in the hydrological response variables due to coal resource development. 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, as well as an acceptance threshold, are defined.

The ensemble represents the changes in hydrological response variables 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.

Parameter sampling

The parameters included in the uncertainty analysis are the same as those used in the calibration, with the exception that the parameter *ne_scale* (scaling factor for effective porosity (dimensionless)) is included in the uncertainty analysis. This is because the effective porosity parameter only affects the deep groundwater flow component in the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L). It is unlikely that the calibration is able to uniquely estimate that parameter from the streamflow record, therefore it was not included in the calibration. Its effect on predictions, however, is not clear a priori, which warranted inclusion in the uncertainty analysis.

Table 11 lists the parameters used in the uncertainty analysis and the range sampled in the design of experiment. The sampling within this range is not uniform but is based on a beta distribution biased towards the mean values of the two model calibrations. The AWRA-L and AWRA river model (AWRA-R) parameters in Table 11 are explained in the AWRA-L v4.5 documentation (Viney et al., 2015) and AWRA-R v5.0 documentation (Dutta et al., 2015), respectively. Parameters with a large order of magnitude range in parameter bounds, or that are thought to be particularly sensitive to low parameter values, are transformed logarithmically to ensure that values near the minimum of the range are adequately sampled.

Table 11 Summary of AWRA-L and AWRA-R parameters for uncertainty analysis

Model	Parameter name	Description	Units	Transformation	Minimum	Maximum
AWRA-L	cGsmax_hruDR	Conversion coefficient from vegetation photosynthetic capacity index to maximum stomatal conductance	na	None	0.02	0.05
	cGsmax_hruSR	Conversion coefficient from vegetation photosynthetic capacity index to maximum stomatal conductance	na	None	0.001	0.05
	ER_frac_ref_hruDR	Ratio of average evaporation rate over average rainfall intensity during storms per unit canopy cover	na	None	0.04	0.25
	FsoilEmax_hruDR	Soil evaporation scaling factor when soil water supply is not limiting evaporation	na	None	0.2	1
	FsoilEmax_hruSR	Soil evaporation scaling factor when soil water supply is not limiting evaporation	na	None	0.2	1
	K_gw_scale	Multiplier on the raster input of K_g	na	log10	0.001	1
	K_rout_int	Intercept coefficient for calculating K_r	na	None	0.05	3
	K_rout_scale	Scalar coefficient for calculating K_r	na	None	0.05	3
	K0sat_scale	Scalar for hydraulic conductivity (surface layer)	na	log10	0.1	10
	Kdsat_scale	Scalar for hydraulic conductivity (deep layer)	na	log10	0.01	1
	Kr_coeff	Coefficient on the ratio of K_{sat} across soil horizons for the calculation of interflow	na	log10	0.01	1
	Kssat_scale	Scalar for hydraulic conductivity (shallow layer)	na	log10	0.0001	0.1

Model	Parameter name	Description	Units	Transformation	Minimum	Maximum
	ne_scale	Scalar for effective porosity	na	None	0.1	1
	Pref_gridscale	Multiplier on the raster input of P_{ref}	na	None	0.1	5
	S_sls_hruDR	Specific canopy rainfall storage capacity per unit leaf area	mm	None	0.03	0.8
	S_sls_hruSR	Specific canopy rainfall storage capacity per unit leaf area	mm	None	0.03	0.8
	S0max_scale	Scalar for maximum water storage (surface layer)	na	None	0.5	5
	Sdmax_scale	Scalar for maximum water storage (deep layer)	na	None	0.5	1
	slope_coeff	Coefficient on the mapped slope for the calculation of interflow	na	log10	0.01	1
	Ssmax_scale	Scalar for maximum water storage (shallow layer)	na	None	0.5	3
	Ud0_hruDR	Maximum root water uptake rates from deep soil store	mm/d	log10	0.001	10
AWRA-R	K_rout	Muskingum routing parameter	sec	log10	0.1	10
	Lag_rout	Muskingum routing parameter	sec	log10	0.1	10

AWRA-L = Australian Water Resources Assessment landscape model; AWRA-R = Australian Water Resources Assessment river model; na = data not applicable, K_g = groundwater drainage coefficient (d^{-1}), K_r = rate coefficient controlling discharge to stream (dimensionless), K_{sat} = saturated hydraulic conductivity (mm d^{-1}), P_{ref} = reference precipitation

Three thousand parameter combinations are generated from the AWRA-L and AWRA-R model parameters according to the ranges and transformations shown in Table 11. These ranges and transformations are chosen by the modelling team based on previous experience in regional and continental calibration of AWRA-L (Vaze et al., 2013) and AWRA-R (Dutta et al., 2015). These mostly correspond to the upper and lower limits of each parameter that are applied during calibration.

The parameter combinations are generated together with the parameter combinations for the groundwater model (see companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)). This linking of parameter combinations allows the results to consistently propagate from one model to another, as outlined in the model sequence section (Section 2.6.1.1).

Each of the 3000 parameter sets is used to drive AWRA-L to generate a runoff time series at each 0.05 x 0.05 degree (~5 x 5 km) grid cell. The resulting runoff is accumulated to the scale of the AWRA-R subcatchments and is used – in conjunction with the sampled AWRA-R parameters – to drive AWRA-R.

Observations

Predictions and observations from 32 streamflow gauges of catchments which contribute flow to the surface water modelling domain in the Namoi subregion are used for uncertainty analysis. Selection of the 32 streamflow gauges is based on three criteria: (i) data length more than

10 years, (ii) not subject to major open-cut and underground mine impacts, and (iii) not subject to major dam control. For these streamflow gauges, historical observations of streamflow are summarised into the nine hydrological response variables for all years. The equivalent simulated hydrological response variable values are computed from the 3000 design of experiment runs. The goodness of fit between these observed and simulated hydrological response variable values is used to constrain the 3000 parameter combinations and select the best 10% of replicates (i.e. 300 replicates) for each hydrological response variable. Predictions from these 300 replicates are reported in Section 2.6.1.6.

Predictions

For each of the 54 model nodes the post-processing of design of experiment results in 3000 time series with a length of 90 years (2013 to 2102) of hydrological response variable values for baseline ($HRV_b(t)$) and CRDP conditions ($HRV_c(t)$).

These time series for baseline and CRDP are summarised through the maximum raw change (*amax*), the maximum percent change (*pmax*) and the year of maximum change (*tmax*). The percent change is defined as:

$$pmax = \frac{amax}{HRV_b(tmax)} * 100 \tag{1}$$

As the predictions include the effect of surface water – groundwater interaction through coupling with the groundwater models, it is possible that the groundwater parameters affect the surface water predictions.

Selection of parameter combinations

The acceptance threshold for each hydrological response variable is set to the 90th percentile of the average goodness of fit between observed and simulated hydrological response variable values obtained from model nodes at 32 streamflow gauging sites. This means that out of the 3000 model replicates, the 300 best (10%) are selected for each hydrological response variable.

The selection of the 10% threshold is based on two considerations: (i) guaranteeing enough prediction samples to ensure numerical robustness, and (ii) the sample's prediction performance is close to that obtained from the high- and low-streamflow model calibrations. Furthermore, it is expected that the full 3000 replicates contain many with infeasible parameter combinations (caused, for example, by parameter correlations that are not considered in the independent random sampling) and that these are likely to be filtered out by sampling only the best 10% of replicates. Nevertheless, selecting the best 10% of replicates is determined arbitrarily, and the implications of this decision are further discussed in Section 1.1.1.5.2.

2.6.1.5.2 Qualitative uncertainty analysis

The major assumptions and model choices underpinning the Namoi subregion surface water model are listed in Table 12. The goal of this qualitative uncertainty analysis is to provide a non-technical overview of the model assumptions, their justification and effect on predictions, as judged by the modelling team. This will also assist in an open and transparent review of the modelling.

Each assumption in Table 12 is rated against three attributes (data, resources and technical) and their effect on predictions.

1. The data rating is the degree to which the question 'If more or different data were available, would this assumption or choice still have been made?' would be answered positively. A low rating means that the assumption is not influenced by data availability, while a high rating indicates that this choice would be revisited if more data were available.
2. The resources rating reflects the extent to which resources available for the modelling, such as computing resources, personnel and time, influenced this assumption or model choice. Again, a low rating indicates the same assumption would have been made with unlimited resources, while a high rating indicates the assumption is driven by resource constraints.
3. The technical rating reflects the extent to which the assumption is influenced by technical and computational issues. A high rating is assigned to assumptions and model choices that are predominantly driven by computational or technical limitations of the model code. These include issues related to spatial and temporal resolution of the models.

The most important rating relates to the effect of the assumption or model choice on the predictions. This is a qualitative assessment by the modelling team of the extent to which a model choice will affect the model predictions, with low indicating a minimal effect and high a large effect.

A detailed discussion of each of the assumptions, including the rationale for the scoring, follows.

Table 12 Qualitative uncertainty analysis as used for the Namoi subregion surface water model

Assumption or model choice	Data	Resources	Technical	Effect on predictions
Selection of calibration catchments	Medium	Low	Low	Low
High-flow and low-flow objective function	Low	Low	High	Low
Selection of goodness-of-fit function for each hydrological response variable	Low	Low	Low	Low
Selection of acceptance threshold for uncertainty analysis	Medium	High	Medium	Medium
Interaction with the groundwater model	Medium	Medium	High	Low
Implementation of the coal resource development pathway	High	Low	Low	High

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. Only a limited number of the model nodes have historical streamflow. To calibrate the surface water model, a number of catchments are selected outside the Namoi subregion. The parameter combinations that achieve an acceptable agreement with observed flows are deemed acceptable for all catchments in the subregion.

The selection of calibration catchments is therefore almost solely based on data availability, which results in a medium rating 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 rating.

The regionalisation methodology is valid as long as the selected catchments for calibration are not substantially incompatible with those in the prediction domain in terms of size, climate, land use, topography, geology and geomorphology. The majority of these assumptions can be considered valid and the overall effect on the predictions is therefore deemed to be low.

High-flow and low-flow objective function

AWRA-L simulates daily streamflow. High-streamflow and low-streamflow conditions are governed by different aspects of the hydrological system and it is difficult for any streamflow model 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 one tailored to low flows.

Even with more calibration catchments and more time available for calibration, a high-flow and low-flow objective function 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 and the bias. The former is most sensitive to differences in simulated and observed daily and monthly streamflow, whereas the latter is most affected by the discrepancy between long-term observed and simulated streamflow. The weighting of both components represents the trade-off between simulating short-term and long-term streamflow behaviour. It also reflects the fact that some parameters are more sensitive to daily behaviour and some are more sensitive to long-term hydrology.

The low-streamflow objective function 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 efficiency transformed by a Box-Cox power of 0.1 and bias, which again represent the trade-off between short-term and long-term 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. Although 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).

Although the selection of objective function and its 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 rating.

Selection of goodness-of-fit function for each hydrological response variable

The goodness-of-fit function for each hydrological response variable for uncertainty analysis 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 are best suited to make the chosen prediction.

Within the context of the bioregional assessment (BA), the calibration aims to provide a parameter set that performs well at a daily resolution, whereas the uncertainty analysis focuses on specific aspects of the yearly hydrograph.

The goodness-of-fit function is tailored to each hydrological response variable and averaged over a number of selected catchments that contribute to flow in the Namoi subregion modelling domain. 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.

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 rating for these attributes.

The impact on the predictions is deemed minimal (low rating) as it is an unbiased estimate of model mismatch and because it summarises the same aspect of the hydrograph as is needed for the prediction.

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 are limited rating curve data available, hence the medium rating. Even if this information were available, the operational constraints within the BA prevent such a detailed analysis – although it is technically feasible. The resources column therefore receives a high rating while the technical column receives a medium rating.

The choice of setting the acceptance threshold equal to the 90th percentile of the summary statistic for a particular hydrological response variable (i.e. selecting the best 10% of replicates) is a subjective decision made by the modelling team. By varying this threshold through a trial-and-error procedure in the testing phase of the uncertainty analysis methodology, the Assessment team learned that this threshold is an acceptable trade-off between guaranteeing enough prediction samples and overall good model performance. Although relaxing the threshold may 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 a medium rating.

Interaction with the groundwater model

The coupling between the results of the groundwater model 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. Even if a suitable algorithm for integrated coupling of fluxes between the surface water and groundwater models were available, the differences in spatial and temporal resolution would require non-trivial upscaling and downscaling of spatio-temporal distributions of fluxes. For these reasons and also for practical reasons related to run times and computational storage issues, the modelling methodology for the Namoi subregion involves a one-directional feed of changes in the groundwater flux to streams from the groundwater model, rather than a fully coupled implementation. Thus the rating for the technical attribute is high.

The data and resources columns are rated medium because even if it were technically feasible to fully integrate the models, the implementation would be constrained by the available data and the operational constraints. In an integrated model, a simulation would likely involve multiple iterations between the groundwater and stream components and increase the computational load significantly.

The overall effect on the predictions is assumed to be small, as the change in baseflow due to coal mining is small compared to the other components of the water balance and the effect of rainfall interception by mine sites (see companion product 2.5 for the Namoi subregion (Crosbie et al., 2018)).

Implementation of the coal resource development pathway

The CRDP is implemented through the interaction with the groundwater model and by removing the fraction of runoff in the catchment that is intercepted by the mine footprint from the total catchment runoff. The key choices that are made in implementing the CRDP are (i) determining which mining developments are included, and (ii) deciding on the spatial and temporal development of their hydrological footprints.

In catchments in which the mine footprint is only a small fraction of the total area of the catchment, the precise delineation of the spatial extent of the mine footprint is not crucial to the predictions. In catchments in which the footprint is a sizeable fraction, accurate delineation of mine footprint becomes very important.

Similarly, the temporal evolution of mine footprints is crucial as it will determine how long the catchment will be affected. This is especially relevant for the post-mining rehabilitation of mine sites, when it becomes possible again for runoff generated within the mine footprint to reach the streams.

In the Namoi subregion, the accuracy with which mine footprints are represented in the model depends largely on the accuracy of the planned mine footprints published or provided by the mine proponents. This therefore is one of the crucial aspects of the surface water model as it potentially has a high impact on predictions and it is driven by data availability rather than availability of resources or technical issues. The data attribute is therefore rated high, while the resources and technical columns are rated low. The effect on predictions is rated high.

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2.6.1.6 Prediction

Summary

This section summarises prediction results of hydrological changes for nine hydrological response variables due to the modelled additional coal resource development. The hydrological changes reported for each model node were generated from among 3000 replicates of the model runs using randomly selected parameter sets.

The prediction results show that additional coal resource development in the Namoi subregion can cause substantial changes in the hydrological response variables. The comparison among the 54 model nodes shows that for the hydrological response variables that characterise high-streamflow conditions, the relative hydrological changes are particularly evident at model nodes where the development footprint forms a large proportion of the node's catchment.

In general, the hydrological changes are greater in the small tributaries of the Namoi River than in the model nodes along the river itself. The biggest hydrological changes occur at Namoi tributary node 25 (Merrygowen Creek), downstream of the Boggabri and Tarrawonga mines, and node 22 (Back Creek) downstream of the Maules Creek Project and the Mooki River tributary node 34 which is affected by the Watermark Coal Project.

The hydrological changes due to the additional coal resource development for the low-streamflow hydrological response variables appear to be greater than for the high-streamflow hydrological response variables. However, the uncertainty in the predicted change is greater for the low-streamflow variables.

The results suggest that changes to low-flow characteristics are caused by a combination of the instantaneous effect of interception from the additional mine footprints and the cumulative effect on baseflow over time caused by groundwater drawdown, whereas the changes to high-flow characteristics are dominated by direct interception of runoff.

The modelling results are used to define a zone of potential hydrological change for surface water in the Namoi subregion. This zone includes locations where the projected change in at least one of the nine hydrological response variables has a 5% chance or greater of exceeding a specified small threshold. The resulting zone of potential hydrological change for surface water includes those parts of the Namoi River and its tributaries downstream of and including the Mooki River, except for Baradine Creek and the uppermost nodes of Bohena Creek and the Mooki River.

2.6.1.6.1 Introduction

Section 1.1.1.6 summarises the prediction results for nine hydrological response variables and for 54 surface water model nodes. The nine hydrological response variables for streamflow are:

- P01 – the daily flow rate at the 1st percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).
- zero-flow days (ZFD) – the number of zero-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).
- low-flow days (LFD) – the number of low-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). The threshold for low-flow days is the 10th percentile from the simulated 90-year period (2013 to 2102)
- low-flow spells (LFS) – the number of low-flow spells per year (perennial streams only). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). A spell is defined as a period of contiguous days of streamflow below the 10th percentile threshold
- length of low-flow spell (LLFS) – the length (days) of the longest low-flow spell each year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).
- P99 – the daily flow rate at the 99th percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).
- high-flow days (FD) – the number of high-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). The threshold for high-flow days is the 90th percentile from the simulated 90-year period (2013 to 2102). In some early products, this was referred to as 'flood days'
- annual flow (AF) – the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).
- interquartile range (IQR) – the interquartile range in daily flow (ML/day); that is, the difference between the daily flow rate at the 75th percentile and at the 25th percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

These hydrological response variables were chosen to enable quantification of changes across the entire flow regime (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)). For each of these hydrological response variables a time series of annual values for the period 2013 to 2102 is constructed for each model node.

For each model node, 3000 sets of randomly selected parameter values were used to generate 3000 replicates of coal resource development impact. From these, the best 300 replicates for each hydrological response variable – as assessed by their ability to predict that hydrological response variable at the 28 sites where suitable observed data was available – were chosen for further analysis. The distributions of hydrological change from the resulting 300 samples are presented in boxplots in Section 1.1.1.6.2. The boxplots show the distributions over the 300 replicates of the maximum raw change (*amax*) in each metric between the baseline and coal resource development pathway (CRDP) predictions, the corresponding maximum percent change (*pmax*) and the year of maximum change (*tmax*). In general, the most meaningful diagnostic for the flux-based metrics (P01, P99, AF and IQR) will be *pmax*, while the most meaningful diagnostic for the frequency-based metrics (LFD, LFS, LLFS, ZFD and FD) will be *amax*.

It is important to recognise that the *amax* and *pmax* values give the largest annual departure between the baseline and CRDP predictions for the respective hydrological response variables. As such, *amax* and *pmax* represent extreme responses. They do not represent the magnitude of responses that would be expected to occur every year.

2.6.1.6.2 Results analysis

The predictions of hydrological change associated with the additional coal resource development are shown in the boxplots in Figure 18 to Figure 26. In these figures, the model nodes are grouped for different river sections and tributaries. Nodes are ordered from downstream to upstream. The tributary grouping 'lower Namoi' includes tributaries (excluding the anabranches) that join the Namoi River from nodes 1 to 18 plus tributary nodes 19 and 20. The tributary grouping 'mid Namoi' includes Maules Creek and the tributaries that join the Namoi River between node 24 and node 30. The tributary grouping 'Mooki' includes nodes on the Mooki River and its tributaries. Within this grouping, the tributaries of the Mooki River have a grey background shading. The tributary group labelled 'upper Namoi' includes all the modelled tributaries of the Namoi River that are upstream of Mooki River. Refer to Figure 5 in Section 2.6.1.3 for a schematic depiction of the model nodes and the network topology.

Annual flow

Figure 18 shows the changes to the annual flow (AF) at the 54 model nodes. The biggest percentage reductions occur in some of the small tributaries of the Namoi and Mooki rivers and range up to a median *pmax* of 23% at node 25 (Merrygowen Creek). Four model nodes have reductions in median *pmax* that exceed 8%. All of these have catchment areas of less than 100 km^2. There are tightly constrained distributions of *pmax* values around these median values at all the heavily affected nodes. Apart from these four model nodes there is little impact on *pmax* in the other nodes in the subregion.

The largest reductions in median *amax* are located in the lower Mooki River and in the middle reaches of the Namoi River and tend to increase with distance downstream as far as node 13. Below node 13 the impact on *amax* is lessened as some of the flow is diverted into Pian and Gunidgera creeks. As a consequence, the biggest effects are at nodes 13 and 18 and result in median changes of around 7 GL/year, which represent about 0.2% of the baseline flow. A significant proportion of this median reduction (4 GL/year) originates in the Mooki River (node 33 and above).

For the nodes with the biggest changes in *pmax*, the median year at which maximum hydrological changes occur is either 2028 or 2034 for the tributaries of the mid Namoi River (nodes 22 and 25), but 2058 for node 34 (a tributary of the Mooki River) and node 54 (a tributary of Lake Goran). There is relatively little uncertainty in these dates. The maximum hydrological changes in the Namoi River itself tend to occur in 2028.

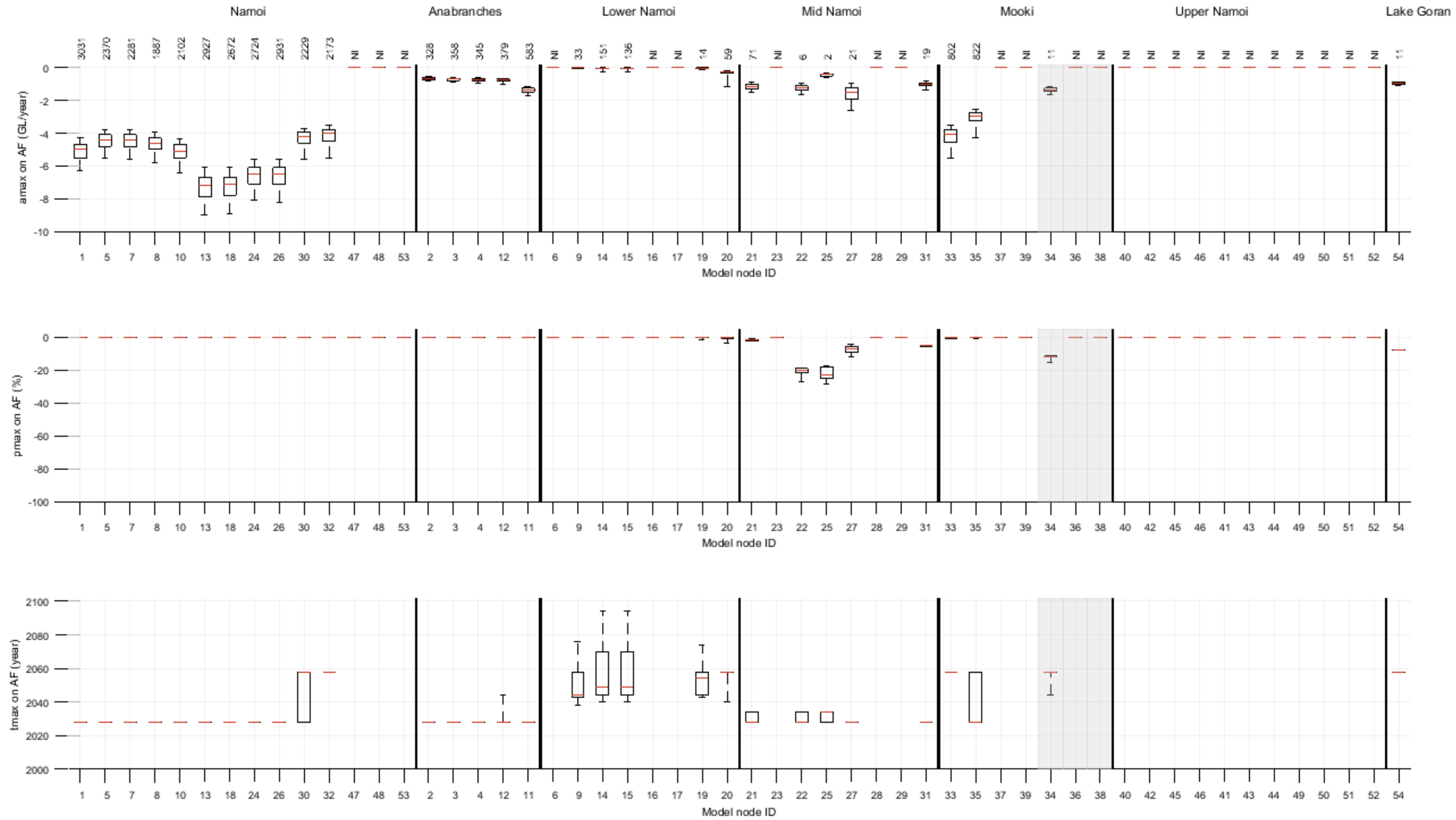

Figure 18 Hydrological changes due to additional coal resource development on annual flow (AF) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact
Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.
Refer to Figure 5 for location of model nodes.
Data: Bioregional Assessment Programme (Dataset 1)
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

Daily streamflow at the 99th percentile

Figure 19 shows the changes to the daily flow rate at the 99th percentile (P99) at each model node. The biggest changes in *pmax* occur at the same four locations with the biggest effect on AF. For P99 the median *pmax* values for these four nodes exceed 8% and range up to 18% for nodes 22 (Back Creek) and 25 (Merrygowen Creek). At most of these sites there is a smaller relative spread of *pmax* values than there is for AF. At most of the affected nodes, the percentage reduction in P99 is smaller than the percentage reduction in AF.

In the heavily affected nodes, the year of maximum change in P99 tends to correspond with the year of maximum change in AF, with the exception that it occurs (2028) earlier in node 25. However, in the nodes of the Namoi River and its anabranches the maximum change tends to be delayed until the early 2040s.

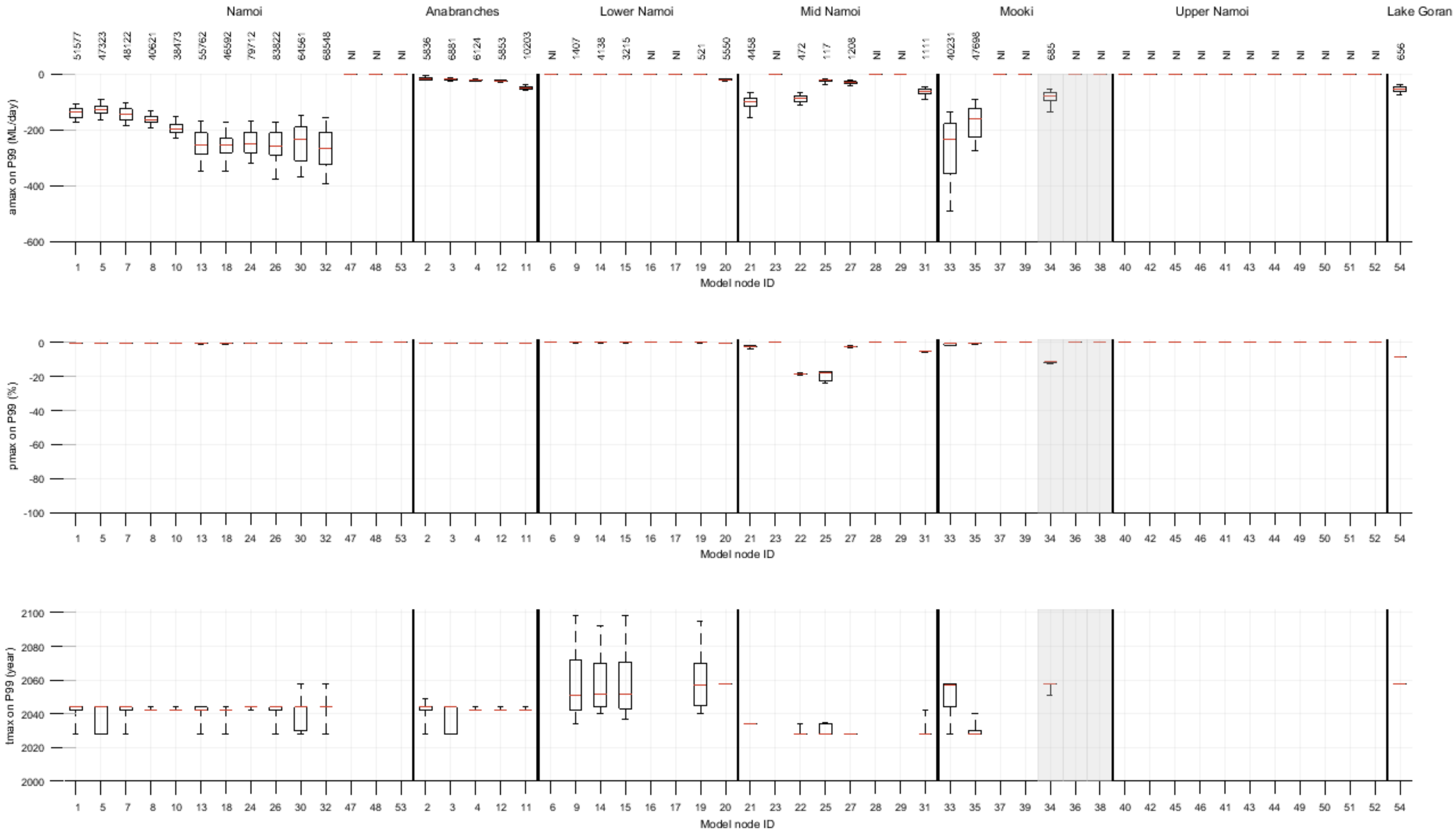

Figure 19 Hydrological changes due to additional coal resource development on daily flow rate at the 99th percentile (P99) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact
Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.
Refer to Figure 5 for location of model nodes.
Data: Bioregional Assessment Programme (Dataset 1)
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

Interquartile range

Figure 20 shows the changes to the interquartile range (IQR) of daily flow rate at each model node. The changes in IQR due to additional coal resource development are always reductions. This implies that the difference in flow rates between high flows (the 75th percentile of daily streamflow) and low flows (the 25th percentile of daily streamflow) is reduced, mostly likely through a decrease in the 75th percentile. The patterns of change are similar to those of AF (Figure 18) and P99 (Figure 19). The biggest reductions in median *pmax* occur at nodes on small tributaries of the mid Namoi River, and include reductions of more than 60% at nodes 22 (Back Creek), 25 (Merrygowen Creek) and 27 (Bollol Creek).

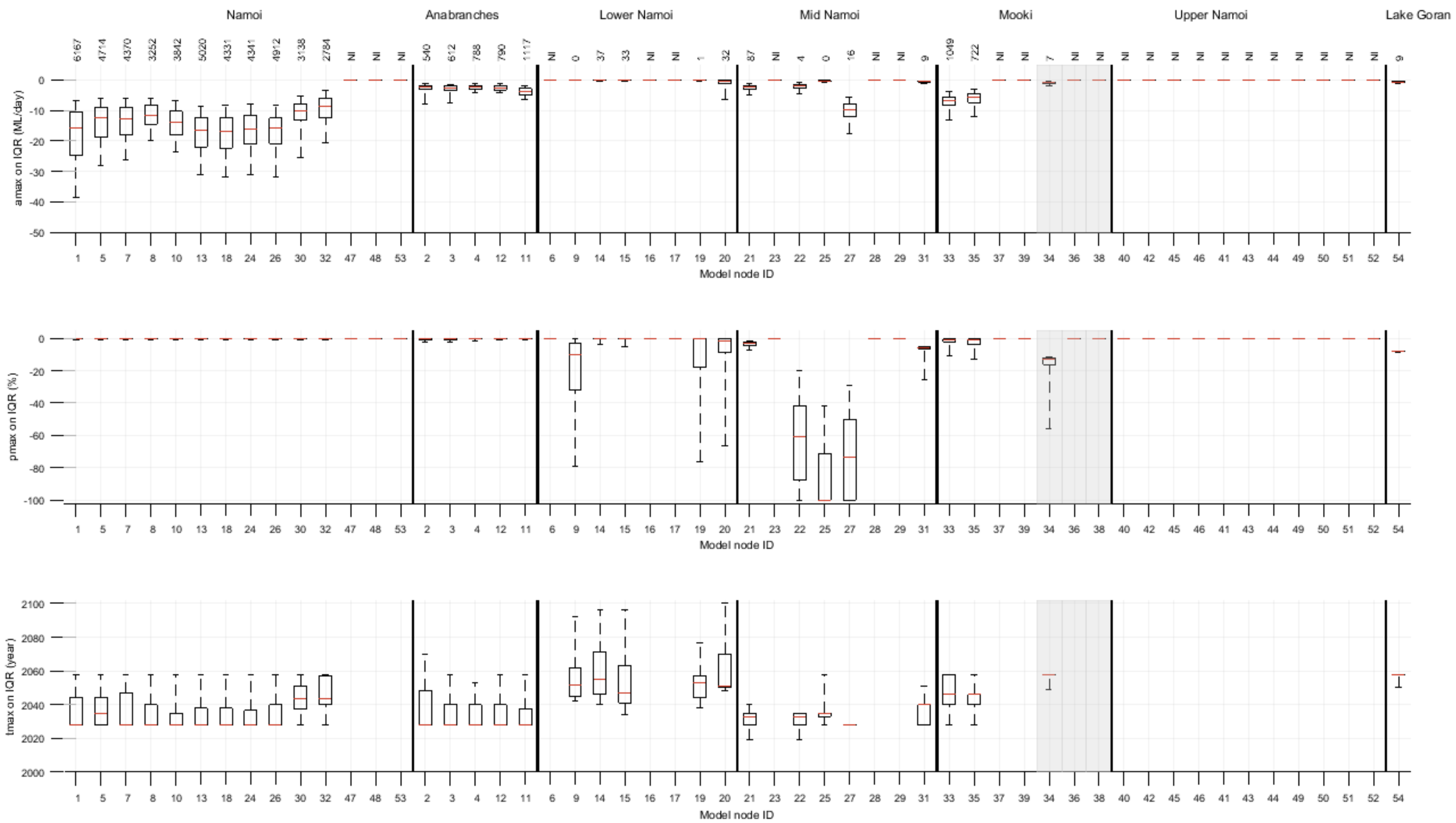

Figure 20 Hydrological changes due to additional coal resource development on interquartile range (IQR) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact
Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.
Refer to Figure 5 for location of model nodes.
Data: Bioregional Assessment Programme (Dataset 1)
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

High-flow days

Figure 21 shows the changes to high-flow days (FD) at each model node. Once again, the largest reductions in the number of high-flow days occur in the small tributaries of the Namoi River as well as in tributaries of the Mooki River and Lake Goran. The biggest change is a maximum reduction in the median number of high-flow days by 33 days per year at node 22 (Back Creek). Six nodes have median reductions in *amax* of more than 5 days per year. However, there is much greater uncertainty around changes in the number of high-flow days (and in the timing of the maximum changes) than there is for changes in AF. Along the Namoi River, FD is reduced by no more than 1 day per year.

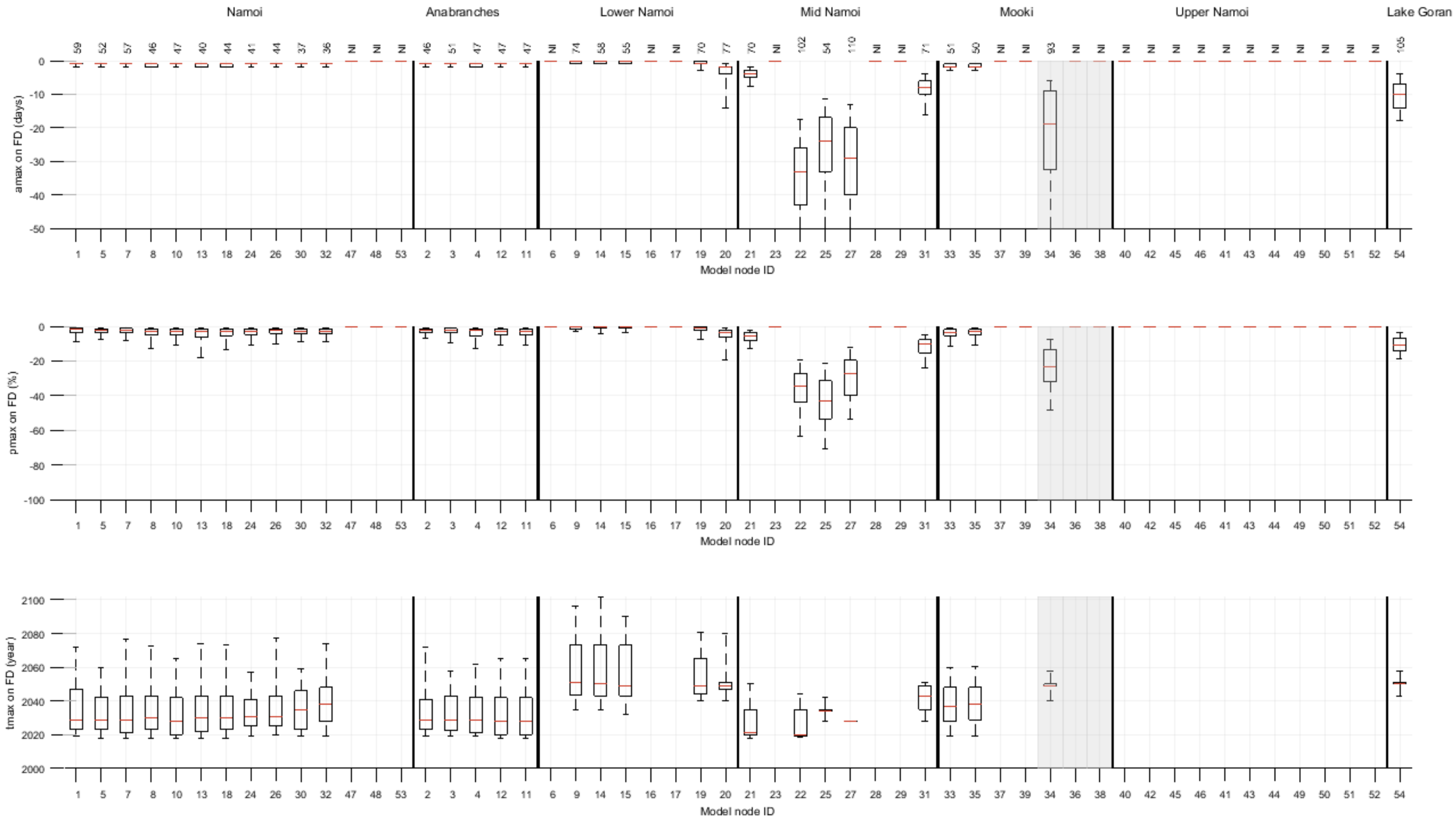

Figure 21 Hydrological changes due to additional coal resource development on the number of high-flow days (FD) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact
Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.
Refer to Figure 5 for location of model nodes.
Data: Bioregional Assessment Programme (Dataset 1)
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

Daily streamflow at the 1st percentile

Figure 22 shows the changes to the daily flow rate at the 1st percentile (P01) at each model node. Reductions in median *pmax* of more than 30% are predicted in many of the tributary nodes, including all nodes with large reductions in high-flow characteristics. Reductions in median *pmax* of 100% are predicted for several mid Namoi and Mooki tributary nodes. These cases are representative of a particular year in a replicate for which there is a non-zero 1st percentile of baseline flow, but the 1st percentile of CRDP flow is zero. In the main channel of the Namoi River below its junction with the Mooki River, reductions in P01 are predicted for every node, but do not exceed 5%.

The timing of the maximum changes tends to be later for P01 than for the high-streamflow hydrological response variables. The median *tmax* for P01 occurs in or later than 2044 at all of the heavily affected nodes except for node 27 (2034).

By comparison to the three flux-based high-streamflow hydrological response variables (AF, IQR and P99), P01 tends to have greater uncertainty – as shown by a large interquartile range relative to the median response – for both *pmax* and *tmax*.

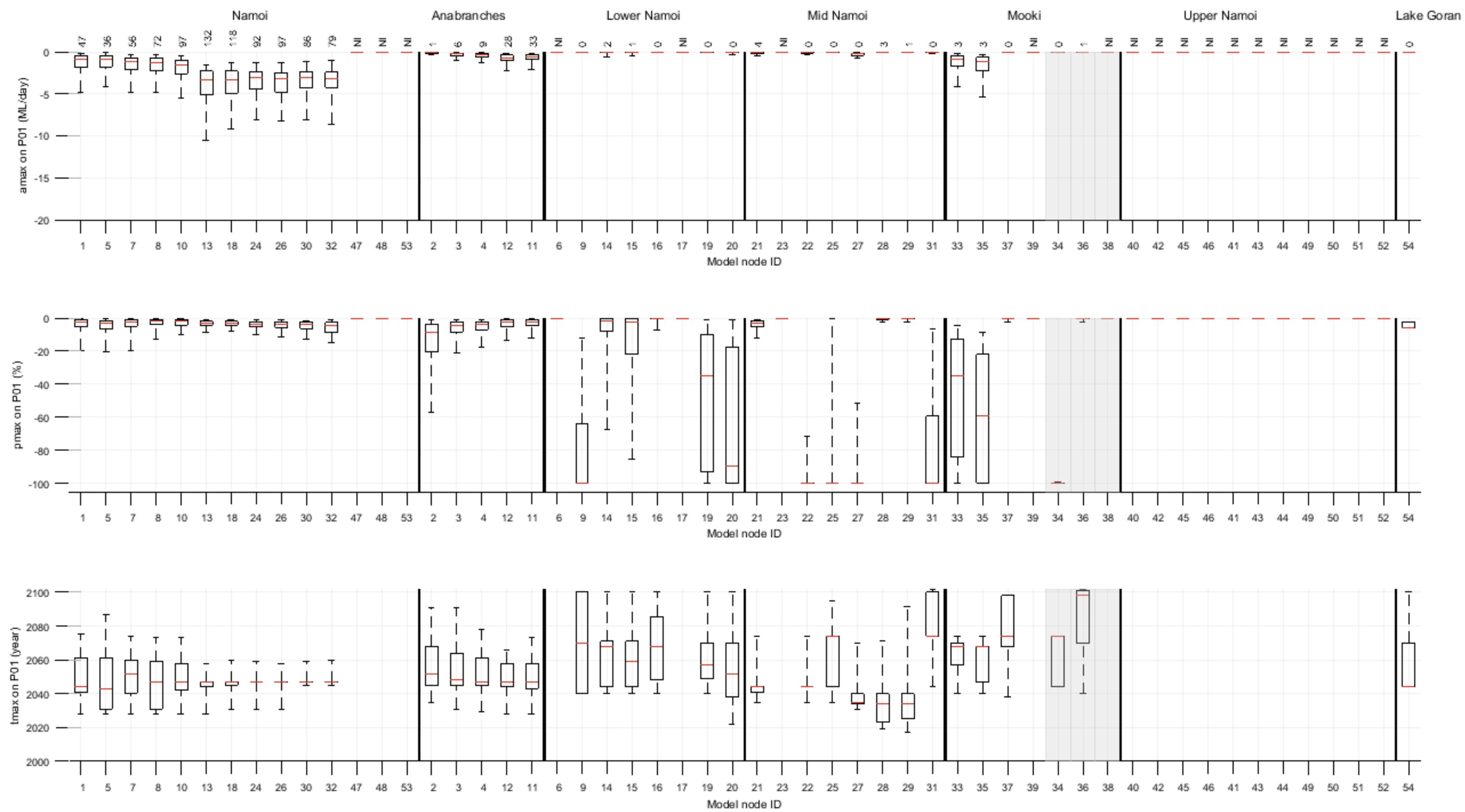

Figure 22 Hydrological changes due to additional coal resource development on daily flow rate at the 1st percentile (P01) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact
Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.
Refer to Figure 5 for location of model nodes.
Data: Bioregional Assessment Programme (Dataset 1)
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

Zero-flow days

Figure 23 shows the increases in the annual number of zero-flow days (ZFD) due to additional coal resource development. All of the model nodes along the Namoi River are perennial in both the baseline and CRDP simulations and therefore show no impact on ZFD. The only model nodes with changes that exceed one or more of the specified thresholds of hydrological change (provided in Section 8.1.4 of companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)) are some of the small tributary nodes of the Namoi River and the nodes of the Mooki River. The largest predicted changes in ZFD are increases of 148 and 189 days/year at nodes 22 and 27. Changes in median *amax* exceed 40 days/year in six other nodes in tributaries of the mid and lower Namoi River and in the Mooki River. However, there is considerable uncertainty in these projections.

Despite this uncertainty in the amount of change, its timing is relatively tightly constrained for three of the most heavily affected nodes (nodes 22, 25 and 27) with median *tmax* falling between 2028 and 2035. However, there is less certainty in *tmax* at other affected locations where the median tends to occur much later.

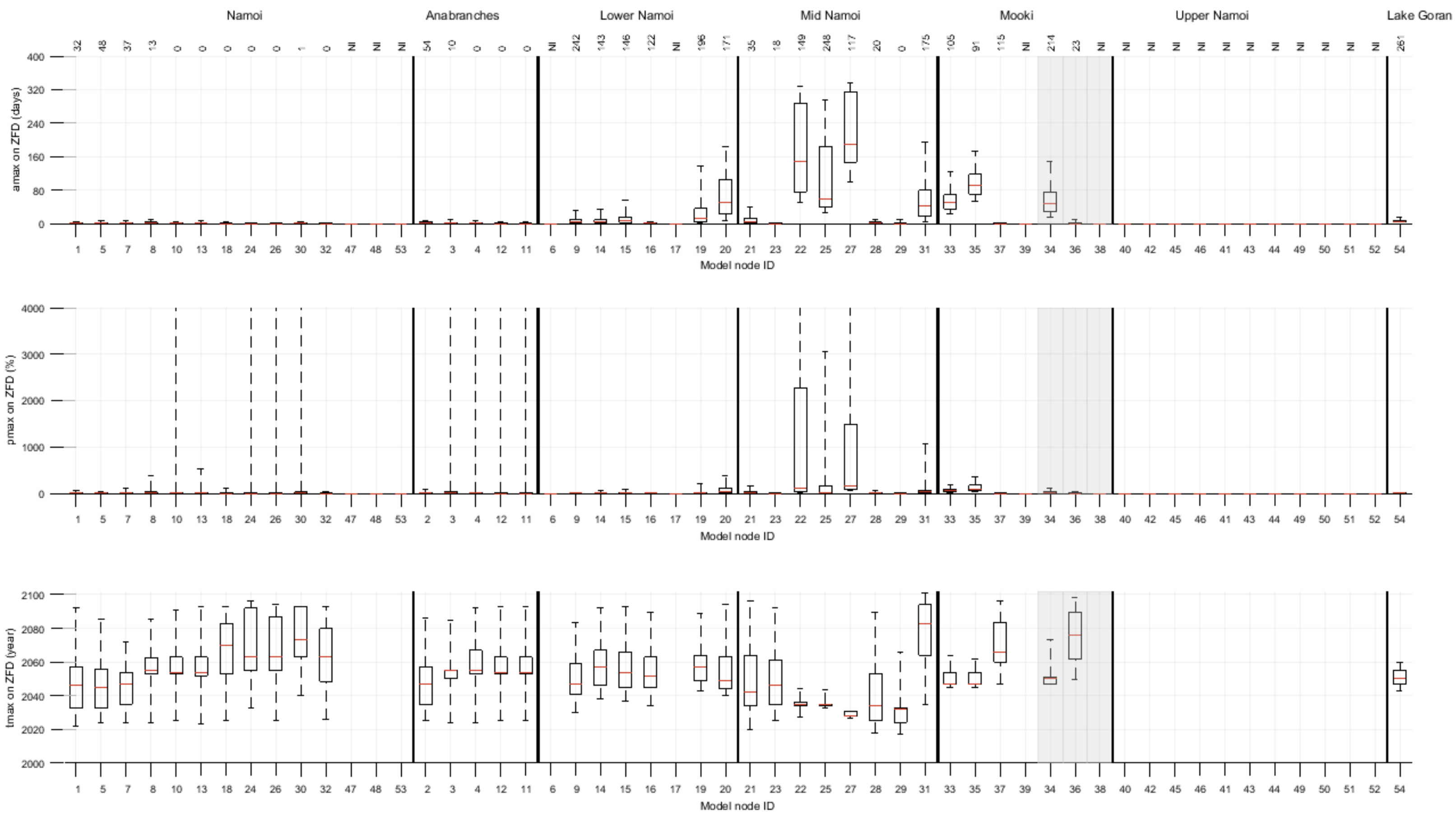

Figure 23 Hydrological changes due to additional coal resource development on the number of zero-flow days (ZFD) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact

Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.

Refer to Figure 5 for location of model nodes.

Data: Bioregional Assessment Programme (Dataset 1)

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

Low-flow days

Figure 24 shows the increases in the annual number of low-flow days (LFD) due to additional coal resource development. There are substantial predicted increases in *amax* in many tributary nodes. The biggest predicted changes are median increases of more than 300 days/year at nodes 22 (Back Creek), 25 (Merrygowen Creek) and 27 (Bollol Creek), and there are seven other tributary nodes with median increases exceeding 50 days/year. The biggest changes along the Namoi River are increases of 3 days/year at nodes 18, 26 and 32.

As is the case with ZFD, there is less uncertainty in *tmax* and earlier median *tmax* values at nodes 22, 25 and 27 than at other heavily affected nodes. For two nodes (nodes 31 in Driggle Draggle Creek and node 37 on the Mooki River) the median *tmax* does not occur until the 2090s.

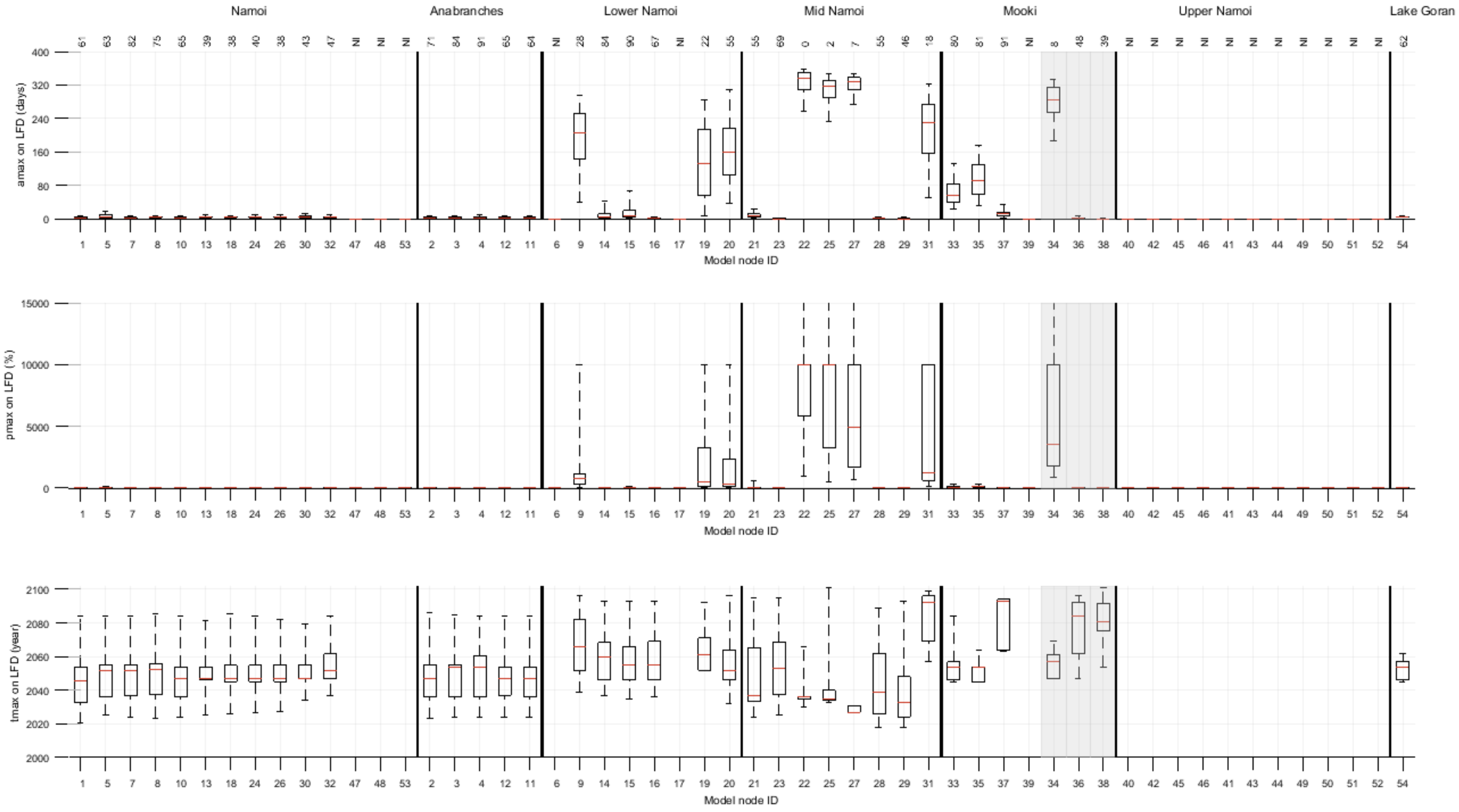

Figure 24 Hydrological changes due to additional coal resource development on the number of low-flow days (LFD) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact

Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.

Refer to Figure 5 for location of model nodes.

Data: Bioregional Assessment Programme (Dataset 1)

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

Low-flow spells

Figure 25 shows the changes in low-flow spells (LFS) due to additional coal resource development. Nodes with large *amax* for LFS are the same as those for LFD and are predominantly in tributaries of the Namoi River. Median *amax* values for LFS range up to 31 spells/year at node 22 (Back Creek). In the Namoi River, no node has a median *amax* value exceeding 1 spell/year. No node has a decrease in the number of LFS, although some do have negative *amax* values at the 5th percentile. These reductions in LFS result when multiple spells coalesce into a single large spell.

There is considerable uncertainty in the projections of both *amax* and *tmax* in Figure 25, although most median *tmax* values occur before 2050.

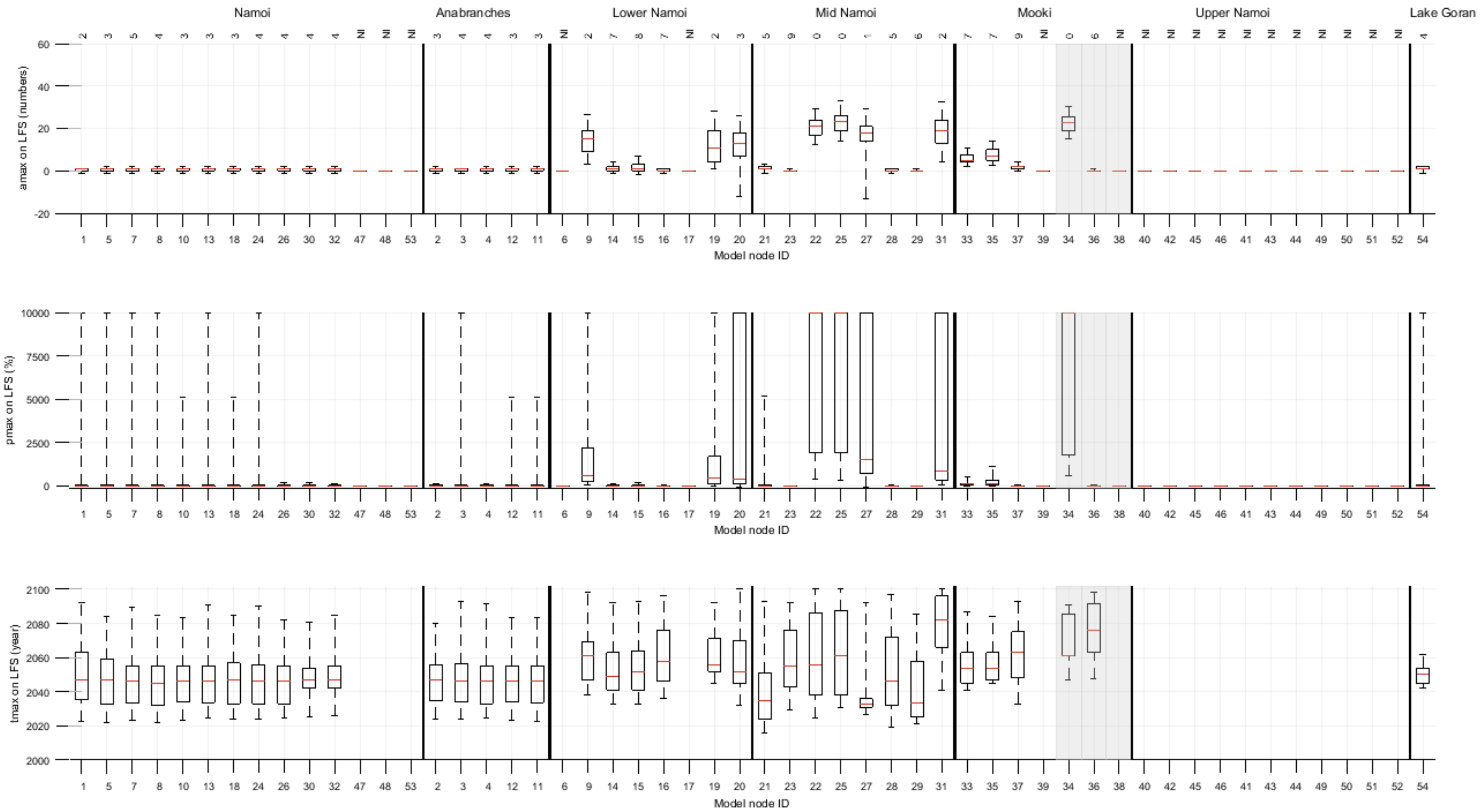

Figure 25 Hydrological changes due to additional coal resource development on the number of low-flow spells (LFS) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact
Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.
Refer to Figure 5 for location of model nodes.
Data: Bioregional Assessment Programme (Dataset 1)
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

Longest low-flow spell

Figure 26 shows the maximum changes to the length of the longest low-flow spell (LLFS). The changes in the LLFS are very similar to those in LFD, with the same three mid Namoi nodes being most affected. The longest low-flow spell is projected to increase in length by nearly 200 days at node 27 (Bollol Creek) and by more than 20 days at nine other small tributary nodes. The biggest change in the Namoi River is an increase of 10 days at node 5, but elsewhere along the Namoi River, the longest low flow spells do not increase by more than 2 days.

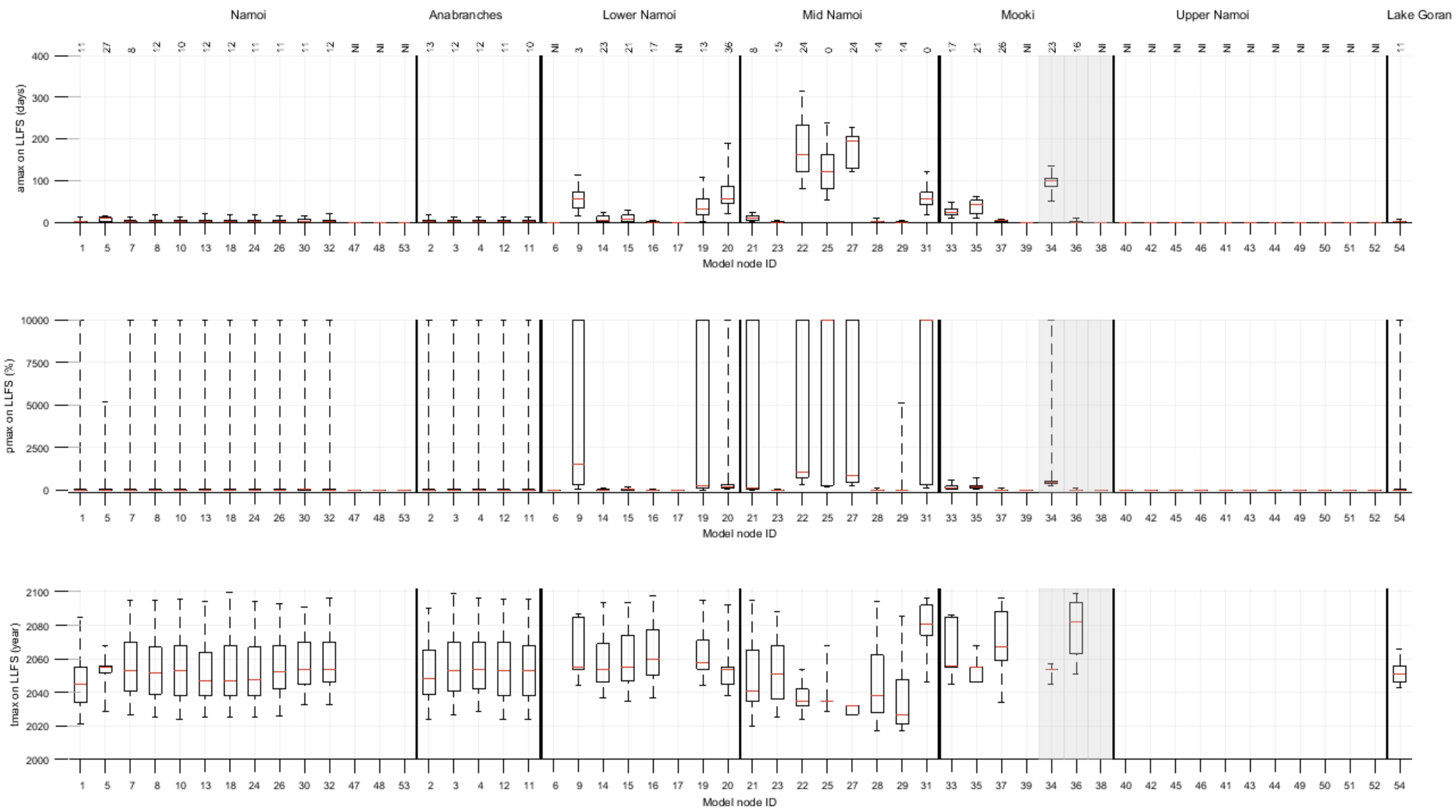

Figure 26 Hydrological changes due to additional coal resource development on the length of the longest low-flow spell (LLFS) at the 54 model nodes within the Namoi subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; NI, no impact
Numbers above the top panel are the median of the best 300 replicates under the baseline for the year corresponding to the median *tmax*. 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 5th and 95th percentiles.
Refer to Figure 5 for location of model nodes.
Data: Bioregional Assessment Programme (Dataset 1)
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

2.6.1.6.3 Conclusion and discussion

The prediction results show that the additional coal resource development in the Namoi subregion has more noticeable effects in hydrological response variables in the small tributaries of the Namoi River, where the proportion of contributing area affected by mining is more likely to be high, than at the nodes along the Namoi River itself. This is particularly apparent in streamflow at nodes 22, 25 and 27, which are on tributaries that enter the Namoi River near Boggabri, and at node 34 which is on a tributary of the Mooki River. For instance, the nodes with the three largest footprints due to additional coal resource development are nodes 25, 22 and 34, where the maximum percentage increases in footprint are 26%, 20% and 17%, respectively. The resulting median *pmax* values for the high-flow flux based variables AF and P99 are around –23%, –19% and –12%, respectively. Node 25 has the largest changes in each of the three flux-based high-streamflow hydrological response variables (AF, P99 and IQR). Its catchment is relatively small (74 km^2), but includes the Boggabri and Tarrawonga additional coal resource developments. The catchments of nodes 22, 27 and 34 include parts of the Maules Creek, Tarrawonga and Watermark mines, respectively. Other nodes with substantial percentage changes in the high-streamflow hydrological response variables are nodes 31 and 54, both of which have parts of additional coal resource development mines in their catchments. All these nodes have relatively small contributing areas. While there are bigger predicted changes in *amax* at nodes further downstream, the proportional impacts of these changes are diluted by relatively unaffected inflows. The prediction that the biggest changes occur downstream of multiple mine developments highlights the cumulative nature of potential hydrological changes.

The biggest changes (in terms of *amax*) on the low-streamflow hydrological response variables are also predicted to occur at these small tributary nodes. However, there is a wider geographic spread of changes for the low-streamflow variables that exceed the specified thresholds. For example, for LFD, LFS and LLFS, there are predicted changes at nodes 9 (Bundock Creek), 19 (Jacks Creek) and 20 (unnamed) that exceed the specified thresholds. These nodes are in the vicinity of the Narrabri Gas Project. The coal seam gas (CSG) development is not expected to directly affect runoff as the amount of water the Narrabri Gas Project proposed to release to the surface water courses is minimal at the regional scale (Santos, no date), but may lower watertables to the extent that baseflow contributions to streamflow may be affected. This would manifest as changes to the low-streamflow hydrological response variables, but would have minimal impact on the high-streamflow variables.

The changes due to the additional coal resource development on the low-streamflow hydrological response variables (P01, LFD, ZFD, LFS and LLFS) appear to be slightly more noticeable than those on the high-streamflow hydrological response variables (AF, P99 and FD). This especially applies to the streams with near zero or very small baseline low flow (e.g. for nodes 22, 25 and 27). The flux-based variables (AF, IQR, P99 and P01) have similar median *pmax* values at the most heavily affected nodes. However, of the two frequency-based variables that are most directly comparable – FD and LFD – the increases in median *amax* values in the latter are typically larger than the decreases in the former. However, the uncertainties in predicted *pmax* (for the flux-based variables), *amax* (for the frequency-based variables) and *tmax* are greater for the low-streamflow variables.

For high-streamflow hydrological response variables, the *tmax* values at model nodes with noticeable changes occur approximately when the maximum footprint for additional coal resource development occurs. This indicates that the rapid streamflow reduction caused by the mine footprint for additional coal resource development dominates *amax* and *pmax* in these hydrological response variables, whereas the changes from the cumulative effect on baseflow over time caused by groundwater drawdown are minimal. This conclusion is supported by the tightly constrained changes in *pmax* at most model nodes for high-streamflow hydrological response variables, which suggest that the biggest impact on the high-streamflow hydrological response variables is caused by interception and retention of surface runoff at the mine sites, rather than by reduced baseflow associated with groundwater drawdown.

For the low-streamflow hydrological response variables, the *tmax* values at nodes with noticeable changes do not coincide consistently with the time of maximum footprint for the additional coal resource development. At many of the most heavily affected nodes, the predicted median *tmax* values tend to be a little later for two of the low-streamflow hydrological response variables – P01 and LLFS. This indicates that the causes of the changes in the low-streamflow hydrological response variables are controlled by a combination of the instantaneous effect from the additional mine footprints and the cumulative effect on baseflow over time caused by groundwater drawdown. Therefore, it is expected that uncertainty in predicting the changes on low-streamflow hydrological response variables is much larger than that on high-streamflow hydrological response variables. This is also shown by the highly variable *pmax* for the low-streamflow hydrological response variables.

The predictions of change in AF in this study are not inconsistent with those of the Schlumberger (2012) modelling study (see Section 2.6.1.2). The Schlumberger study predicts reductions in annual flow of approximately 0.1% at locations in the Namoi River that are roughly corresponding with nodes 18, 26 and 32. In this study the projected reductions are 0.3%, 0.2% and 0.2%, respectively. Similarly, in the Mooki River at locations approximately corresponding with nodes 33 and 35, the Schlumberger study predicts reductions of 0.2% and 0.0% whereas this study predicts 0.5% and 0.3%. The Schlumberger study therefore predicts slightly smaller changes than this study. This outcome is unsurprising since the Schlumberger study gives changes averaged over a 90-year period, while this study gives the changes in the single year with biggest change over a similar 90-year period.

2.6.1.6.4 Defining thresholds for hydrological change

The consequences of the changes to streamflow characteristics on landscape classes and water-dependent assets are considered in companion product 3-4 (impact and risk analysis) for the Namoi subregion (as listed in Table 2). In order to rule out surface water dependent landscape classes and assets that are unlikely to be impacted by changes in surface water hydrology, it is necessary to define a threshold, above which changes in hydrology will be considered further, and which reaches of the stream network are and are not showing this hydrological change. Specified thresholds of hydrological change are provided for each of the nine hydrological response variables in Section 8.1.4 of companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016):

- the flux-based hydrological response variables – AF, P99 and IQR – is a 5% or greater chance of a 1% or greater change in the variable (i.e. if at least 5% of model replicates show a maximum difference between the CRDP and baseline of at least 1% of the baseline value)
- the flux-based hydrological response variable – P01 – is a 5% or greater chance of a 1% or greater change in the variable and the change in runoff depth is greater than 0.0002 mm. Note that the addition of a runoff depth threshold is a departure from Viney (2016) and is designed to exclude reaches where the absolute change in runoff is minimal
- the frequency-based metrics – FD, LFD, LLFS and ZFD – is a greater than 5% chance of there being a change in the variable of at least 3 days in any year
- the frequency-based metric – LFS – is a greater than 5% chance of there being a change in the variable of at least 2 spells in any year.

Table 13 summarises the hydrological changes due to the additional coal resource development for each of the surface water modelling nodes in the Namoi subregion for each hydrological response variable that exceed the specified thresholds.

At 18 nodes (node 6, node 17 and nodes 38 to 53, all of which are upstream of the proposed developments) there are no hydrological changes in any hydrological response variable that exceed the specified threshold. This includes Baradine Creek, the uppermost nodes of Bohena Creek and Mooki River, and all reaches on the Namoi River and its tributaries upstream of the junction with the Mooki River. At nodes 21, 22, 25, 27, 31, 34 and 54, there are changes in all nine hydrological response variables that exceed the specified thresholds. At all other nodes, there are changes in some hydrological response variables where the specified thresholds are exceeded, but not in others.

The last row in Table 13 gives the number of nodes for which there is a change for each hydrological response variable that exceeds the specified thresholds. The low-streamflow hydrological response variables (LLFS, LFD, P01, ZFD and LFS), each of which has change that exceeds the specified thresholds in at least 30 nodes, are markedly more affected than the high-streamflow hydrological response variables (AF, FD and P99).

Figure 27 shows reaches predicted to experience a change in at least one hydrological response variable that exceeds the specified threshold due to additional coal resource development.

Table 13 Hydrological changes due to additional coal resource development at each model node (row) for each hydrological response variable (column)

E = exceeds specified threshold; – indicates that it does not exceed specified threshold

	AF	P99	IQR	FD	P01	LFD	LFS	LLFS	ZFD	Total for node
1	–	–	–	–	E	E	–	E	E	4
2	–	–	E	–	E	E	E	E	E	6
3	–	–	E	–	E	E	E	E	E	6
4	–	–	E	–	E	E	E	E	E	6
5	–	–	–	–	E	E	E	E	E	5
6	–	–	–	–	–	–	–	–	–	0
7	–	–	–	–	E	E	E	E	E	5
8	–	–	–	–	E	E	E	E	E	5
9	–	–	E	–	E	E	E	E	E	6
10	–	–	–	–	E	E	E	E	E	5
11	–	–	–	–	E	E	E	E	E	5
12	–	–	E	–	E	E	E	E	E	6
13	–	–	–	–	E	E	E	E	E	5
14	–	–	E	–	E	E	E	E	E	6
15	–	–	E	–	E	E	E	E	E	6
16	–	–	–	–	E	E	–	E	E	4
17	–	–	–	–	–	–	–	–	–	0
18	–	E	–	–	E	E	E	E	E	6
19	E	–	E	E	E	E	E	E	E	8
20	E	–	E	E	E	E	E	E	E	8
21	E	E	E	E	E	E	E	E	E	9
22	E	E	E	E	E	E	E	E	E	9
23	–	–	–	–	–	–	–	E	–	1
24	–	–	–	–	E	E	E	E	–	4
25	E	E	E	E	E	E	E	E	E	9
26	–	–	–	–	E	E	E	E	–	4
27	E	E	E	E	E	E	E	E	E	9
28	–	–	–	–	E	E	–	E	E	4
29	–	–	–	–	E	E	–	E	E	4
30	–	–	E	–	E	E	E	E	E	6
31	E	E	E	E	E	E	E	E	E	9

	AF	P99	IQR	FD	P01	LFD	LFS	LLFS	ZFD	Total for node
32	–	–	–	–	E	E	E	E	–	4
33	–	E	E	E	E	E	E	E	E	8
34	E	E	E	E	E	E	E	E	E	9
35	–	E	E	E	E	E	E	E	E	8
36	–	–	–	–	E	E	–	E	E	4
37	–	–	–	–	E	E	E	E	–	4
38	–	–	–	–	–	–	–	–	–	0
39	–	–	–	–	–	–	–	–	–	0
40	–	–	–	–	–	–	–	–	–	0
41	–	–	–	–	–	–	–	–	–	0
42	–	–	–	–	–	–	–	–	–	0
43	–	–	–	–	–	–	–	–	–	0
44	–	–	–	–	–	–	–	–	–	0
45	–	–	–	–	–	–	–	–	–	0
46	–	–	–	–	–	–	–	–	–	0
47	–	–	–	–	–	–	–	–	–	0
48	–	–	–	–	–	–	–	–	–	0
49	–	–	–	–	–	–	–	–	–	0
50	–	–	–	–	–	–	–	–	–	0
51	–	–	–	–	–	–	–	–	–	0
52	–	–	–	–	–	–	–	–	–	0
53	–	–	–	–	–	–	–	–	–	0
54	E	E	E	E	E	E	E	E	E	9
Total E	**9**	**10**	**19**	**11**	**35**	**35**	**30**	**36**	**31**	

Shortened forms of hydrological response variables are defined in Section 1.1.1.6.1. Specified thresholds for each hydrological response variable are provided in Section 2.6.1.6.4.
Data: Bioregional Assessment Programme (Dataset 1)

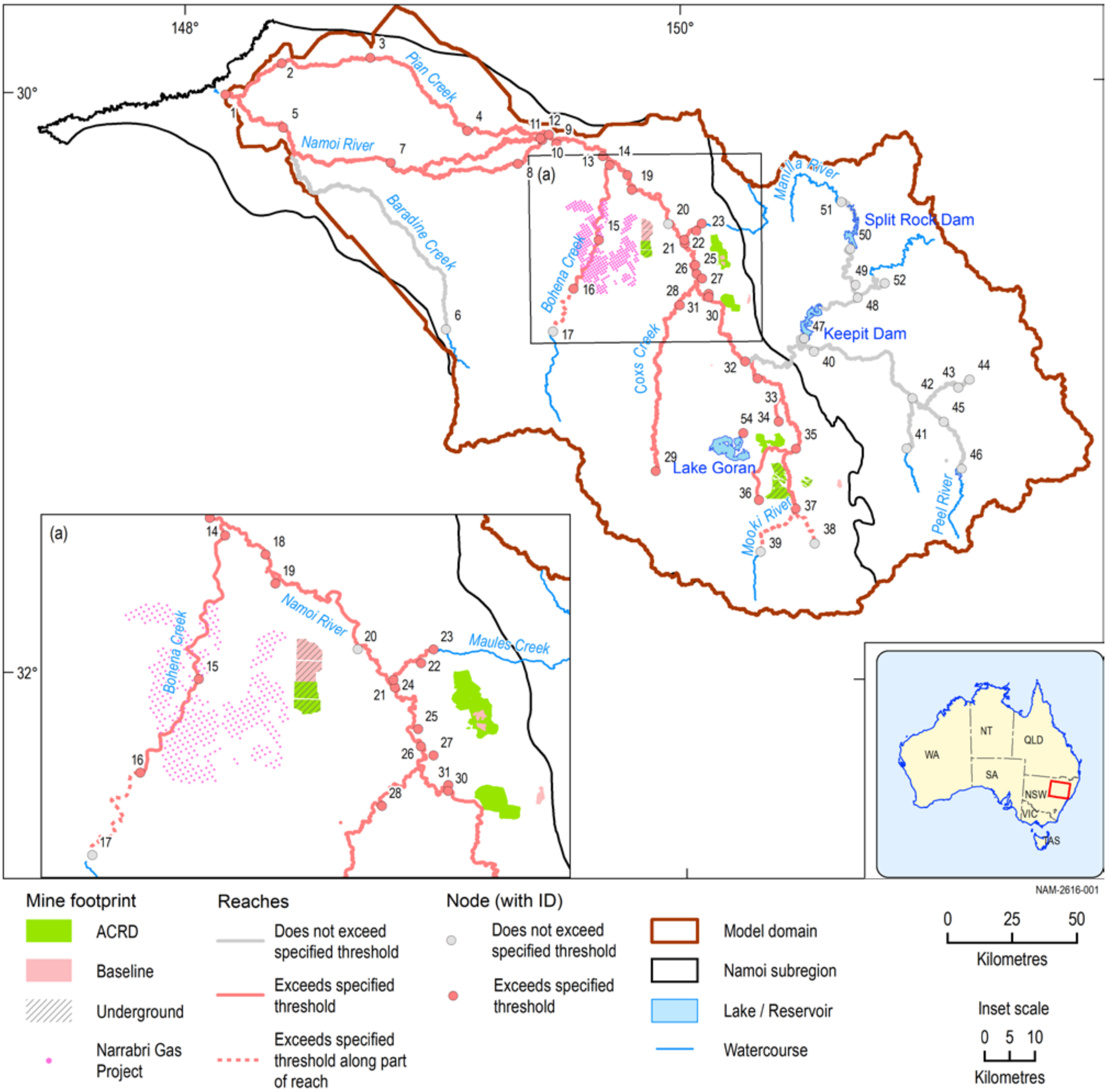

Figure 27 Model nodes and links with changes in at least one hydrological response variable that exceeds specified thresholds due to additional coal resource development in the Namoi subregion

ACRD = additional coal resource development; AWRA-R = Australian Water Resources Assessment river model
Data: Bioregional Assessment Programme (Dataset 1); Bureau of Meteorology (Dataset 2)

For some reaches (e.g. those below nodes 38 and 39 but above node 37), hydrological change can change from exceeding specified thresholds to not exceeding these thresholds between the two nodes. These reaches are shown as dashed pink lines and other information is needed to delineate the change on these reaches. Similarly, upstream of the headwater nodes exceeding the threshold change in hydrology, there will be some length of stream that is also potentially affected by coal resource development.

To define the zone of potential hydrological change for the impact and risk analysis – that is, the area outside of which it is very unlikely that landscape classes and assets will be impacted – we need to determine the upstream extents of the stream network likely to experience hydrological changes that exceed the threshold. This final step is reported in companion product 3-4 (impact and risk analysis) for the Namoi subregion (as listed in Table 2), where drawdown results from the groundwater modelling and mine footprint data are used to identify stream reaches that are not explicit in the surface water node-link network and where hydrological changes from additional coal resource development are likely to exceed specified thresholds.

The implications of potential changes in hydrology from additional coal resource development for the Namoi subregion landscape classes and assets are described in companion products 2.7 (receptor impact modelling) and 3-4 (impact and risk analysis) for the Namoi subregion (listed in Table 2).

2.6.1.6.5 Gaps

The AWRA-L calibration tends to under estimate zero-flow days, low-flow days, low-flow spells and length of the longest low-flow spell. The AWRA-R is also calibrated poorly for zero-flow days and low-flow days. This is true for all subregions including the Namoi subregion which, for most parts, is a comparatively drier basin compared to the Hunter subregion. There are a number of reasons for this:

- The lower end of the rating curve tends to be highly variable due to physical changes taking place in the stream channel bed, making the lower low-flow measurement *relatively* more prone to error.
- Modelled results usually comprise long tails of very low flows asymptotic to zero requiring guessing a threshold value below which all modelled values are taken as zero.
- Although transformed flow was used with a combination of Nash–Sutcliffe efficiency and bias as objective function to improve the goodness of fit of the lower flow values, the tendency of the Nash–Sutcliffe efficiency to match higher flow, combined with the uncertainty in the extent of appropriate transformation, leads to the errors in low-streamflow calibration.

The difference in modelled and observed values are caused by errors (i) in input streamflow data, (ii) in input climate data, (iii) in model structure, and (iv) due to use of non-optimal parameter values. The model calibration minimises only the fourth error (iv) (Madsen, 2000).

Inherent problems with poor low-streamflow calibration will always exist unless all of the reasons described above are eliminated. However, effects of the poor low-streamflow calibration become less crucial in the bioregional assessment (BA) as the difference between CRDP and baseline would cancel out some of the errors caused. Besides, the results reported in the BA are based on the best 300 replicates obtained by comparing observed and modelled low-streamflow related hydrological response variables.

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Datasets

Dataset 1 Bioregional Assessment Programme (2017) Namoi AWRA-R model implementation (post groundwater input). Bioregional Assessment Derived Dataset. Viewed 25 October 2017, http://data.bioregionalassessments.gov.au/dataset/8681bd56-1806-40a8-892e-4da13cda86b8.

Dataset 2 Bureau of Meteorology (2011) Geofabric Surface Cartography - V2.1. Bioregional Assessment Source Dataset. Viewed 07 December 2016, http://data.bioregionalassessments.gov.au/dataset/5342c4ba-f094-4ac5-a65d-071ff5c642bc.

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

amax: maximum raw change

annual flow (AF): the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

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

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

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

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

consequence: synonym of impact

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

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

dataset: a collection of data in files, in databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file).

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

diversion: see extraction

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

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

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

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

Geofabric: a nationally consistent series of interrelated spatial datasets defining hierarchically-nested river basins, stream segments, hydrological networks and associated cartography groundwater: water occurring naturally below ground level (whether stored in or flowing through aquifers or within low-permeability aquitards), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

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

groundwater system: see water system

high-flow days (FD): the number of high-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). The threshold for high-flow days is the 90th percentile from the simulated 90-year period. In some early products, this was referred to as 'flood days'.

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

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

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

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

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

interquartile range (IQR): the interquartile range in daily flow (ML/day); that is, the difference between the daily flow rate at the 75th percentile and at the 25th percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

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

length of low-flow spell (LLFS): the length (days) of the longest low-flow spell each year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

low-flow days (LFD): the number of low-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). The threshold for low-flow days is the 10th percentile from the simulated 90-year period.

low-flow spells (LFS): the number of low-flow spells per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). A spell is defined as a period of contiguous days of flow below the 10th percentile threshold.

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

model spin-up period: a period of time in which the model is allowed to run prior to the period for which predictions are required. A spin-up period allows the initial values of any model stores (such as the soil water stores) before the prediction period begins.

Namoi subregion: The Namoi subregion is located within the Murray–Darling Basin in central New South Wales. The subregion lies within the Namoi river basin, which includes the Namoi, Peel and Manilla rivers. However, the subregion being assessed is smaller than the Namoi river basin because the eastern part of the river basin does not overlie a coal-bearing geological basin. The largest towns in the subregion are Gunnedah, Narrabri and Walgett. The main surface water resource of the Namoi subregion is the Namoi River. There are three large dams that supply water to the subregion, of which Keepit Dam is the main water storage. More than half of the water released from Keepit Dam and river inflow may be extracted for use for agriculture, towns and households. Of this, the great majority is used for agricultural irrigation. The landscape has been considerably altered since European settlement for agriculture. Significant volumes of groundwater are also used for agriculture (cropping). Across the subregion there are a number of water-dependent ecological communities, and plant and animal species that are listed as threatened under either Commonwealth or New South Wales legislation. The subregion also contains Lake Goran, a wetland of national importance, and sites of international importance for bird conservation.

overbank flow: flood condition where water flows beyond and sub-parallel to the main channel of a river, but within the bounding floodplain

P01: the daily flow rate at the 1st percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

P99: the daily flow rate at the 99th percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

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

pmax: maximum percent change

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

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

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

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

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

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

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

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

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

sustainable yield: the level of water extraction from a particular system that, if exceeded, would compromise the productive base of the water resource and important environmental assets or ecosystem functions tmax: year of maximum change

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 allocation: the specific volume of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development

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

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

zero-flow days (ZFD): the number of zero-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

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