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

Surface water numerical modelling for the Hunter subregion

Product 2.6.1 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment

2018

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

The Bioregional Assessment Programme

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

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

Department of the Environment and Energy

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.

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Cover photograph

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

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

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CSIRO

Executive summary

Coal resource development can potentially affect water-dependent assets (either negatively or positively) through impacts on surface water hydrology. This product presents the modelled hydrological changes in response to likely coal resource development in the Hunter subregion after December 2012.

To quantify impacts of coal resource development in the Hunter 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 commercially producing as at 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 Hunter subregion, including expansions of baseline operations, that are expected to begin commercial production after December 2012.

In the Hunter subregion, coal mining has been occurring for over 100 years. The BA for the Hunter subregion includes 42 baseline mines and 22 additional coal resource developments. Twelve baseline mines were not modelled because they were within the tidal zone of the river system or under Lake Macquarie and adjacent urban areas, did not have associated additional coal resource developments and/or due to lack of data. Five additional coal resource developments were not modelled due to lack of data, low likelihood of impact at the surface or being under Lake Macquarie. Therefore, the surface water numerical modelling in the Hunter subregion includes 47 mines comprising 30 baseline mines and 17 additional coal resource developments. In the Hunter subregion, there are no CSG fields in the CRDP.

Surface water modelling of the Hunter subregion follows the companion submethodology M06 for surface water modelling. In particular, the modelling is undertaken as follows:

- The model includes rainfall-runoff 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).
- Changes in baseflow from the Hunter subregion groundwater model are also fed into the AWRA-R model at points along the river network.
- The river model integrates the potential baseflow and runoff changes due to the modelled coal resource developments.

- The modelling domain includes part of the Hunter river basin and part of the Macquarie-Tuggerah lakes basin.
- Daily streamflow predictions are produced at 65 model nodes.
- The model simulation period is from 2013 to 2102.

Evaluation 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 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.

The surface water modelling results show that the additional coal resource development in the Hunter subregion has the potential to cause large changes in the flow regime of some streams. This is particularly evident for the hydrological response variables that characterise high-streamflow conditions at model nodes where the additional coal resource developments cover a large proportion of the contributing area.

In general, the hydrological effects attributable to the additional coal resource development are greater in the small tributaries of the Hunter River than along the river itself. The biggest impacts (flow reductions of up to 80%) occur at nodes 7 to 9 (Loders Creek, including Doctors Creek), which enter the Hunter River just upstream of Singleton, and at nodes 52 (Dry Creek) and 55 (unnamed creek) in the vicinity of Muswellbrook. The catchments of nodes 7 to 9 include the Bulga and Mount Thorley–Warkworth mines, while the catchments of nodes 52 and 55 include the Bengalla and Mount Pleasant mines. Other nodes with substantial percentage changes in the high-streamflow hydrological response variables are nodes 26, 27, 29 and 35. The first three of these nodes are all located in the vicinity of the Glendell, Integra, Liddell and Mount Owen mines, while the catchment of node 35 includes parts of the Drayton South and Mount Arthur mines. All these nodes have relatively small catchment areas. Although there are bigger predicted changes in maximum raw change (*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 changes to the low-streamflow hydrological response variables attributable to the additional coal resource development appear to be slightly larger than those to the high-streamflow hydrological response variables. However, the uncertainty in the predicted change and the timing of the maximum change are greater for the low-streamflow variables.

There is a substantial change in the low-streamflow hydrological response variables in the two nodes of the Wyong river basin. These nodes are located near the proposed Wallarah 2 and Mandalong underground mines. In the most heavily affected year, these reductions in baseflow are predicted to turn a perennial stream into one that flows on only about 40% of days. Although this is a large reduction, it must be remembered that the projections presented in Section 2.6.1.6 are for the worst-case year during the entire simulation period (2013 to 2102). There is no implication, particularly for the low-flow variables, that the changes will be this severe in every year. When local hydrogeological and geological data are used to constrain groundwater model results in the Wyong river basin, groundwater drawdowns are predicted to be smaller and less extensive, resulting in little to no changes in baseflow (product 2.6.2). Where results from the regional scale modelling flag a risk of large hydrological changes from additional coal resource development, a more locally relevant assessment of potential hydrological changes should be made using local information to constrain the set of regional simulations to those representative of the local conditions.

The results suggest that 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 watertable drawdown. The changes to high-streamflow characteristics are dominated by direct interception of runoff.

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

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- Additional Reviewers: Mark Simons (NSW Department of Primary Industries (Office of Water)) Abi Javam (NSW Department of Primary Industries (Office of Water)).

Currency of scientific results

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

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

Introduction

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

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

The IESC has been involved in the development of *Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (the BA methodology; Barrett et al., 2013) and has endorsed it. The BA methodology specifies how BAs should be undertaken. Broadly, a BA comprises five components of activity, as illustrated in Figure 1. Each BA 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.

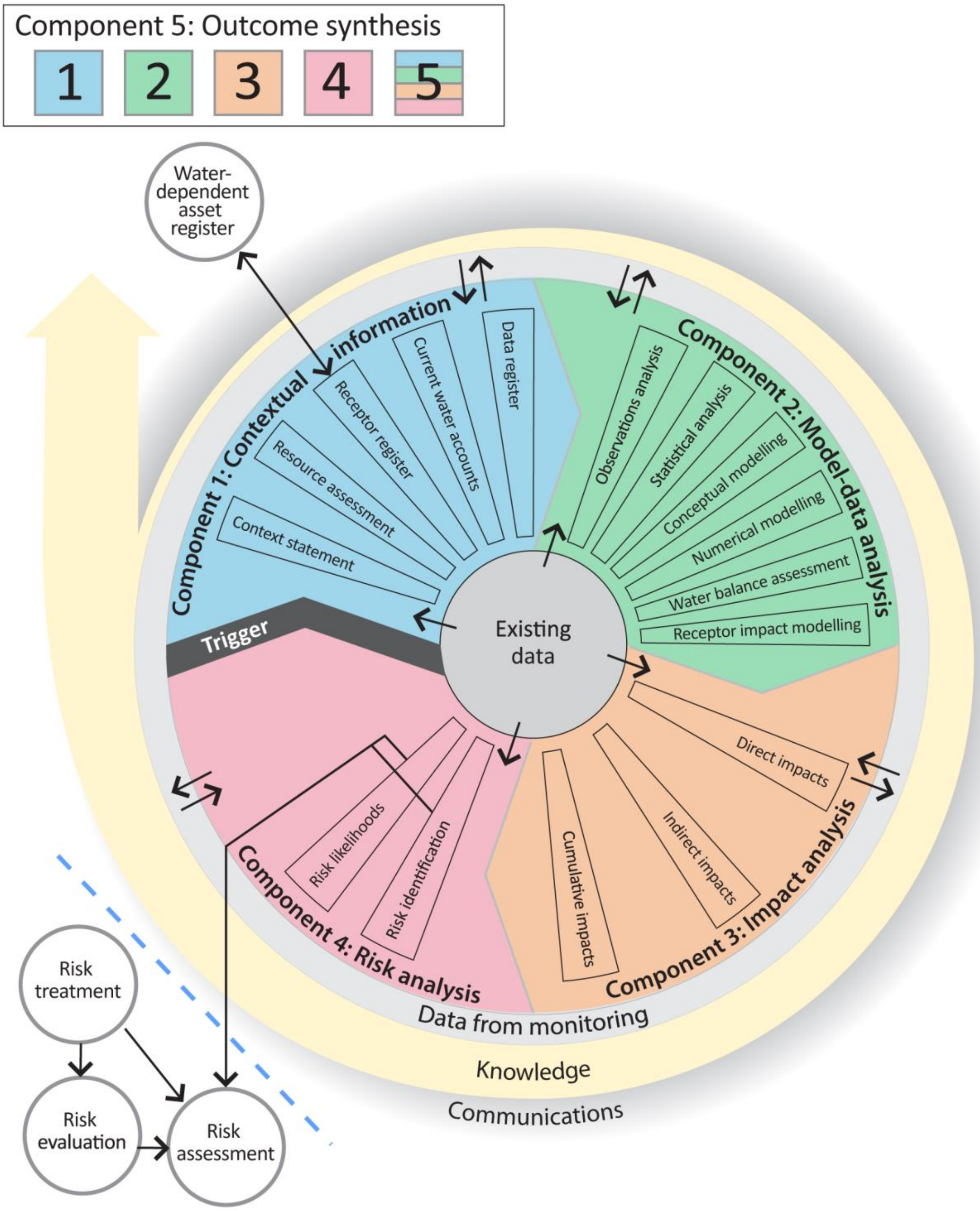

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

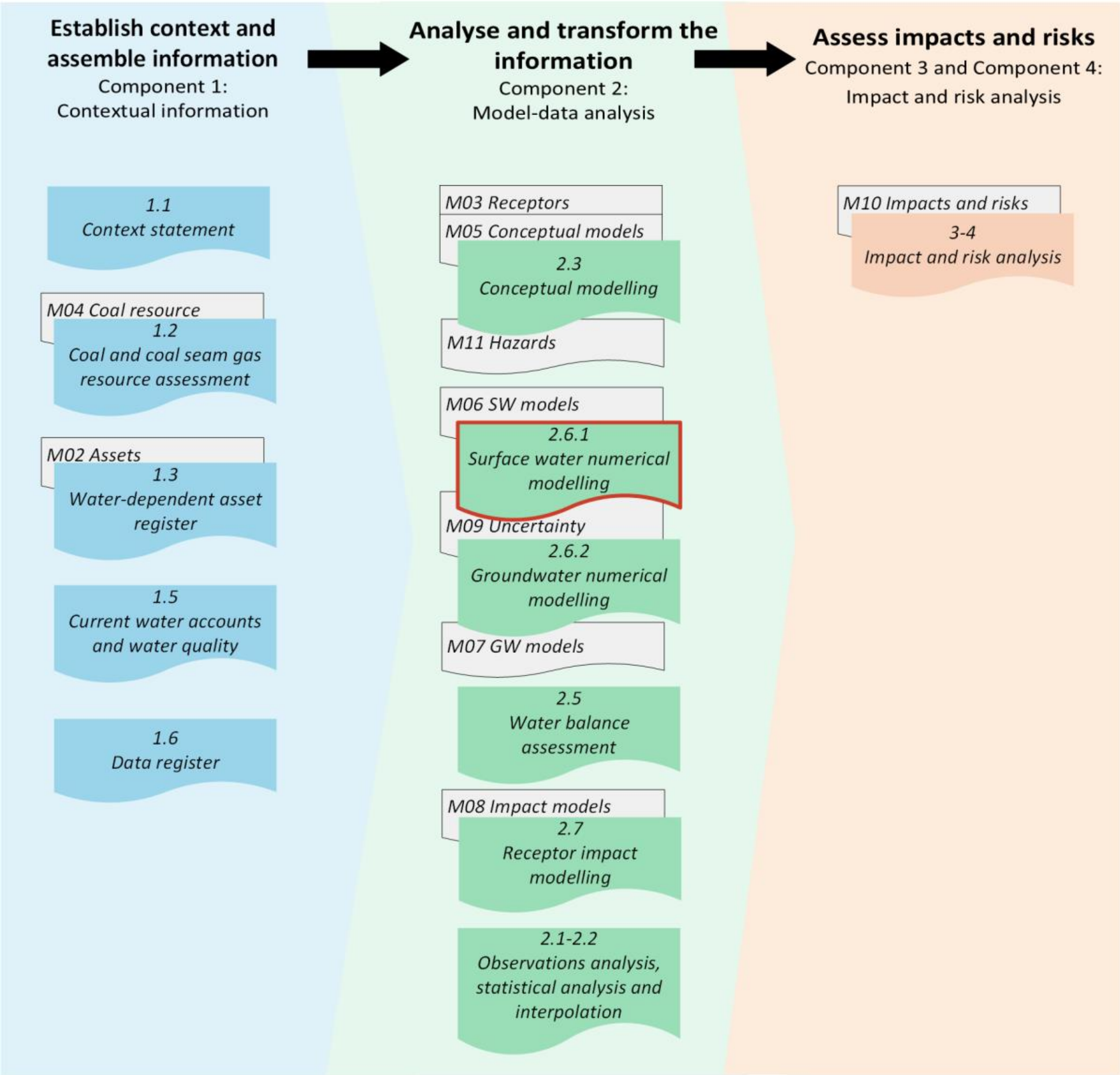

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Hunter subregion

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

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

[a]The types of products are as follows:

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

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

About this technical product

The following notes are relevant only for this technical product.

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

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Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 2 March 2018, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 2 March 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 Hunter 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 Hunter 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 modelling in the Bioregional Assessment Programme appears in companion submethodology M06 (as listed in Table 1) (Viney, 2016). This section describes the departures from that generic methodology that have been applied in the Hunter subregion.

Surface water modelling of the Hunter 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 Hunter 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 numerical surface water modelling in a bioregional assessment has a very specific objective: to probabilistically evaluate potential hydrological change in the coal resource development pathway (CRDP) relative to the baseline at specified locations in the subregion to inform the impact and risk analysis reported in product 3-4. Outputs from the surface water modelling are also used as inputs to product 2.7 (receptor impact modelling) to facilitate evaluation of the cumulative impacts of mining on water-dependent ecological and economic assets.

The probabilistic aspect of the analysis implies that modelling does not provide a single best estimate of the change, but rather an ensemble of estimates. This ensemble enables statements such as: 'In 95% of the simulations, the change at location x,y does not exceed z.'

To generate these ensembles of predictions, a large number of model parameter sets are evaluated for the surface water and groundwater models. The range of parameters reflects both the natural variability of the system and the uncertainty in the understanding of the system. 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 and model choices necessary to create the models. 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. In the numerical modelling the precautionary principle is adopted: impacts are over estimated rather than under estimated. As long as it can be shown that an assumption over estimates – not under estimates – impacts, the assumption is considered valid for the specific purpose of this modelling.

However, an overly conservative estimate of impact is not desirable either. If there are sound reasons to believe that predicted impacts are deemed unrealistically high (e.g. in comparison to earlier modelling efforts in the bioregion or subregion), the assumptions may need to be revisited.

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

This product starts with an overview of the methods as applied to the Hunter subregion (Section 2.6.1.1.2), focusing on the interaction between the surface water and groundwater model, followed with a review of the existing surface water models (Section 2.6.1.2). Section 2.6.1.3 and Section 2.6.1.4 describe the development of the model and its calibration. Next is the uncertainty analysis (Section 2.6.1.5), which contains the justification of assumptions and the resulting ensembles of predicted impacts. The product concludes by describing the predictions arising from the surface water model (Section 2.6.1.6).

2.6.1.1.2 Surface water numerical modelling

Surface water modelling in the Hunter 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 Hunter river basin covers a large area and comprises both regulated and unregulated river sections. Downstream of Glenbawn Dam and Glennies Creek Dam, the Hunter River and Glennies Creek are regulated. This means that in addition to inflows from unregulated tributaries and groundwater, river flow in these reaches reflects releases of water stored in the dams to meet the needs of downstream users, including the environment. These characteristics dictate that a river model is required to translate streamflows generated by the landscape model. This is done using the AWRA river model (AWRA-R) (Dutta et al., 2015), an overview of which is provided in Viney (2016).

The exception here is for the Wyong River in the Macquarie-Tuggerah lakes basin, which is smaller and unregulated and no river modelling is applied. In this catchment, the salient features of streamflow can be simulated solely with the rainfall-runoff model. Gridded output from AWRA-L is accumulated to the model nodes without any lagged routing.

The regulated section of the Hunter River from Glenbawn Dam to Singleton is the focus of the Hunter River Salinity Trading Scheme (HRSTS), which was established to manage discharges of water to the Hunter River by the mining and power generation sectors to minimise water quality impacts. New Hunter-specific functionality has been added to AWRA-R to mimic the effects of the HRSTS. Details of this part of the model are given in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a).

In all other respects, the surface water modelling in the Hunter subregion follows the methodology set out in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

2.6.1.1.3 Model sequencing

For the Hunter subregion, the modelling suite includes the AWRA-L landscape model (Viney et al., 2015) to calculate the surface runoff to streams; the Multiphysics Object-Oriented Simulation Environment (MOOSE) groundwater model to simulate watertables and baseflows (MOOSE, 2016; Herron et al., 2018b); and the AWRA-R river routing model (Dutta et al., 2015) by which river flows are propagated downstream. The individual models have different spatial and temporal resolution which requires a set of customised processing steps to upscale or downscale model data to allow the models to be linked.

Figure 3 illustrates the model sequencing, parameters exchanged between models and outputs generated at model nodes to inform the receptor impact modelling. The MOOSE, AWRA-L and AWRA-R baseline runs simulate the changes arising from coal mines that were commercially producing coal as at December 2012. The corresponding CRDP runs simulate the combined changes arising from the baseline coal resource development and those expected to begin commercial production after 2012.

The landscape model, AWRA-L, delivers surface runoff to the river model, AWRA-R. This flux includes the effects of any coal development on surface runoff generation. AWRA-R also receives information on changes to baseflow generation associated with the coal resource developments from the groundwater model. The differences in streamflow between coal resource developments in the CRDP and baseline are obtained from the output of AWRA-R.

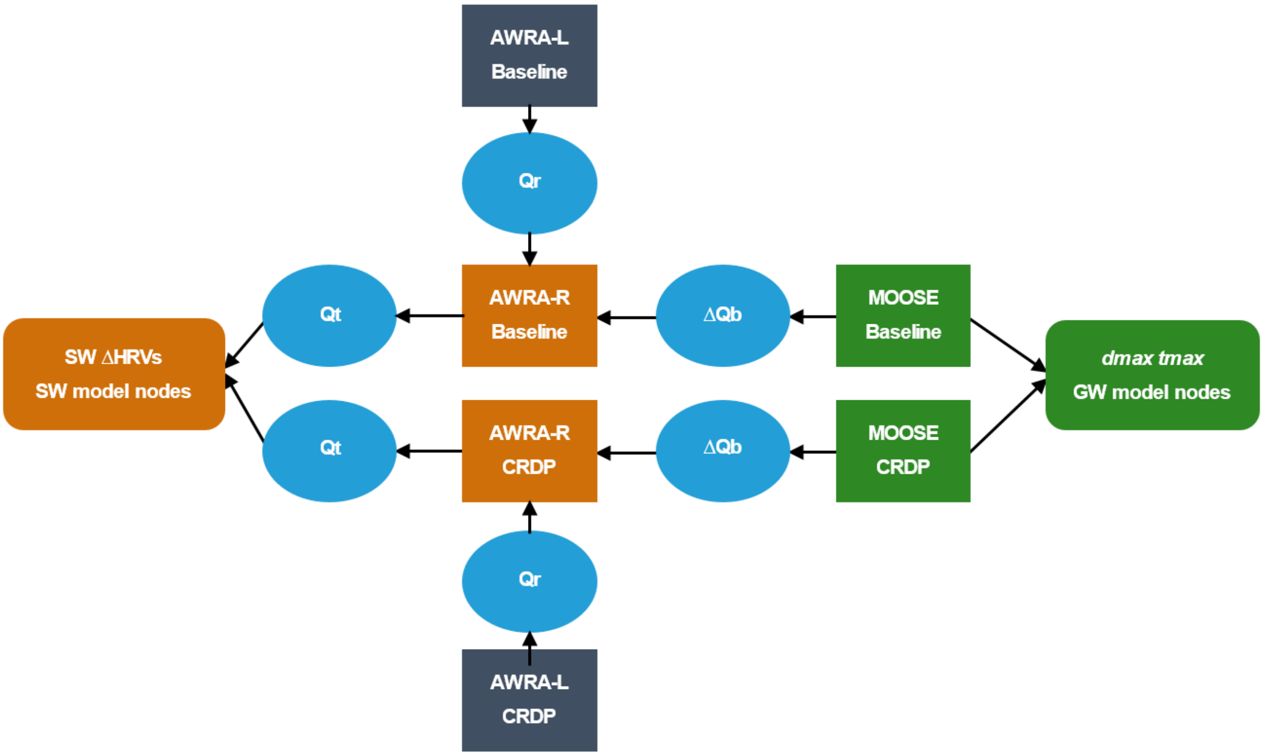

Figure 3 Model sequence for the Hunter subregion

AWRA = Australian Water Resources Assessment; AWRA-L = landscape model; AWRA-R = river model; CRDP = coal resource development pathway; *dmax* = maximum drawdown; GW = groundwater; ΔHRV = change in hydrological response variable; MOOSE = groundwater model; ΔQb = change in baseflow relative to no development baseflow; Qr = surface runoff; Qt = total streamflow; SW = surface water; *tmax* = year of maximum change

2.6.1.1.4 Integration with sensitivity and uncertainty analysis workflow

Companion submethodology M09 (as listed in Table 1) (Peeters et al., 2016) discusses in detail the propagation of uncertainty through the numerical models in the bioregional assessments. The goal of the uncertainty analysis is to provide, for each hydrological response variable at each model node, an ensemble of the predicted maximum absolute and relative change and time to this change.

To generate these ensembles, a large number of 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.

While the Approximate Bayesian Computation methodology outlined in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016) requires that this acceptance threshold be specified independently, preferably based on assessment of the observational uncertainty, this is generally not possible for the various surface water response variables. A pragmatic choice is made to set the acceptance threshold to the 90th percentile of goodness of fit for the large number of model evaluations. The ensemble of predictions for each hydrological response variable is thus based on the top 10% of parameter combinations for that hydrological response variable. The reasons for and implications of this assumption are discussed in Section 2.6.1.5.

The uncertainty methodology proposes the development of numerical emulators to mimic the relationship between parameter values and the response of hydrological variables due to the additional coal resource development to generate the posterior prediction ensembles. Due to the long model runtimes and the independently defined acceptance threshold, such emulators are used for the groundwater modelling to ensure a sufficiently large ensemble of predictions is obtained within the operational constraints to allow robust estimates of the 5th, 50th and 95th percentiles of the prediction ensemble.

For surface water modelling, creating emulators is not necessary as the pragmatic acceptance threshold ensures that, in the case of the 3000 model evaluations for the Hunter subregion, 300 (i.e. 10%) will be accepted in the posterior ensemble of predictions. Tests of this assumption suggest that this number is large enough to estimate the 5th, 50th and 95th percentiles robustly.

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2.6.1.2 Review of existing models

Summary

Mining companies undertake assessments of the impacts on surface water from mining developments as part of their approvals process. These assessments use models to determine risks from local effects such as erosion, flooding and ponding, and to quantify components of the mine site water balance. The models are local scale and address local issues that are not within the scope of the bioregional assessments. A review of these models has not been undertaken.

There is one regional scale surface water modelling system in regular use in the Hunter subregion: the Hunter Integrated Quantity-Quality Model (IQQM). It is used by the NSW Department of Primary Industries primarily to inform water resources planning and management. With further development, it could be made suitable for a bioregional assessment, but proprietary issues meant this was not an option. Instead, the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and AWRA river model (AWRA-R) have been adopted for the Bioregional Assessment Programme.

Time series of outputs from the Hunter IQQM, including volume of water stored in reservoirs, reservoir releases and surface water diversions, have been used to develop and calibrate the AWRA-R model, in order to simulate the change in hydrological effects of baseline and coal resource development pathway in the Hunter subregion.

As part of their approvals process, mining companies are required to undertake environmental assessments to evaluate the potential effects on the environment from mining and inform monitoring and mitigation strategies. An assessment of the potential impacts on surface water form part of these assessments. In general, the modelling that is undertaken is to investigate things like channel scour; impacts on bank stability; risks of local flooding; and potential drainage issues, such as local ponding; and quantify components of the mine site water balance. The focus of this modelling tends to be local in scale, with a view to minimising off-site impacts through on-site water management. These surface water assessments do not require regional scale river models. A review of the models used for this range of purposes has not been undertaken.

In NSW, the state agency river model is the Integrated Quantity-Quality Model (IQQM) (Simons et al., 1996). IQQMs have been constructed for most river basins in NSW to assist in water resources planning and management, such as determining annual water allocations for the various users (irrigation, electricity generation, town water supply) within water sharing plan areas. They use Sacramento (Burnash et al., 1973) rainfall-runoff models to estimate catchment runoff contributions to the IQQM link-node network. Much of the Hunter subregion is included in the Hunter IQQM (Simons et al., 1996); the Macquarie-Tuggerah lakes basin is not.

The Hunter IQQM represents the inflows and outflows along the regulated river system from Glenbawn Dam to Greta. It simulates, amongst other things, streamflows, volume of water stored in reservoirs, reservoir releases and surface water diversions. It has not been specifically constructed to model the impacts of coal resource developments on streamflow, and cannot be used for a bioregional assessment in its current form, although, at considerable effort, it could be customised to do so. However, proprietary issues also meant that the Hunter IQQM was not an option for the bioregional assessment for the Hunter subregion. Instead, NSW DPI Water generously agreed to assist the bioregional assessment hydrologists to incorporate some components of its implementation in the Hunter Australian Water Resources Assessment (AWRA) river model (AWRA-R) built for the assessment for the Hunter subregion. These include:

- time series of surface water diversions to represent current demands on water resources
- time series of the volume of water stored in reservoirs and reservoir releases

and pertain to the Water Sharing Plan for the Hunter Regulated River which commenced in 2004 and the development and licensing conditions in 2012. Details of how these IQQM datasets are used in calibrating the AWRA-R model are given in Section 2.6.1.4.

The AWRA landscape model (AWRA-L) and AWRA-R have been adopted for the Bioregional Assessment Programme. AWRA-L is a grid-based model which can represent the spatial variability in physical attributes that influence catchment runoff over time. The AWRA-R model is a link-node model that can receive inputs (e.g. inflows from AWRA-L; groundwater contributions from a groundwater model; dam releases; diversions from the river; discharges to river) and propagate those changes through the river network. Readers are referred to companion submethodology M06 (Viney, 2016) for further details.

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2.6.1.3 Model development

Summary

This section summarises the key steps taken in developing the surface water models for predicting hydrological changes arising from coal resource development in the Hunter 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 includes the catchment of the Hunter River above Greta (17,600 km^2) and the catchment of the Wyong River above Wyong (400 km^2). Within this domain, 65 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 Meteorological Research Institute (Japan) 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 1.5% per degree of global warming.

2.6.1.3.1 Spatial and temporal dimensions

The Hunter subregion comprises two separate river basins (Figure 4). The Hunter River drains the majority of the subregion, while numerous small rivers drain a coastal section of the subregion that is known as the Macquarie-Tuggerah lakes basin. The modelling domain for surface water modelling in the Hunter subregion includes part of the Hunter river basin and part of the Macquarie-Tuggerah lakes basin.

In the Hunter river basin the modelling domain consists of the catchment of the Hunter River above Greta. Greta is chosen as the lower limit for the modelling domain because it marks the approximate point in the river below which tidal influences become important. The catchment of the Hunter River above Greta covers an area of about 17,600 km^2.

The part of the Macquarie-Tuggerah lakes basin that is included in the modelling domain is the catchment of the Wyong River above Wyong. This point also represents the approximate tidal limit and is about 8 km above the location where the Wyong River discharges into Tuggerah Lake. Other parts of the Macquarie-Tuggerah lakes basin are not included because estimates of baseflow changes from groundwater drawdown are not available. The catchment of the Wyong River above Wyong covers an area of about 400 km^2.

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 Hunter subregion follows the methodology set out in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

2.6.1.3.2 Location of model nodes

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 mine developments
- at locations required for receptor impact analysis.

The 63 model nodes in the Hunter river basin include 34 streamflow gauging locations and 29 other locations (Figure 4). Nodes are numbered by location along the stream network from downstream to upstream. There are two model nodes in the Wyong river basin.

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 Hunter River at Greta. Numbers progress along the main river channel and up each tributary with a node in the order that tributaries meet the main river channel. This is illustrated in Figure 5. In the Wyong river basin, numbering starts at node 64 and completes with node 65.

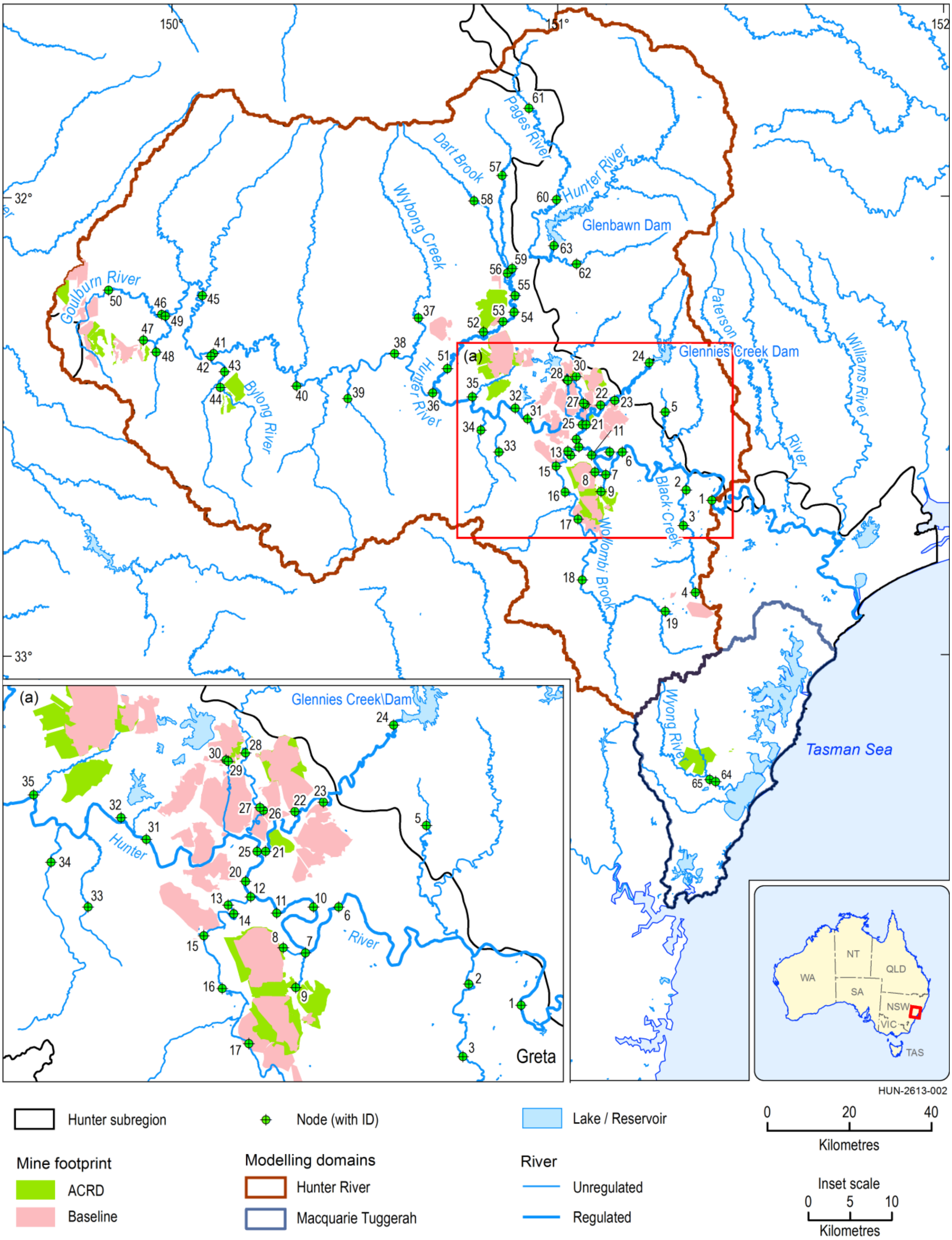

Figure 4 Hunter subregion surface water modelling domain, location of model nodes and maximum extents of mine footprints

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, Dataset 4, Dataset 5, Dataset 6)

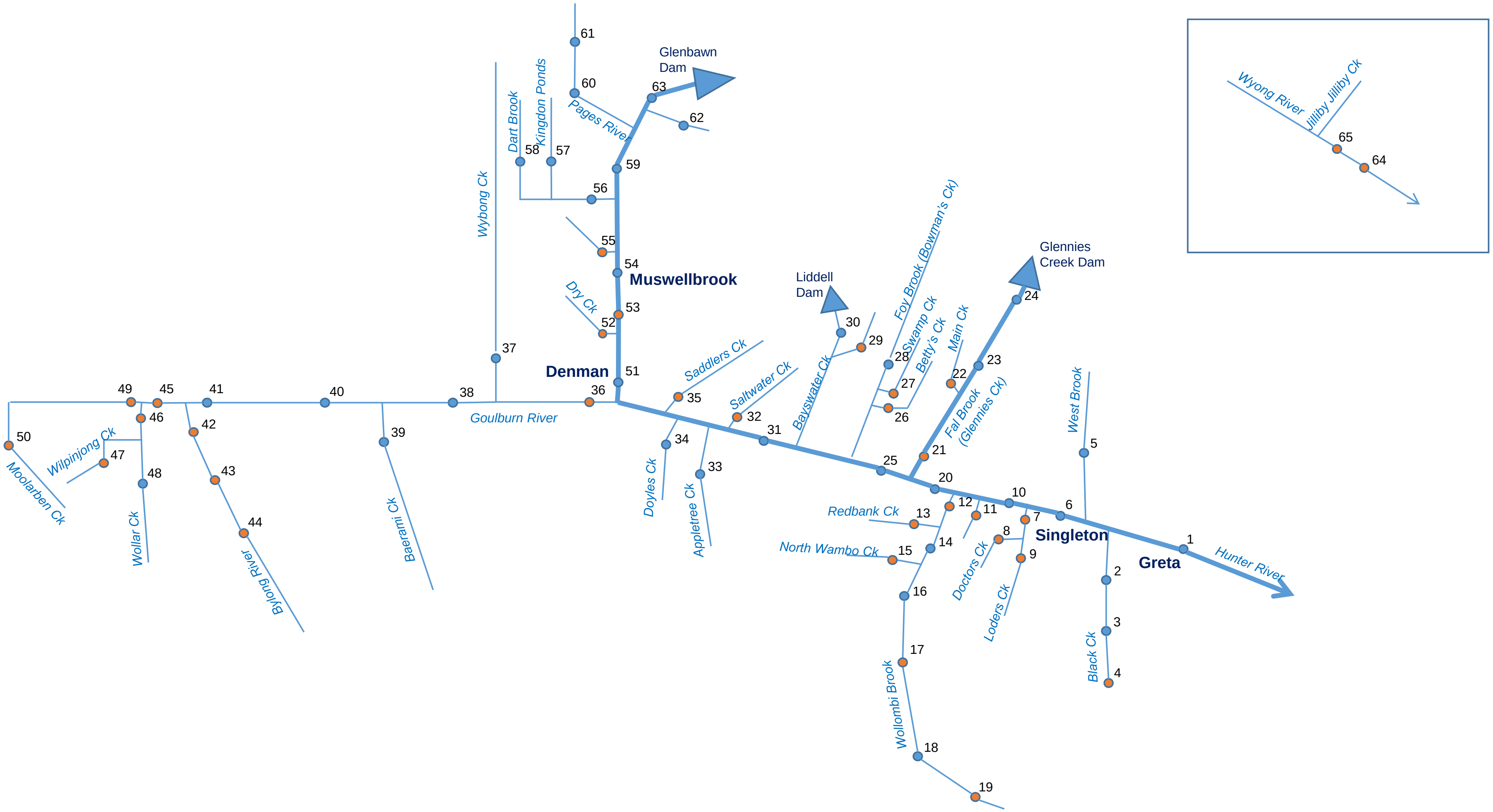

Figure 5 Schematic representation of the node-link network for Hunter subregion surface water modelling

Main figure for the Hunter river basin; inset of the Wyong river basin. Model nodes number from most downstream node upstream. Blue nodes correspond to stream gauging stations; orange nodes correspond to model-specific nodes. The thicker blue line depicts the regulated part of the river system.

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 Hunter subregion. There are 15 available GCMs (as presented in Table 3) 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 Hunter subregion are shown in Table 3 for each GCM. The 15 GCMs predict changes in mean annual precipitation ranging from –6.2% (i.e. a reduction in mean annual precipitation) to 8.3% (i.e. an increase in mean annual precipitation). The GCM with the median change is MRI (from the Meteorological Research Institute, Japan). The corresponding projected change in mean annual precipitation per degree of global warming is a reduction of 1.5%, or about 11 mm. The seasonal scaling factors for MRI are +5.4%, –3.4%, –8.1% and –1.8% 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 3 List of 15 global climate models (GCMs) and their predicted change in mean annual precipitation across the Hunter subregion per degree of global warming

GCM	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 the Korea Meteorological Administration, Korea	4.9%
MIROC3	Centre for Climate Research, Japan	3.7%
CCCMA T63	Canadian Climate Centre, Canada	2.7%
NCAR-PCM	National Center for Atmospheric Research, USA	2.1%
NCAR-CCSM	National Center for Atmospheric Research, USA	1.4%
INMCM	Institute of Numerical Mathematics, Russia	0.7%
MRI	**Meteorological Research Institute, Japan**	**–1.5%**
CSIRO-MK3.0	CSIRO, Australia	–1.6%
GFDL2.0	Geophysical Fluid, Dynamics Lab, USA	–1.7%
IAP	LASG/Institute of Atmospheric Physics, China	–2.3%
MPI-ECHAM5	Max Planck Institute for Meteorology, German Climate Computation Centre (DKRZ), Germany	–3.1%
IPSL	Institut Pierre Simon Laplace, France	–4.0%
GISS-AOM	NASA/Goddard Institute for Space Studies, USA	–5.0%
CNRM	Meteo-France, France	–6.2%

Data: CSIRO (Dataset 7)

The seasonal scaling factors associated with MRI are used to generate trended precipitation 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 Hunter subregion is shown in Figure 6. It depicts a cycle of 1983 to 2012 climate that is repeated a further three times but with increasingly trended climate change scalars. It can be seen from Figure 6 that the decrease in precipitation from 2013 to 2102 is less than the typical inter-annual variability. Furthermore, it reduces annual precipitation rates to levels that remain much higher than were typically encountered in the first half of the 20th century.

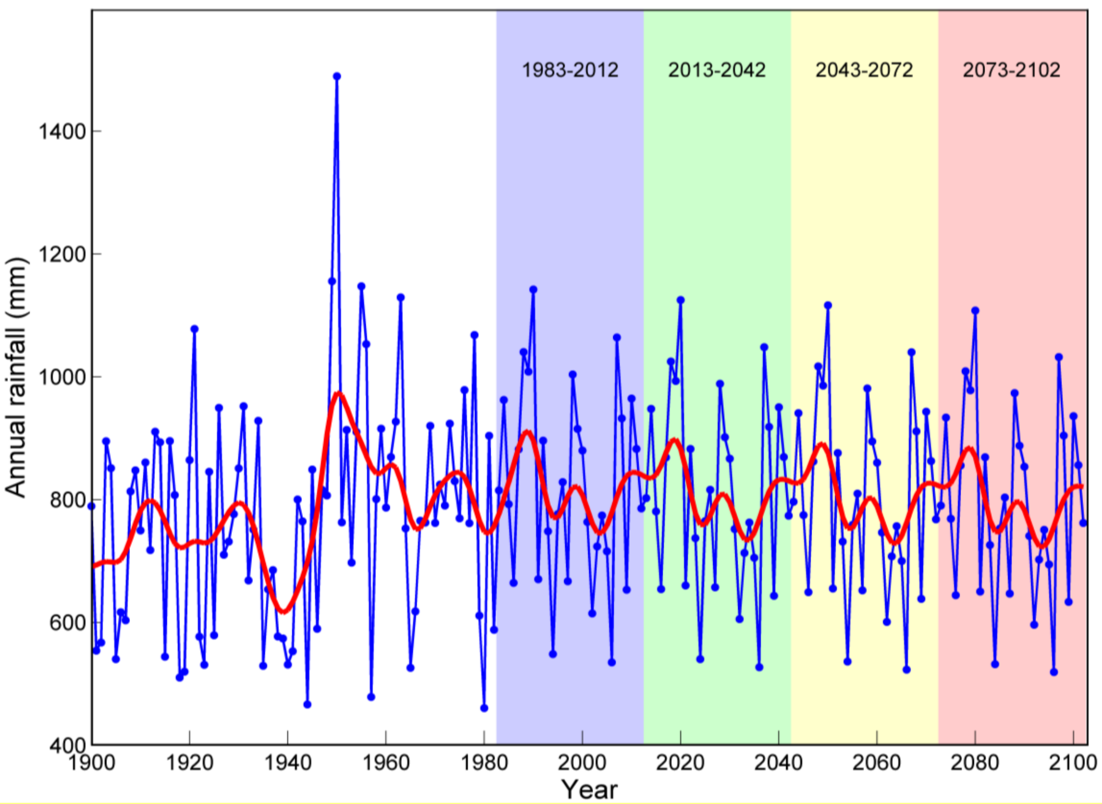

Figure 6 Time series of observed and projected annual precipitation averaged over the Hunter subregion

The blue line shows the time series. The red line is a centrally weighted moving average.
Data: Bioregional Assessment Programme (Dataset 8)

2.6.1.3.4 Representing the hydrological changes from mining

Mine footprints

One important impact of coal mines is the interception of surface runoff that would otherwise flow to the stream network. 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, the surface water footprint covers the entire area disturbed by mine operations, including pits, roads, 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 rehabilitated areas from which surface runoff can enter the stream network, or catchment areas upstream of drainage channels that divert water around a mine site but 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 are intended to remain on the site after final rehabilitation.

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. Details of data sources and methods used to define mine footprint time series, including the assumptions made, are provided in Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a).

Figure 7 provides an example of temporal evolution of the mine footprint area derived for the Ashton Coal Mine's open-cut and underground mines. The open-cut mine is included in the baseline and CRDP, whereas the underground mining is a baseline activity only. For modelling purposes, it is assumed that the additional coal resource development for the open-cut mine starts in 2018, with the maximum footprint area occurring in 2022, before reducing to a final void area in 2035. The underground mine is assumed to commence operation in 2006 and to reach its final extent by 2023.

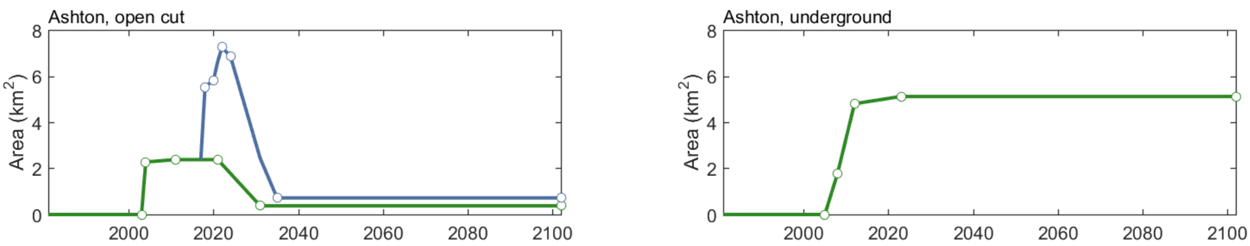

Figure 7 Time series of the mine footprint area for Ashton Coal Mine's open-cut and underground mines

The green line shows the baseline; the blue line shows the coal resource development pathway (CRDP).
Data: Bioregional Assessment Programme (Dataset 9)

The full set of surface water mine footprint time series (for the 30 modelled baseline mines and 17 modelled additional coal resource developments) can be found in Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a). The maximum extents of the mine footprints are shown in Figure 4.

Table 4 provides details of the maximum mine footprint areas for open-cut and underground for the baseline and additional coal resource development by contributing area for each AWRA-R model node. Node 1, which is the most downstream node in the Hunter River network, has the largest contributing area and its mine footprint areas represent the totals from all mines upstream of that point. Note that there can be instances where the combined maximum footprint areas of the baseline and additional coal resource development exceed the contributing area because of assumed changes in the timing of baseline rehabilitation due to the additional coal resource development.

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.

The hydrological change to baseflow is estimated using the groundwater model, which is described in detail in Section 2.6.2.3 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b). The groundwater model estimates monthly baseflow for each surface water 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.

Additional coal resource developments that were not modelled due to insufficient data (see Section 2.3.4 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018)) are considered further in the impact and risk analysis (see companion product 3-4 for the Hunter subregion, as listed in Table 2).

Table 4 Contributing area and maximum mine footprint area to each model node in AWRA-R

Model	Contributing area	Baseline	Baseline	ACRD	ACRD
1	17787	315.0	116.0	167.2	56.4
2	352	1.1	4.1	0.0	0.0
3	197	1.1	4.1	0.0	0.0
4	11	0.0	4.1	0.0	0.0
5	72	0.0	0.0	0.0	0.0
6	16471	313.6	111.8	167.0	56.4
7	76	30.9	0.1	26.8	0.0
8	13	12.0	0.0	7.2	0.0
9	38	17.1	0.1	14.6	0.0
10	16331	281.0	111.8	141.6	56.4
11	15	8.4	0.0	3.6	0.0
12	1878	28.2	32.8	17.4	0.0
13	13	4.3	0.0	0.0	0.0
14	1849	23.6	32.8	17.1	0.0
15	48	10.4	0.0	0.0	0.0
16	1674	6.6	32.8	12.0	0.0
17	1336	0.6	26.6	4.1	0.0
18	1089	0.1	12.6	0.0	0.0
19	97	0.0	12.3	0.0	0.0
20	14393	239.1	79.0	124.5	56.4
21	514	22.4	10.1	5.9	0.0
22	21	0.4	7.5	1.5	0.0
23	445	0.4	0.2	0.0	0.0
24	226	0.0	0.0	0.0	0.0
25	13857	214.9	68.9	122.7	56.4
26	18	5.9	3.9	5.2	0.0
27	25	13.1	0.2	11.0	0.0
28	185	4.0	0.0	1.4	0.0
29	7	5.2	0.0	0.7	0.0
30	87	7.7	0.0	0.0	0.0
31	13339	132.0	49.2	102.2	56.4
32	54	0.1	0.0	0.2	0.0
33	29	0.0	0.0	0.0	0.0
34	200	0.0	0.0	0.0	0.0

Model	Contributing area	Baseline	Baseline	ACRD	ACRD
35	96	21.0	0.0	19.0	8.4
36	7802	53.0	44.1	29.4	37.4
37	668	0.0	0.0	0.0	0.0
38	6815	37.6	44.1	29.4	37.4
39	385	0.0	0.0	0.0	0.0
40	4981	37.6	44.1	29.4	37.4
41	3403	37.6	44.1	29.4	37.0
42	705	0.0	0.0	8.5	17.7
43	666	0.0	0.0	8.5	17.7
44	303	0.0	0.0	8.5	3.0
45	2510	37.6	44.1	20.8	19.3
46	530	13.2	0.0	20.1	5.8
47	192	13.2	0.0	17.0	5.8
48	259	0.0	0.0	0.1	0.0
49	617	31.8	44.1	0.8	13.5
50	317	31.8	40.1	0.8	13.5
51	4313	48.5	5.1	53.3	10.7
52	25	0.6	0.0	16.6	0.0
53	4117	3.9	5.1	21.8	0.0
54	3999	3.5	5.1	10.8	0.0
55	18	0.0	0.6	10.3	0.0
56	789	0.0	1.3	0.0	0.0
57	178	0.0	0.0	0.0	0.0
58	237	0.0	0.0	0.0	0.0
59	2992	0.0	0.0	0.0	0.0
60	1069	0.0	0.0	0.0	0.0
61	295	0.0	0.0	0.0	0.0
62	400	0.0	0.0	0.0	0.0
63	1297	0.0	0.0	0.0	0.0
64	402	0.0	0.0	0.1	40.6
65	353	0.0	0.0	0.0	34.0

ACRD = additional coal resource development
Data: Bioregional Assessment Programme (Dataset 5, Dataset 6)

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 Hunter River, but this is undertaken differently to the Hunter Integrated Quantity-Quality Model (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 bioregional assessment for the Hunter subregion was not specifically developed for river operations planning and management and, without further development, should not be used for this purpose.

The Hunter River is regulated by two major dams, Glenbawn Dam (capacity of 750,000 GL) and Glennies Creek Dam (283,000 GL) (Figure 4). These dams supply water to downstream irrigation, industry and town water. Basic characteristics controlling the operations of these dams (e.g. dead volume, surface area and the split values for releases to various types of water user) are taken from IQQM inputs. Other variables required for AWRA-R are largely based on existing management rules.

2.6.1.3.6 Rules to simulate industry water discharge

A simple set of rules to simulate industry water discharge within the Hunter River Salinity Trading Scheme (HRSTS) was developed based on the analysis reported in Section 2.1.4 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a). The resulting rules are not intended to replicate the operations of HRSTS, which is a real-time scheme contingent upon human decision making. Instead, the summary rules were developed that describe the gross characteristics of the scheme and are amenable to prospective (i.e. future) modelling.

Discharges under HRSTS are simulated when modelled streamflow exceeds the prescribed thresholds at three locations along the Hunter River. Discharge amounts at these locations are modelled as functions of the mean annual HRSTS discharges and the rate of discharge as a function of streamflow volume in exceedance of the thresholds. Both these variables were obtained from analysis of historical releases. Any modelled discharges are assumed to be distributed from all mines upstream of the three reaches.

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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 Hunter 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 14 unregulated catchments using two calibration schemes: one biased towards high streamflow, and another biased towards low streamflow. The two parameter sets obtained from the two model calibrations are used to guide the generation of the 3000 parameter sets used for the uncertainty analysis (Section 2.6.1.5) and predictions (Section 2.6.1.6). 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 noticeably over estimate high-flow days (FD) and interquartile range (IQR), but under estimate zero-flow days (ZFD), low-flow days (LFD), low-flow spells (LFS) and length of the longest low-flow spell (LLFS).

AWRA-R is calibrated for 20 streamflow gauging sites of the Hunter 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 low-streamflow calibration is markedly better than the high-streamflow calibration for six out of nine hydrological response variables (including all low-streamflow metrics); and marginally worse for IQR, FD and daily streamflow at the 99th percentile (P99).

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.

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 was from 1983 to 2012, which includes both wet and dry periods.

The landscape water balance model 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 Hunter subregion (Herron et al., 2018).

Daily stage and streamflow data from 14 streamflow gauging stations with unregulated catchments located in and near the Hunter subregion were used to calibrate AWRA-L. These gauging stations and the catchments subtended by them are shown in Figure 8. Ten stations are located in the Hunter river basin and four in the Macquarie-Tuggerah lakes basin. Of the 14 stations, ten are located within the modelling domain (Section 2.6.1.3) and four are located very close by. Site details are summarised in Section 2.1.4 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018). Observed daily mean streamflow data for the above gauges for 1983 to 2012 were derived from NSW DPI water data supplied by the Bureau of Meteorology (Dataset 2).

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 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 Hunter subregion and have similar catchment sizes and climate regimes.

Catchment boundaries for the 14 calibration catchments were delineated using the Australian Hydrological Geospatial Fabric (Geofabric) (Bureau of Meteorology, Dataset 5).

Figure 8 The 14 streamflow gauging stations used for AWRA-L model calibration and their contributing areas

AWRA-L = Australian Water Resources Assessment landscape model

Data: Bioregional Assessment Programme (Dataset 3, Dataset 4), Bureau of Meteorology (Dataset 5)

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; the second biased 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 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 5 summarise results of the two model calibrations for the 14 calibration catchments in terms of the three performance metrics. The parameter values for the two calibrations are included in Bioregional Assessment Programme (Dataset 6). The high-streamflow calibration yields a reasonable Nash–Sutcliffe efficiency of daily streamflow, indicated by a median $E_d(1.0)$ of 0.45 and interquartile range of 0.4 to 0.6. Overall model bias is low with a median bias of –0.03, but the interquartile range indicates variability across the 14 catchments with considerable overestimation in some catchments. The high-streamflow calibration yields a median F_1 of 0.37, which is only 0.08 less than the median $E_d(1.0)$, indicating overall low model bias. The $E_d(1.0)$ value is negative (suggesting poor simulation) for one catchment: –0.16 at gauging station 211010 on the Wyong River, with a prediction bias of 0.68.

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 similar efficiency to the high-streamflow calibration, indicated by a median $E_d(1.0)$ of 0.41. The $E_d(1.0)$ is greater than 0.34 for 11 of the 14 catchments and remains above zero for all catchments. The median bias of –0.12 indicates an overall tendency for underprediction by the low-streamflow calibration.

The performance of the high-streamflow calibration for the 14 catchments is not significantly related to catchment wetness, as it does not perform better or worse with a wetter climate. The $E_d(0.1)$ values of the low-streamflow calibration are moderately correlated with catchment wetness ($r^2 = 0.51$, $p < 0.01$), but the statistical significance of this correlation does not extend to F_2.

The 14 calibration catchments cover a wide range of climate and topographic conditions, with mean annual flow (AF) ranging from 33 mm/year at catchment 210040 (Wybong Creek) to 425 mm/year at catchment 210011 (Williams River) (Table 5). This suggests that AWRA-L can predict streamflow variability reasonably in the Hunter subregion where climate conditions vary widely.

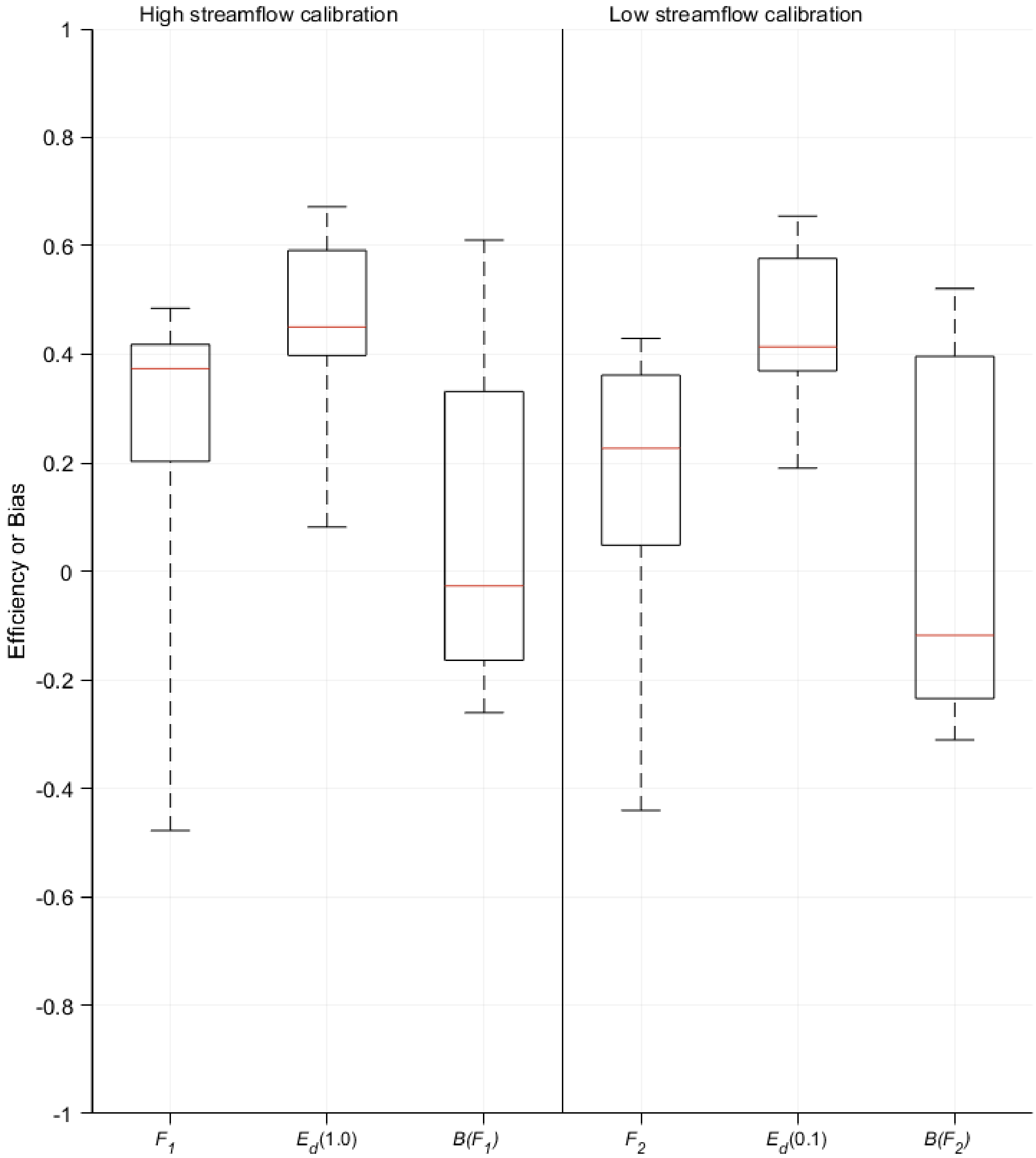

Figure 9 Summary of two AWRA-L model calibrations for the Hunter subregion

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 6)

Table 5 Calibration statistics for the 14 AWRA-L calibration catchments

Streamflow gauge ID	Mean annual streamflow (mm/y)	High-streamflow calibration			Low-streamflow calibration		
		F_1	E_d(1.0)	Bias (F_1)	F_2	E_d(0.1)	Bias (F_2)
210011	425	0.35	0.59	–0.26	0.23	0.64	–0.31
210014	125	0.37	0.40	–0.13	0.40	0.58	–0.23
210017	265	0.41	0.41	0.04	0.65	0.65	0.06
210022	420	0.31	0.63	–0.28	0.09	0.67	–0.34
210040	33	0.42	0.43	0.10	0.34	0.34	–0.02
210048	80	–0.22	0.55	0.60	0.05	0.37	0.40
210052	64	0.40	0.47	–0.16	0.22	0.41	–0.23
210080	133	0.38	0.40	–0.10	0.06	0.20	–0.21
210093	44	0.82	0.84	0.11	–0.43	0.10	0.50
210123	164	0.20	0.23	–0.11	0.38	0.57	–0.24
211008	266	0.45	0.56	–0.20	0.36	0.52	–0.22
211009	185	–0.41	0.11	0.50	–0.04	0.37	0.44
211010	212	–1.12	–0.16	0.68	–0.54	0.40	0.67
211013	242	0.43	0.65	0.33	0.27	0.42	0.28
Median	**175**	**0.37**	**0.45**	**–0.03**	**0.23**	**0.41**	**–0.12**

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 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 6)

Nine hydrological response variables (Table 6) 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- and low-streamflow calibrations. Overall, the low-streamflow calibration outperforms the high-streamflow calibration across the nine hydrological response variables with smaller median model biases and narrower interquartile ranges for the 14 catchments. Only for AF does the high-streamflow calibration yield better predictions than the low-streamflow calibration. Both calibrations tend to over estimate both the high-streamflow metrics high-flow days (FD) and interquartile range (IQR), but tend to under estimate daily streamflow at the 99th percentile (P99). Both calibrations tend to under estimate the low-streamflow metrics: low-flow days (LFD), low-flow spells (LFS) and longest low-flow spell (LLFS). The median bias for daily streamflow at the 1st percentile (P01) is close to zero for both calibrations, but some catchments over estimate P01 significantly. Neither calibration predicts zero-flow days (ZFD) well, although for most subcatchments there are very few days in the observed data without flow.

Table 6 Hydrological response variables used to characterise hydrological changes of coal resource development

Hydrological response variable	Definition	Unit
annual flow (AF)	The annual flow volume	GL/year
P99	The daily streamflow at the 99th percentile	ML/day
interquartile range (IQR)	The interquartile range in daily streamflow (ML/day); that is, the difference between the daily streamflow rate at the 75th percentile and at the 25th percentile	ML/day
high-flow days (FD)	The number of high-flow days per year. 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
P01	The daily streamflow at the 1st percentile	ML/day
zero-flow days (ZFD)	The number of zero-flow days per year	Days
low-flow days (LFD)	The number of low-flow days per year. The threshold for low-flow days is the 10th percentile from the simulated 90-year period (2013 to 2102).	ML/day
low-flow spells (LFS)	The number of low-flow spells per year. A spell is defined as a period of contiguous days of streamflow below the 10th percentile threshold.	Times/year
longest low-flow spell (LLFS)	The length (days) of the longest low-flow spell each year	Days

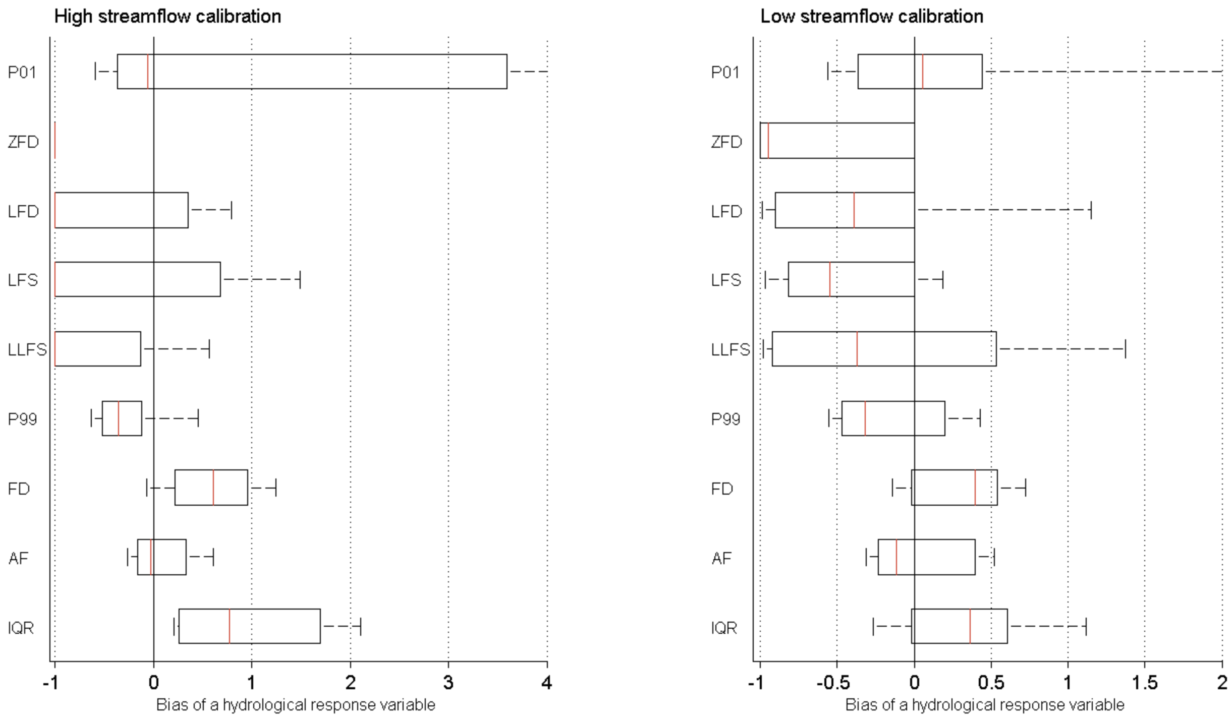

Figure 10 Summary of model bias for the nine simulated hydrological response variables for high-streamflow and low-streamflow calibrations

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 6.
Data: Bioregional Assessment Programme (Dataset 6)

It is noted that the parameter sets obtained from the regional model calibrations are not applied directly to the uncertainty analysis (Section 2.6.1.5). However, they are 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 5 and Figure 9) suggest that AWRA-L performs reasonably well in estimating high streamflow and low streamflow in the Hunter subregion.

It is noted that when the model is calibrated against observations from 14 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. For instance, the high-streamflow model calibration generates a poor model performance at gauge 211010. The model noticeably under estimates streamflow for gauges 211010 and 210048. For other gauges in the Hunter subregion, AWRA-L performs well in terms of model efficiency and bias.

As opposed to model calibration against observation at each individual catchment, a key characteristic of regional model calibration against observations from multiple catchments is that there is no noticeable degradation from model calibration to model prediction (Viney et al., 2014). For both the high- and low-streamflow calibrations, the biases at the majority of individual stream gauging sites are in the range –20% 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.

The results from the simulated hydrological response variables (Figure 10) show that in the Hunter subregion, AWRA-L calibrated against high daily streamflow is not always better for estimating the high-streamflow hydrological response variables; and the model calibrated against low daily streamflow performs consistently better than that based on the high-streamflow calibration for estimating most hydrological response variables. Both calibrations, however, show large uncertainty in predicting some of the hydrological response variables. In general, one or other of the two calibration sets provides predictions of the hydrological response variables with little bias. An exception is for the variable describing the number of low-flow days, which both parameter sets severely under-predict. This suggests that less confidence may be ascribed to the prediction of this variable in Section 2.6.1.6 than to the prediction of the other variables. Using both calibration parameter sets to generate the 3000 parameter sets for the simulations is expected to provide a reasonable estimate of uncertainty for each hydrological response variable.

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 power generation 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 generally covered 1981 to 2012. However, some calibration datasets did not cover this entire period and suitable periods were chosen based on data availability; details of these datasets are provided below.

The only direct climate input into AWRA-R is daily precipitation, which is used to calculate precipitation directly on the river channel 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 Hunter river system AWRA-R node-link network (Bioregional Assessment Programme, Dataset 7 and Dataset 8).

Daily estimates of potential evaporation and catchment runoff were obtained from the calibrated AWRA-L simulation (Bioregional Assessment Programme, Dataset 6) and aggregated to the reach scale defined by the Hunter river system node-link network (Bioregional Assessment Programme, Dataset 7 and Dataset 8) for input into AWRA-R.

Industry diversions (including those for power stations and town water supply) are not calibrated and are used as inputs in AWRA-R (NSW Office of Water, Dataset 9).

The AWRA-R model used for calibration comprises 52 nodes and their contributing areas, shown in Figure 11. These include the 34 gauging stations for which stage and streamflow data were obtained for model calibration (Bureau of Meteorology, Dataset 5). Twenty of the gauging stations are non-headwater gauges: they include 11 on the Hunter River, three on each of Wollombi Brook and the Goulburn River and three on other Hunter River tributaries (red triangles in Figure 11). The other 32 calibration model nodes (black dots in Figure 11) comprise the 14 gauging stations on headwater streams, plus 18 of the 29 model nodes (see Section 2.6.1.3.2), located on ungauged headwater streams. Daily streamflows at the 18 ungauged nodes are simulated by AWRA-L (Bioregional Assessment Programme, Dataset 6) and stages obtained from idealised cross-sections at each location (see companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018); Bioregional Assessment Programme, Dataset 10). Eleven model nodes, located on ungauged reaches downstream of other model nodes, are not used in the calibration but are needed for the AWRA-R model simulations.

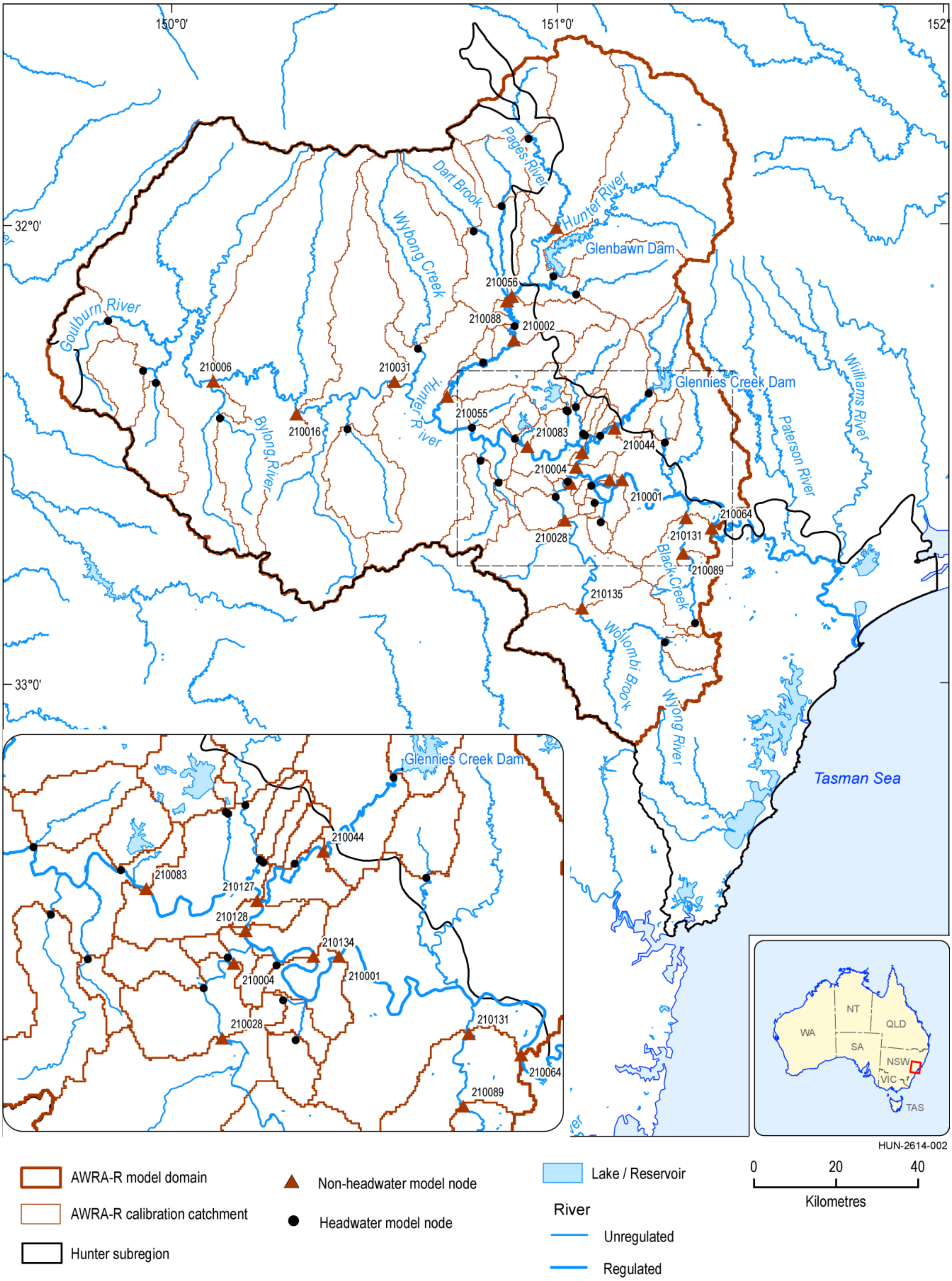

Figure 11 Streamflow gauging stations and ungauged upland headwater nodes used for AWRA-R model calibration and their contributing areas

AWRA-R = Australian Water Resources Assessment river model
Data: Bureau of Meteorology (Dataset 5), Bioregional Assessment Programme (Dataset 7, Dataset 8)

Daily irrigation and mining diversions were sourced from the Hunter Integrated Quantity-Quality Model (IQQM) (NSW Office of Water, Dataset 9), aggregated to monthly for the period 1981 to 2012. Irrigation diversions were used to calibrate the AWRA-R irrigation and dam storage and releases modules. Mining diversions were used as inputs in the calibration. Since mining diversions have similar seasonal patterns to irrigation diversions, the AWRA-R irrigation module is used to simulate mining diversions under baseline and CRDP.

Available observed stored volumes as well as allocations (NSW Office of Water, Dataset 9) were used in preference to simulated data for calibration of the dam storage module. These data were available from 1993 to 2012.

Daily dam releases (for Glenbawn Dam and Glennies Creek Dam) were sourced from the Hunter IQQM (NSW Office of Water, Dataset 9). These data were available from 1981 to 2012.

All data used for calibration of allocation, dam storage and dam releases overlapped the period from 1993 to 2012, hence this period was chosen for calibration of these components.

Model calibration results

Streamflow routing and reach water balance

AWRA-R was calibrated using 34 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 6). Eight of the 11 AWRA-R parameters (Viney, 2016) were calibrated; one routing parameter was fixed and the floodplain module (two parameters) was not implemented. The parameter values for the two calibrations are included in Bioregional Assessment Programme (Dataset 6).

The agreement of both high- and low-streamflow AWRA-R calibrations were assessed using the daily 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 2.6.1.4.1). 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 20 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 and 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 20 gauges. Table 7 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 0.73 (interquartile range of 0.53 to 0.79) and a median bias of 0.005. Thirteen of the 20 reaches have an $E_d(1.0)$ greater than 0.6, whereas only reach 210006 (Goulburn River at Coggan) has an $E_d(1.0)$ less than 0.25.

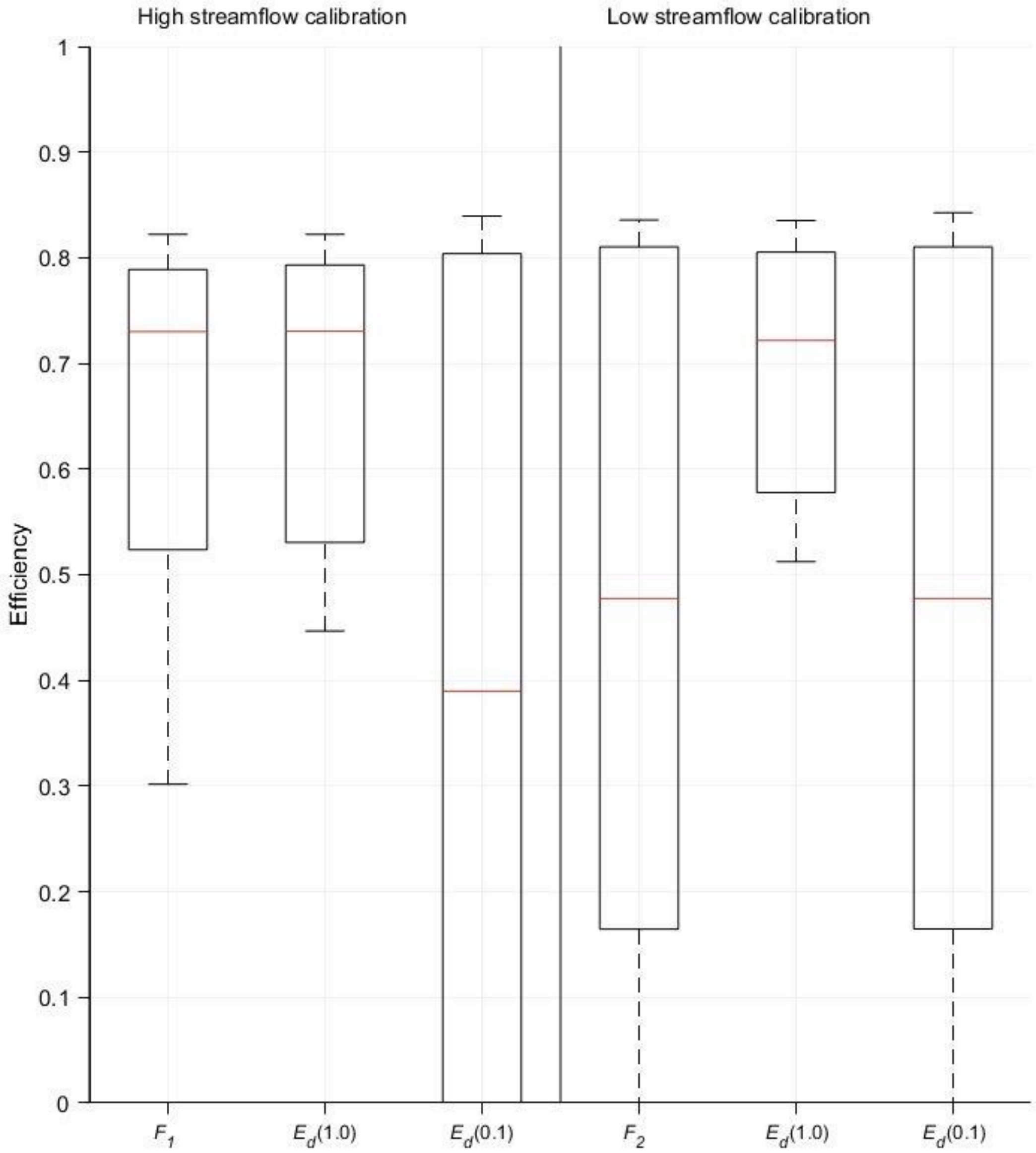

Figure 12 Summary of two AWRA-R model calibrations for the Hunter River

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 6)

Overall agreement in terms of $E_d(0.1)$ (emphasis on medium to low flows) for the AWRA-R high-streamflow calibration is poorer than $E_d(1.0)$, with a median value of 0.39 (interquartile range of 0.15 to 0.80). Eight of the 20 reaches have an $E_d(0.1)$ greater than 0.5. Low $E_d(0.1)$ values (<0.3) are observed in some reaches in the Goulburn River and Wollombi Brook, where the intermittent nature of streamflow is not captured by the model. This is highlighted in the flow duration curves for gauging stations in both Wollombi Brook and Goulburn River (Figure 13). The high-streamflow calibration yields a median F_1 of 0.52 and median bias is about 0.005. It should be noted that no Goulburn River catchments were included in the regional AWRA-L calibration as they were impacted by coal mining developments and did not meet the criteria for inclusion (see Section 2.6.1.4.1 and Figure 8).

The overall results in the 20 main calibration gauges are generally better than those obtained at other river basins across Australia (Dutta et al., 2015).

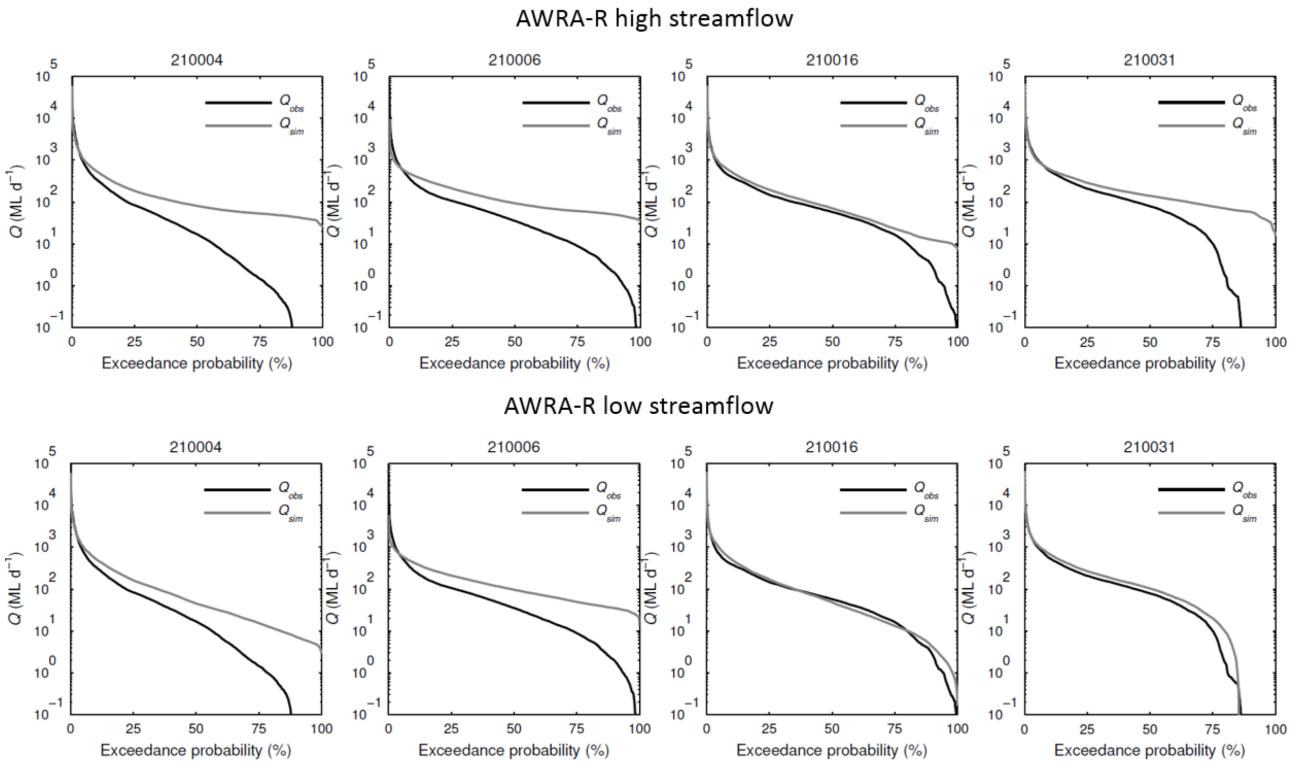

Figure 13 Flow duration curves for selected stations in Wollombi Brook (210004) and Goulburn River (210006, 210016, 210031) for AWRA-R high-streamflow calibration (top row) and AWRA-R low-streamflow calibration (bottom row), respectively

AWRA-R = Australian Water Resources Assessment river model
Data: Bioregional Assessment Programme (Dataset 6)

The AWRA-R low-streamflow calibration has a median $E_d(1.0)$ of 0.72 (interquartile range of 0.58 to 0.81). Fourteen out of the 20 reaches have an $E_d(1.0)$ greater than 0.6 and, again, only reach 210006 (Goulburn River at Coggan) has an $E_d(1.0)$ value less than 0.49. In terms of $E_d(0.1)$ for AWRA-R low-streamflow calibration, model performance is markedly better than for the AWRA-R high-streamflow calibration, with a median value of 0.48 (interquartile range of 0.16 to 0.81). Only eight reaches have an $E_d(0.1)$ greater than 0.6. The performance in the reaches in the Goulburn River and Wollombi Brook improve remarkably with the six reaches in those streams having a median $E_d(0.1)$ of 0.38 for AWRA-R low-streamflow calibration, compared to a median $E_d(0.1)$ of 0.05 for AWRA-R high-streamflow calibration. As a result the model agrees better with medium to low streamflow and the intermittent nature of streamflow at some of these gauging stations. This is particularly evident in the flow duration curves for 210016 and 210031 shown in Figure 13 for high- and low-streamflow calibrations. The low-streamflow calibration has a median F_2 value of 0.48 and a median bias of 0.002.

Table 7 Summary of AWRA-R calibration for the 20 reaches in the Hunter subregion

Streamflow gauge ID	Mean annual streamflow (ML/y)	High-streamflow calibration			Low-streamflow calibration		
		F_1	$E_d(1.0)$	$E_d(0.1)$	F_2	$E_d(1.0)$	$E_d(0.1)$
210001	524	0.74	0.74	0.83	0.83	0.74	0.83
210002	248	0.73	0.73	0.80	0.80	0.72	0.80
210004	112	0.53	0.53	–0.22	0.20	0.63	0.20
210006	70	0.21	0.21	–0.28	0.07	0.25	0.07
210016	96	0.69	0.69	0.45	0.69	0.68	0.69
210028	76	0.79	0.79	–0.04	0.21	0.84	0.21
210031	152	0.73	0.73	–0.03	0.58	0.72	0.58
210044	55	0.53	0.53	0.42	0.16	0.56	0.16
210052	70	0.66	0.66	0.20	0.38	0.69	0.38
210055	241	0.79	0.79	0.77	0.78	0.79	0.78
210056	234	0.81	0.81	0.81	0.82	0.82	0.82
210064	624	0.89	0.89	0.81	0.82	0.89	0.82
210083	356	0.81	0.81	–4.16	–4.56	0.82	–4.56
210088	11	–1.11	0.55	–4.92	–5.55	0.53	–4.47
210089	24	0.52	0.52	0.35	–0.20	0.57	–0.20
210127	337	0.76	0.76	0.90	0.91	0.76	0.91
210128	362	0.78	0.79	0.85	0.84	0.79	0.85
210131	50	0.50	0.50	0.30	0.43	0.58	0.43
210134	440	0.83	0.83	0.52	0.52	0.83	0.52
210135	59	0.39	0.39	–0.18	0.17	0.49	0.17
Median	**132**	**0.73**	**0.73**	**0.39**	**0.48**	**0.72**	**0.48**

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 6)

The impact of including seven additional reaches on the calibration of AWRA-R generally degrades agreement with observations in the reaches immediately downstream of these reaches. For example, the median $E_d(1.0)$ using the high-streamflow calibration with the additional reaches is 0.66 (range 0.12 to 0.88). The largest degradation is for the Hunter River at Denman (210055), where $E_d(1.0)$ decreases from 0.79 to 0.59, followed by Wollombi Brook at Bulga (210028) (0.77 to 0.63) and Hunter River at Liddell (210083) (0.81 to 0.67). Changes in $E_d(1.0)$ are marginal (<0.05) in the rest of the gauging stations. Again, median bias is less than 0.005.

Boxplots in Figure 14 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 2.6.1.4.1). Similar to the AWRA-L results, these boxplots show that generally the AWRA-R low-streamflow calibration has smaller model biases and narrower interquartile ranges than the AWRA-R high-streamflow calibration for the low-streamflow metrics (LFD, LFS, LLFS and P01). ZFD remains poorly simulated. The median biases in the high-streamflow metrics are generally marginally smaller in the high-streamflow calibration, and the interquartile ranges are narrower, highlighting less variability among the hydrological response variables in the calibrated Hunter reaches.

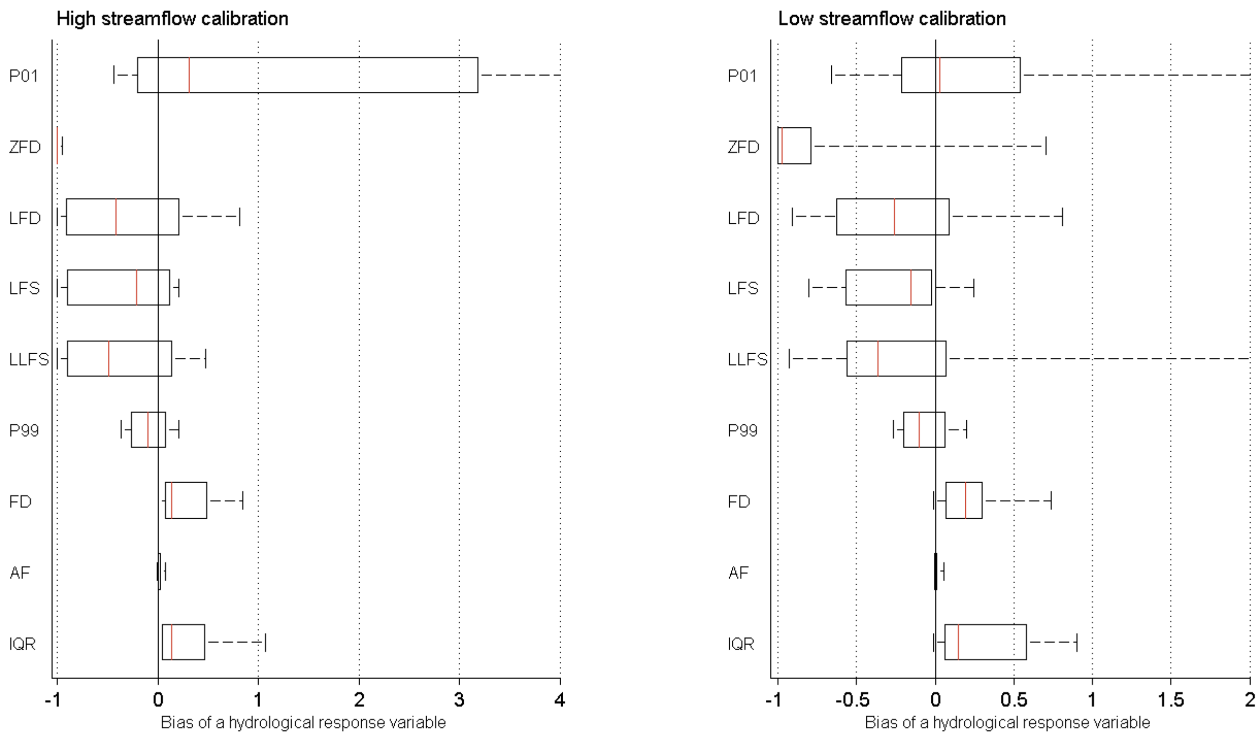

Figure 14 Summary of performance of the nine simulated hydrological response variables obtained using the two AWRA-R model calibrations

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 20 AWRA-R calibration reaches.
Shortened forms of hydrological response variables are defined in Table 6.
Data: Bioregional Assessment Programme (Dataset 6)

Irrigation module

The irrigation module in AWRA-R was calibrated in nine reaches along the Hunter River and one reach of Glennies Creek (210044). Calibration was performed against monthly IQQM simulated diversions for the period 1986 to 2012 using allocation data (NSW Office of Water, Dataset 9) and AWRA-R simulated streamflow (Bioregional Assessment Programme, Dataset 6). Details of the land use dataset and how it was used to parameterise the irrigation module are provided in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018).

Table 8 presents a summary of goodness-of-fit metrics used to evaluate the performance of calibration. Simulated and observed diversions were compared using the (i) coefficient of determination (r^2), which indicates the agreement in temporal patterns, (ii) 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. Good diversion patterns were simulated in all reaches, with a median r^2 of 0.82 (range 0.71 to 0.91).

Table 8 Summary of AWRA-R irrigation calibration for nine reaches in the Hunter subregion

Streamflow gauge ID	Mean annual irrigation diversion (ML/y)	r^2	E_m	B
210001	5215	0.88	0.77	0.00
210002	11789	0.88	0.74	–0.03
210044	853	0.76	0.52	–0.13
210055	5788	0.71	0.43	–0.03
210064	16142	0.91	0.79	0.03
210083	12516	0.86	0.71	–0.03
210127	760	0.82	0.67	–0.10
210128	356	0.76	0.56	0.03
210134	2020	0.71	0.49	0.03
Median	**5215**	**0.82**	**0.67**	**-0.03**

AWRA-R = Australian Water Resources Assessment river model; r^2 = coefficient of determination; E_m = monthly Nash–Sutcliffe efficiency; B = model bias
Data: Bioregional Assessment Programme (Dataset 6), NSW Office of Water (Dataset 9)

Figure 15 shows time series of observed and simulated diversions for the four reaches of the Hunter River with the highest water use. Inter-annual and intra-annual variability are generally captured by the model, with a mean E_m of 0.67 (range 0.43 to 0.79).

The variance in E_m is greater than the variance in r^2 (Table 8), indicating model overestimation or underestimation (van Dijk et al., 2008). Diversions are under estimated in five reaches, but the underestimation only exceeds 10% in reach 210044. The mean absolute bias in all reaches is 0.04.

Dam storage volumes, releases and allocations

Storage volumes for Glenbawn Dam and Glennies Creek Dam, releases and allocations were calibrated as a whole system against observed daily storage volumes and IQQM simulated releases (NSW Office of Water, Dataset 9). Individual dam volumes and releases were subsequently estimated from the allocations and a split value based on IQQM simulated releases. The calibration methodology and justification is described in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

Goodness-of-fit metrics used to evaluate the performance on calibrated storage volumes and dam releases included 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.

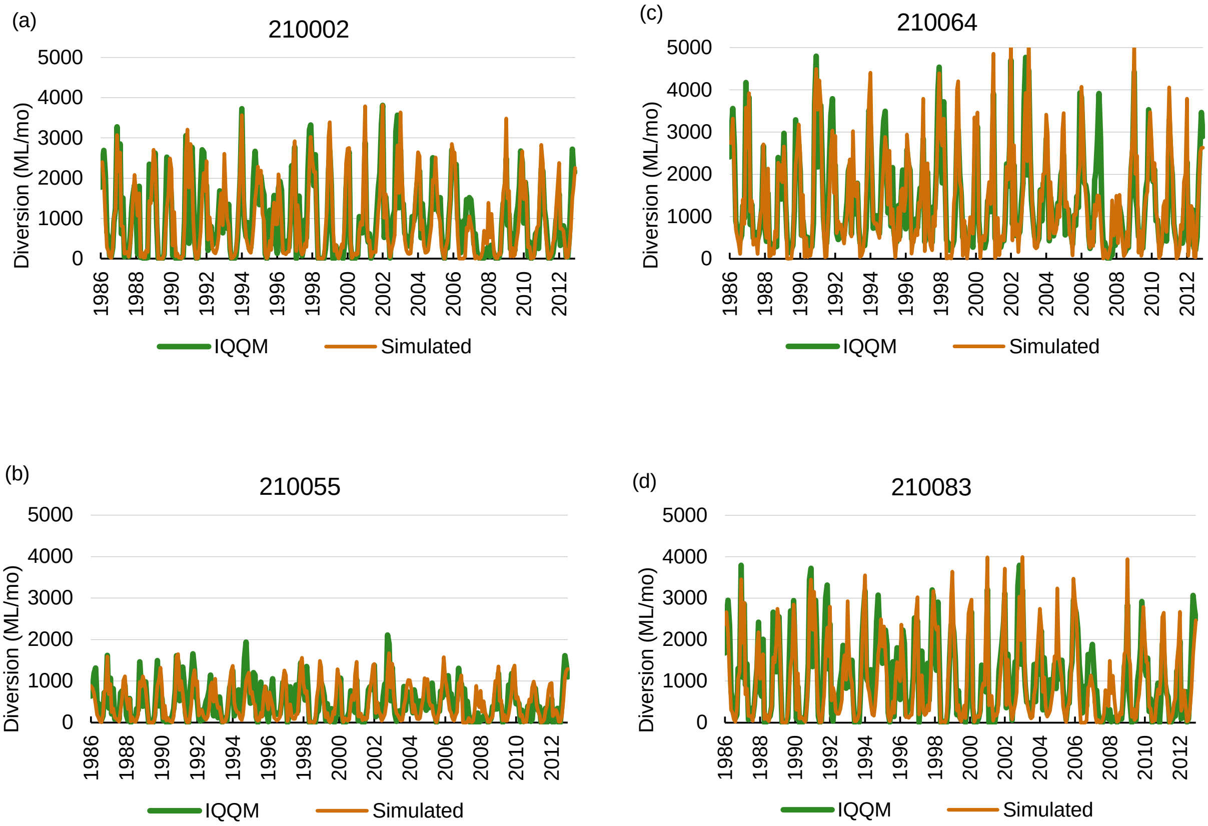

Figure 15 Example of IQQM and simulated monthly irrigation diversions for four reaches in the Hunter River

IQQM = Integrated Quantity-Quality Model
Data: Bioregional Assessment Programme (Dataset 6), NSW Office of Water (Dataset 9)

For illustrative purposes, time series of monthly storage volumes are shown in Figure 16a and Figure 16c. Temporal patterns agree well with observations, with r^2 values of 0.87 and 0.89 for Glenbawn Dam and Glennies Creek Dam, respectively. In contrast, modelled volumes are modest for Glenbawn Dam (E_m = 0.37) and poor for Glennies Creek Dam (E_m = 0.1). The RMSE is 79 GL and 33 GL for Glenbawn Dam and Glennies Creek Dam, respectively, or about 15% of their mean storage volumes. It can be seen in Figure 16 that AWRA-R generally under estimates storage volumes between 1993 and 2002, but over estimates them during the dry period between 2003 and 2008.

Time series of monthly dam releases are shown in Figure 16b and Figure 16d. Temporal patterns agree reasonably well with observations, with r^2 values of 0.5 and 0.84 for Glenbawn Dam and Glennies Creek Dam, respectively. Simulated releases are poor for Glenbawn Dam (E_m = 0.01) but good for Glennies Creek Dam (E_m = 0.65). The RMSE for the calibration period (1993 to 2012) is 9.4 GL and 1.5 GL for Glenbawn Dam and Glennies Creek Dam releases, respectively.

Figure 17 summarises the monthly percentage error (computed as the percentage of the difference between volume simulated and observed divided by simulated volume) for both dams. The error is generally –20% to +20%, which suggests that the modelled allocations will generally be within this margin of error.

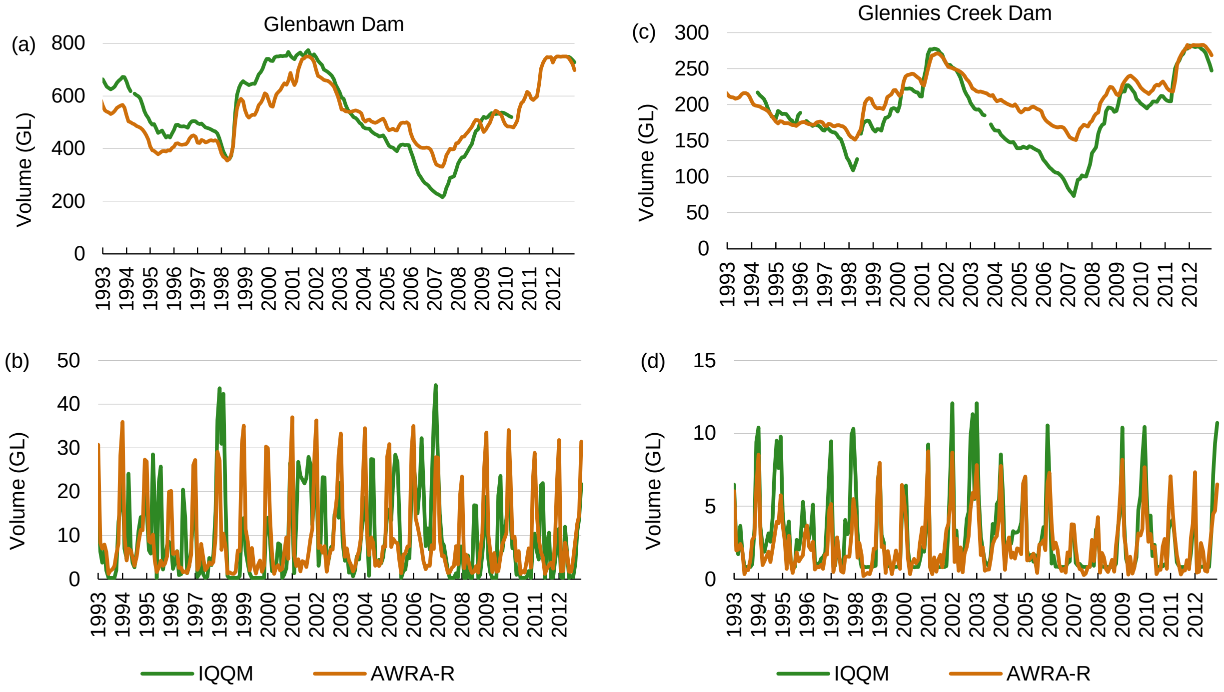

Figure 16 Observed and AWRA-R simulated monthly dam storage volume for (a) Glenbawn Dam and (c) Glennies Creek Dam; and IQQM and AWRA-R simulated monthly releases for (b) Glenbawn Dam and (d) Glennies Creek Dam

AWRA-R = Australian Water Resources Assessment river model; IQQM = Integrated Quantity-Quality Model
Data: Bioregional Assessment Programme (Dataset 6), NSW Office of Water (Dataset 9, Dataset 11)

The poor monthly efficiencies for the simulated releases from Glenbawn Dam can be attributed to the imposed releases in December and January to satisfy water demand for the environment and for electricity generation. Although electricity generation demand does not dominate the variance in the dam releases (r^2 = 0.15, whereas for irrigation and mine demand r^2 = 0.27), it drives some of the peak releases, particularly during the dry period of 2003–2008. As a result, the dam model misses some of these peaks (i.e. those occurring in months other than December and January), or simulates greater peaks in December and January. When only irrigation and mining demand are considered, AWRA-R releases can explain 45% of the variance. In the case of Glennies Creek Dam releases, the model conceptualisation captures well the downstream irrigation and mining demand, which comprises about 100% of diversions.

Time series of observed and estimated allocations are shown in Figure 18. Simulated allocations are less than 100% during 1995 to 1999 and during 2006 to 2008. Observed allocations are 100% during 1995 to 1999 despite dam volumes being around 50% full; this may reflect changes in licence volumes and/or policy that are not considered in the model. Allocations are over estimated by the model in the second dry period (2006 to 2008) when dams are at around 30% of their capacity, mainly because differences between simulated and observed dam volumes are about 30% and 50% for Glenbawn Dam and Glennies Creek Dam, respectively.

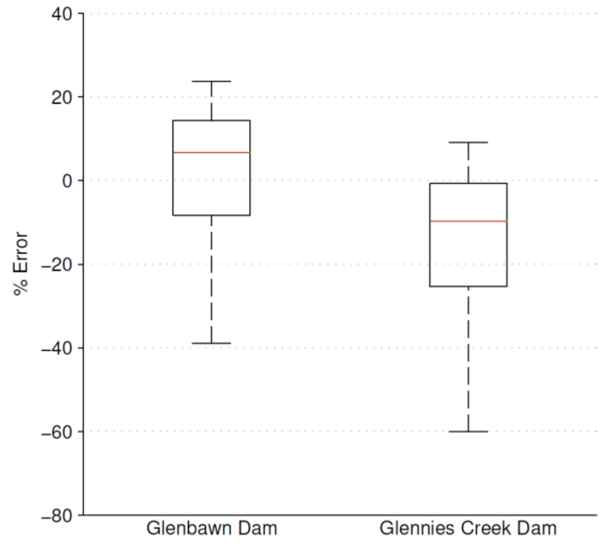

Figure 17 Percentage error for monthly dam storage volumes for Glenbawn Dam and for Glennies Creek Dam

Data: Bioregional Assessment Programme (Dataset 6), NSW Office of Water (Dataset 9)

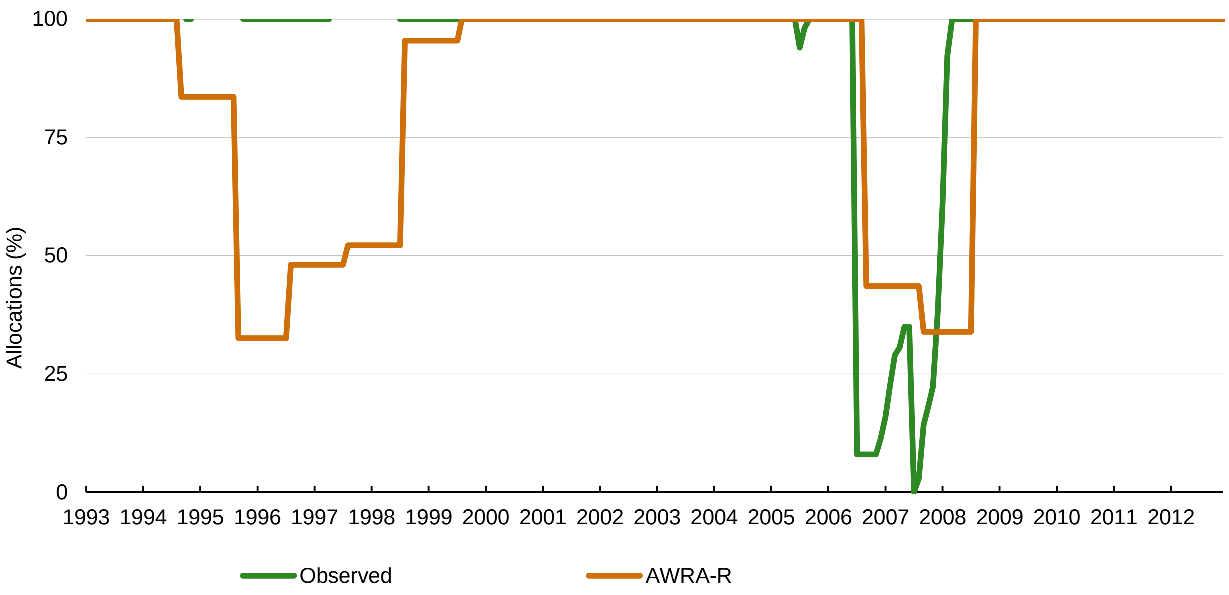

Figure 18 Observed and AWRA-R simulated allocations for the AWRA-R Hunter river system

AWRA-R = Australian Water Resources Assessment river model
Data: Bioregional Assessment Programme (Dataset 6), NSW Office of Water (Dataset 9)

Implications for model predictions

Overall, AWRA-R streamflow is reasonably well simulated using both high- and low-streamflow calibrations. As expected, the low-streamflow calibration performed markedly better when the evaluation was focused on the low flows, particularly in intermittent streams. The better performance of the low-streamflow calibration was also observed in terms of the hydrological response variables used to quantify the hydrological changes due to the additional coal resource development, particularly for the variables characterising low streamflow, although the performance for the variables characterising high flows was typically only marginally worse. Generally, the hydrological response variables characterising low-streamflow conditions are under estimated, whereas those characterising high-streamflow conditions are over estimated. The number of ZFD 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- and low-streamflow calibrations show large uncertainty in predicting the nine hydrological response variables. Prior distributions of the model parameters are used in Approximate Bayesian Computation uncertainty analysis to generate 3000 parameter sets which cover wide boundary ranges for two of the AWRA-R calibration parameters (see Section 2.6.1.5). 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 the additional coal resource development on the nine hydrological response variables in each model node in the Hunter subregion (Section 2.6.1.6).

A wide range of dam operating conditions are represented in the model as a result of choosing a 20-year calibration period that included significant dry and wet periods. This ensures that the model can be used in some of the extreme conditions imposed by modelling of the additional coal resource development. The simple soil water deficit that computes releases for irrigation, and the scheme (through a similar deficit proxy) that computes releases for mining perform reasonably well. This is highlighted in the reasonably good agreement (r^2 and E_m both greater than 0.6) between simulated and IQQM-modelled releases for Glennies Creek Dam, for which irrigation and mining diversions comprise about 100% of surface water diversions; and by Glenbawn Dam releases explaining 45% of the variance when only irrigation and mining demand are considered.

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). Most of the mismatch can be attributed to imposing a pattern of summer dam releases for the environment and for electricity generation (the largest water user in the Hunter river basin) on the model, which does not accurately reflect the actual demand pattern. It is acknowledged that a more robust scheme is needed to simulate releases to satisfy water demand for electricity generation.

Overestimation of releases during the dry period between 2003 and 2008 can be partly explained by high water demand for electricity generation, but also by AWRA-L inflows to both dams, as AWRA-L tends to over estimate streamflow in the Hunter 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.

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Dataset 11 NSW Office of Water (2016) HUN AWRA-R Observed storage volumes Glenbawn Dam and Glennies Creek Dam. Bioregional Assessment Source Dataset. Viewed 08 September 2016, http://data.bioregionalassessments.gov.au/dataset/9c2dccdb-ef46-48c7-bfe1-946ab57645e5.

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 maximum percent change and the year of maximum change for each hydrological 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.

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 is defined and an acceptance threshold defined.

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

Parameter sampling

For AWRA-L, the parameters varied in the uncertainty analysis are those used in the calibration, with the addition of the parameter for scaling effective porosity, *ne_scale*. For AWRA-R, two of eight calibrated parameters, *K_rout* and *Lag_rout*, are included in the uncertainty analysis. The remaining AWRA-R parameters are set to their values from the low-streamflow calibration and not varied in the uncertainty analysis: variability in surface water – groundwater interactions (two parameters) and catchment runoff (one parameter) is already captured in inputs from the groundwater model and AWRA-L simulations; the three irrigation parameters are fixed as changes in irrigation management are not in the scope of this study.

Table 9 lists the parameters used in the uncertainty analysis and the range uniformly sampled in the design of experiment. The Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and AWRA river model (AWRA-R) parameters in Table 9 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 which 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.

Three thousand parameter combinations are generated from the AWRA-L and AWRA-R model parameters according to the ranges and transformations shown in Table 9 using a space-filling Latin Hypercube sampling algorithm (Santner et al., 2003) that efficiently covers the sample space. 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 generated include all the parameter combinations for the groundwater model (see companion product 2.6.2 for the Hunter subregion (Herron 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.

Table 9 Summary of AWRA-L and AWRA-R parameters for uncertainty analysis

Model	Parameter name	Description	Units	Transfor-mation	Minimum	Maximum
AWRA-L	cGsmax _hruDR	Conversion coefficient from vegetation photosynthetic capacity index to maximum stomatal conductance	na	none	0.02	0.05
AWRA-L	cGsmax _hruSR	Conversion coefficient from vegetation photosynthetic capacity index to maximum stomatal conductance	na	none	0.001	0.05
AWRA-L	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
AWRA-L	FsoilEmax _hruDR	Soil evaporation scaling factor when soil water supply is not limiting evaporation	na	none	0.2	1
AWRA-L	FsoilEmax _hruSR	Soil evaporation scaling factor soil water supply is not limiting evaporation	na	none	0.2	1
AWRA-L	K_gw_scale	Multiplier on the raster input of K_g	na	log10	0.001	1
AWRA-L	K_rout_int	Intercept coefficient for calculating K_r	na	none	0.05	3
AWRA-L	K_rout_scale	Scalar coefficient for calculating K_r	na	none	0.05	3
AWRA-L	K0sat_scale	Scalar for hydraulic conductivity (surface layer)	na	log10	0.1	10

Model	Parameter name	Description	Units	Transfor-mation	Minimum	Maximum
AWRA-L	Kdsat_scale	Scalar for hydraulic conductivity (deep layer)	na	log10	0.01	1
AWRA-L	Kr_coeff	Coefficient on the ratio of K_{sat} across soil horizons for the calculation of interflow	na	log10	0.01	1
AWRA-L	Kssat_scale	Scalar for hydraulic conductivity (shallow layer)	na	log10	0.0001	0.1
AWRA-L	ne_scale	Scalar for effective porosity	na	none	0.1	1
AWRA-L	Pref_gridscale	Multiplier on the raster input of P_{ref}	na	none	0.1	5
AWRA-L	S_sls_hruDR	Specific canopy rainfall storage capacity per unit leaf area	mm	none	0.03	0.8
AWRA-L	S_sls_hruSR	Specific canopy rainfall storage capacity per unit leaf area	mm	none	0.03	0.8
AWRA-L	S0max_scale	Scalar for maximum water storage (surface layer)	na	none	0.5	5
AWRA-L	Sdmax_scale	Scalar for maximum water storage (deep layer)	na	none	0.5	1
AWRA-L	slope_coeff	Coefficient on the mapped slope for the calculation of interflow	na	log10	0.01	1
AWRA-L	Ssmax_scale	Scalar for maximum water storage (shallow layer)	na	none	0.5	3
AWRA-L	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
AWRA-R	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 = not applicable (dimensionless)

Observations

Predictions and observations from 22 streamflow gauges whose catchments contribute flow to the surface water modelling domain in the Hunter subregion are used for uncertainty analysis. Selection of the 22 catchments 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 catchments, historical observations of streamflow are summarised into the nine hydrological response variables for all years. The equivalent historical simulated hydrological response variable values are computed from the 3000 design of experiment runs. The goodness of fit between these observed and simulated historical 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. These 300 replicates are used for predictions in Section 2.6.1.6.

Predictions

For each of the 65 model nodes the post-processing of design of experiment results in 3000 time series with a length of 90 years (2013–2102) of hydrological response variable values for baseline, $HRV_b(t)$, and coal resource development pathway (CRDP) conditions, $HRV_c(t)$.

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

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

As the predictions include the effect of surface water – groundwater interaction through coupling with the groundwater models, groundwater parameters will also 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 historical hydrological response variable values obtained from nodes at 22 streamflow gauging sites. This means that out of the 3000 model replicates, the 300 best (or 10% best) 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) their performance approaching 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 strength and weakness of this decision are further discussed in Section 2.6.1.5.2.

2.6.1.5.2 Qualitative uncertainty analysis

The major assumptions and model choices underpinning the Hunter subregion surface water model are listed in Table 10. The goal of the qualitative uncertainty analysis is to provide a non-technical overview of the model assumptions, and 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 10 is rated against three attributes (data, resources, technical) and their effect on predictions.

1. The data column is the degree to which the question 'If more or different data were available, would this assumption/choice still have been made?' would be answered positively. A low rating indicates the assumption is not influenced by data availability, 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 flags 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 the assumption or model choice has 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.

Table 10 Qualitative uncertainty analysis as used for the Hunter 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	Medium
Implementation of the coal resource development pathway	High	Low	Low	High
Streamflow routing	Low	Low	Low	Low

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

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 Hunter 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 score for this criterion. As it is technically trivial to include more calibration catchments in the calibration procedure and as it would not appreciably change the computing time required, both the resources and technical columns have a low 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 (see Section 2.6.1.6) 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 (*E*) and the bias. The former is most sensitive to differences in simulated and observed daily and monthly streamflow, while 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 *E* 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. While different choices of the weights will result in a different set of optimised parameter values, experience in the Water Information Research and Development Alliance (WIRADA) project, in which the AWRA-L is calibrated on a continental scale, has shown the calibration to be fairly robust against the weights in the objective function (Vaze et al., 2013).

While 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, while 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 Hunter 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 low 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. While 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 medium.

Interaction with the groundwater model

The coupling between the outputs of the groundwater model and the surface water models, 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 Hunter 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 predictions is rated as medium. While changes in baseflow are generally small compared to runoff, the low flow regime can be sensitive to them.

Implementation of the coal resource development pathway

The CRDP is implemented through the interaction with the groundwater models 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 the 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 Hunter subregion, the accuracy of the mine footprints represented in the model largely reflects the accuracy of the 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 scored high, while the resources and technical columns are scored low. The effect on predictions is scored high.

Streamflow routing

Streamflow routing is taken into account in the Hunter AWRA-R as the Hunter River is a large system and routing can lag flows by several days. Streamflow routing is not taken into account in the Macquarie-Tuggerah lakes basin since it is unregulated and sufficiently small that lags in streamflow due to routing will be within a daily time step. The effect on the prediction of not incorporating routing is therefore minimal. Given the small potential for impact, resourcing the development of a river-routing model for this region was not warranted. All attributes are rated low as it is technically feasible and within the operational constraints of the BA to carry out streamflow routing. Doing so would only minimally affect the predictions.

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2.6.1.6 Prediction

Summary

Section 2.6.1.6 summarises prediction results of hydrological changes for nine hydrological response variables due to the modelled additional coal resource development. The hydrological changes on each model node were generated from among 3000 replicates of the model runs using randomly selected parameter sets.

The prediction results show that the additional coal resource development in the Hunter subregion can cause substantial changes in the hydrological response variables. The comparison among the 65 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 footprint forms a large proportion of the node catchment.

In general, the hydrological changes are greater in the small tributaries of the Hunter River than in the model nodes along the river itself. The biggest hydrological changes (flow reductions of up to 80%) occur at nodes 7 to 9 (Loders Creek, including Doctors Creek), which enter the Hunter River just upstream of Singleton, and at nodes 52 (Dry Creek) and 55 (unnamed creek) in the vicinity of Muswellbrook. The catchments of nodes 7 to 9 include the Bulga and Mount Thorley–Warkworth mines, while the catchments of nodes 52 and 55 include the Bengalla and Mount Pleasant mines. The prediction that the biggest hydrological changes occur downstream of multiple mine developments highlights the cumulative nature of potential hydrological changes, particularly on low-flow characteristics.

The hydrological changes due to the additional coal resource development on the low-streamflow hydrological response variables appear to be slightly larger than those on the high-streamflow hydrological response variables. However, the uncertainties in the predicted change and the timing of the maximum change are greater for the low-streamflow hydrological response 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 watertable drawdown, while the changes to high-flow characteristics are dominated by direct interception of runoff.

2.6.1.6.1 Introduction

Section 2.6.1.6 summarises the prediction results for nine hydrological response variables and for 65 surface water model nodes. The nine hydrological response variables for streamflow are:

- AF – the annual flow volume (GL/year)
- P99 – the daily streamflow rate at the 99th percentile (ML/day)
- IQR – the interquartile range in daily streamflow (ML/day); that is, the difference between the daily streamflow rate at the 75th percentile and at the 25th percentile

- FD – the number of high-flow days per year. 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'
- P01 – the daily streamflow rate at the 1st percentile (ML/day)
- ZFD – the number of zero-flow days each year
- LFD – the number of low-flow days per year. The threshold for low-flow days is the 10th percentile from the simulated 90-year period (2013 to 2102)
- LFS – the number of low-flow spells per year. A spell is defined as a period of contiguous days of streamflow below the 10th percentile threshold
- LLFS – the length (days) of the longest low-flow spell each year.

These hydrological response variables were chosen to be able to quantify changes across the entire flow regime (see submethodology M06 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 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 22 observation sites – were chosen for further analysis. The 22 assessment nodes are chosen for their availability of suitable observational data. Each boxplot was generated from the resulting 300 samples. 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 magnitudes of responses that would be expected to occur every year.

Results are for those additional coal resource developments that were able to be modelled. As discussed in companion product 2.3 (conceptual modelling) for the Hunter subregion (Dawes et al., 2018), there was insufficient data to model West Muswellbrook and Mandalong developments; Wambo and Mount Arthur developments were assessed as not causing any additional impact on catchment runoff and therefore were not modelled; and the Chain Valley extension is under Lake Macquarie and does not affect surface runoff. The potential effects on surface water from developments at West Muswellbrook and Mandalong are considered qualitatively in companion product 3-4 (impact and risk analysis) for the Hunter subregion (as listed in Table 2).

2.6.1.6.2 Results analysis

The predictions of hydrological change associated with additional coal resource development are shown in the boxplots in Figure 19 to Figure 27. In these figures, the model nodes are grouped for different river sections and tributaries. Within these groupings, small tributaries have a darker background shading. Nodes are ordered from downstream to upstream. The tributary grouping labelled 'u/s Greta' (u/s = upstream of) includes tributaries that join the Hunter River between nodes 1 and 20. The tributary grouping labelled 'u/s Glennies Creek' includes tributaries that join the Hunter River between nodes 25 and 51. The tributary grouping labelled 'u/s Denman' includes tributaries that join the Hunter River above node 51. Refer to Figure 5 in Section 2.6.1.3 for a schematic depiction of the model nodes and the network topology. The implications of these hydrological changes on landscape classes and assets are not discussed here, but are the focus of the impact and risk analysis reported in companion product 3-4 for the Hunter subregion (as listed in Table 2).

Figure 19 shows the changes to the annual flow (AF) at the 65 model nodes. The biggest percentage reductions occur in some of the small tributaries of the Hunter River, and range up to a median *pmax* of 81% at node 8 (Doctors Creek). Nine model nodes have reductions in median *pmax* that exceed 20%. Seven of these have catchment areas of less than 25 km^2 and all have areas of less than 80 km^2. There are tightly constrained distributions of *pmax* values around these median values at all the heavily affected nodes except for node 11, where the 5th to 95th percentile range in *pmax* is –51% to –30%. Apart from reductions in median *pmax* of about 8% at nodes 46 (Wollar Creek) and 47 (Wilpinjong Creek) there is little effect on AF in the nodes in the Goulburn and Wyong river basins or in those along Wollombi Brook, where the median *pmax* reductions are less than 2% of baseline flow. The largest reductions in median *amax* are located in the lower Hunter River and increase with distance downstream. The biggest effects are at nodes 1 and 6 and result in losses of around 29 GL/year, which represent about 3% of the baseline flow. A large proportion of this median reduction (13 GL/year) originates in the Loders Creek tributary (node 7), with the remainder propagating from upstream (node 10).

For the heavily affected nodes, the median year at which maximum hydrological changes occurs is either 2022 or 2037 for the tributaries of the lower Hunter River (nodes 7, 8, 9 and 11), but 2028 for tributaries upstream of Glennies Creek. There is relatively little uncertainty in these dates. The maximum hydrological changes in the Hunter River itself tend to occur in 2037.

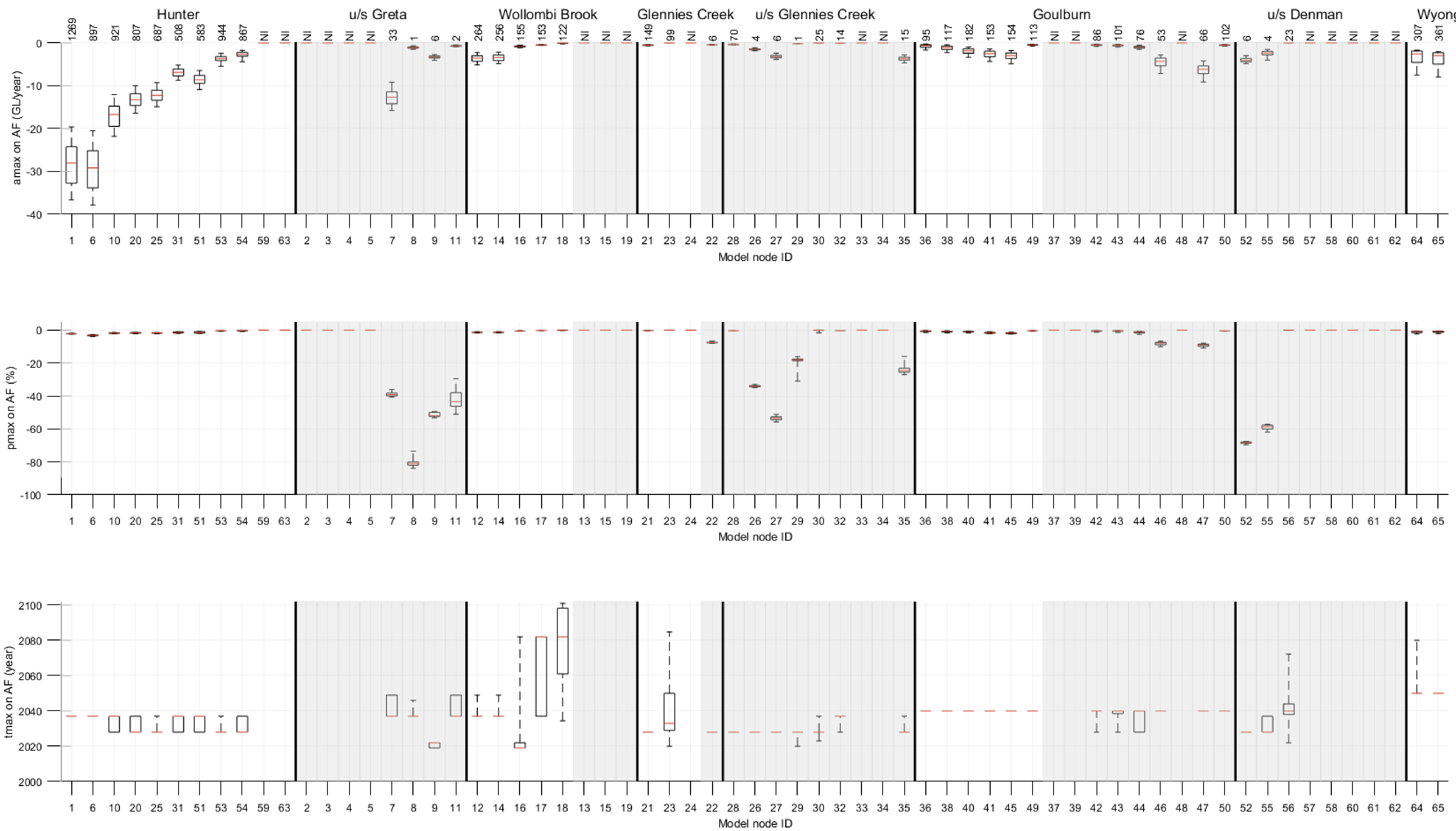

Figure 19 Hydrological changes due to additional coal resource development on annual flow (AF) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.
Refer to Figure 4 in Section 2.6.1.3 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).

Figure 20 shows the changes to the daily streamflow rate at the 99th percentile (P99) at each model node. The biggest changes in *pmax* occur at the same nine locations with the biggest effect on AF. For P99 the median *pmax* values for these nine nodes exceed 20% and range up to 68% for node 52 (Dry Creek). At most of these sites there is a greater spread of *pmax* values than there is for AF. At most of the affected nodes, the percentage reduction in P99 is greater than the percentage reduction in AF.

The year of maximum change in P99 tends to correspond with the year of maximum change in AF, with the exception that it occurs later in the heavily affected nodes 7 and 8 (2052 and 2049, respectively).

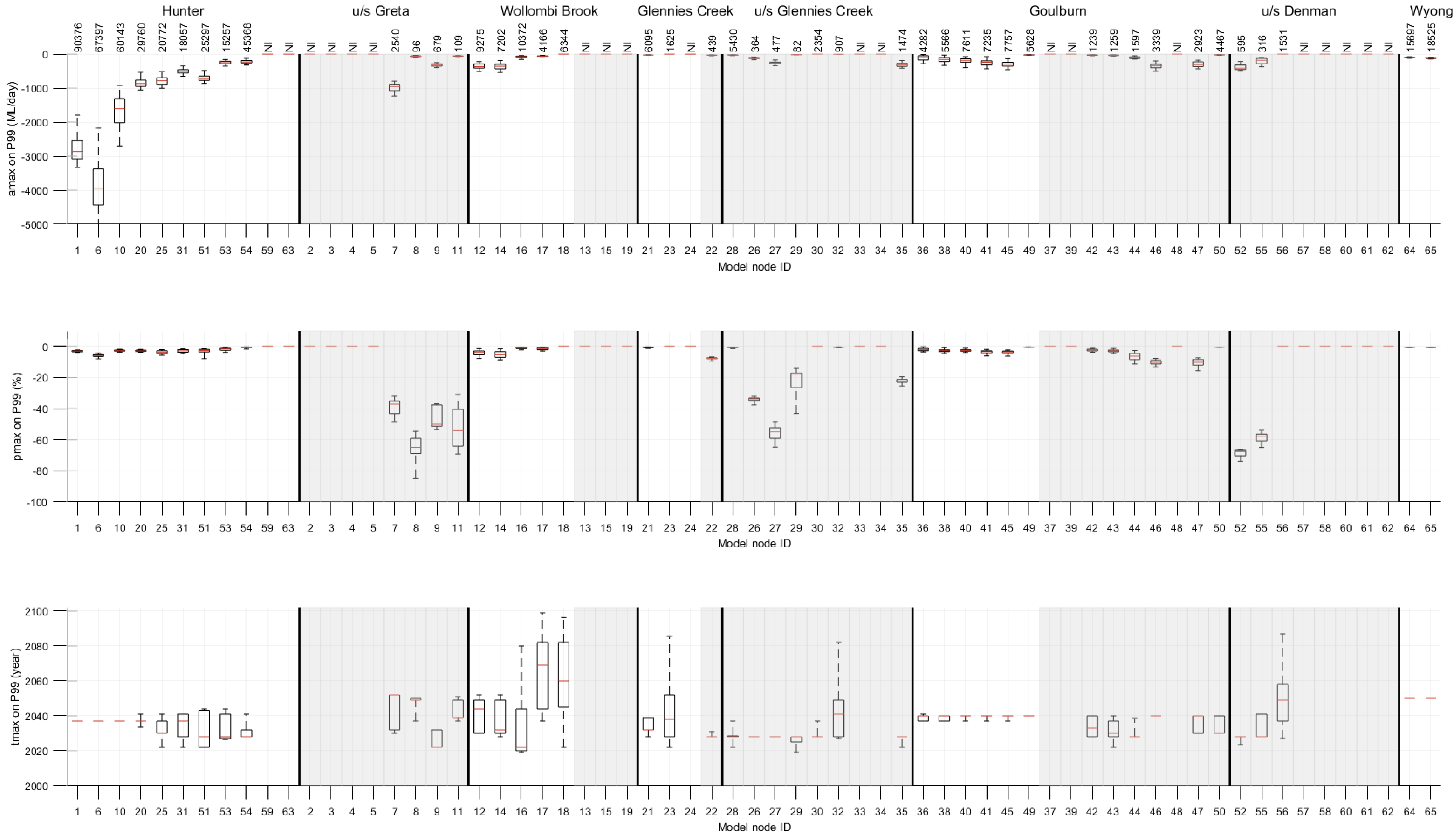

Figure 20 Hydrological changes due to additional coal resource development on daily streamflow at the 99th percentile (P99) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.
Refer to Figure 4 in Section 2.6.1.3 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).

Figure 21 shows the changes to the interquartile range (IQR) at each model node. The changes in IQR associated with the 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, most likely through a decrease in the 75th percentile. The patterns of change are similar to those of AF (Figure 19) and P99 (Figure 20). The biggest reductions in median *pmax* occur at nodes on small tributaries of the Hunter River, and include reductions of more than 70% at nodes 8 (Doctors Creek), 52 (Dry Creek) and 55 (unnamed creek west of Muswellbrook). Each of these nodes have catchment areas of less than 25 km^2.

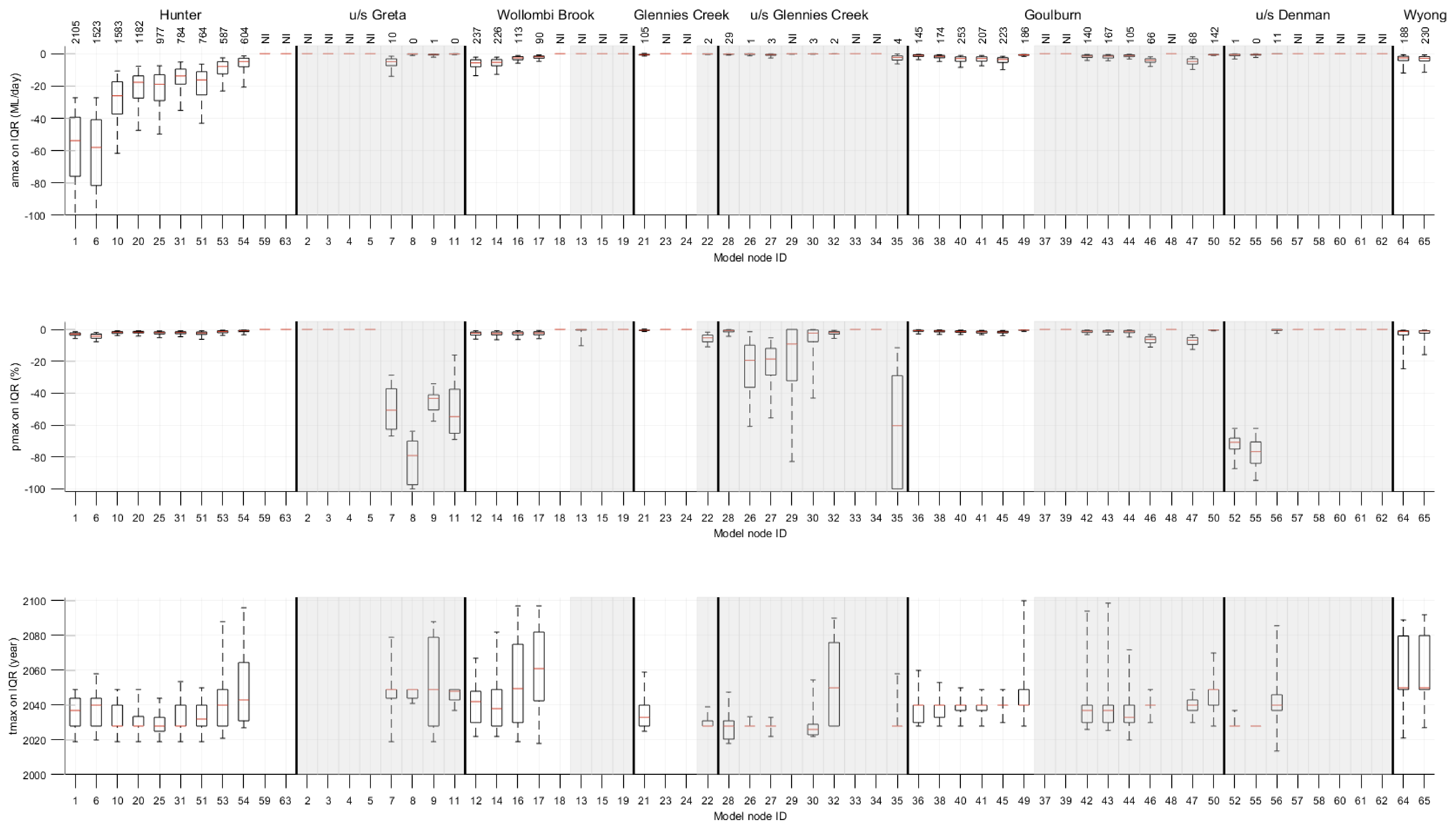

Figure 21 Hydrological changes due to additional coal resource development on interquartile range (IQR) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.

Refer to Figure 4 in Section 2.6.1.3 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).

Figure 22 shows the changes to high-flow days (FD) at each model node. Once again, the largest reductions in the number of FD occur in the small tributaries of the Hunter River, but there are also largish reductions at two tributary nodes in the Goulburn river basin. The biggest change is a maximum reduction in the median number of FD by 46 days/year at node 52 (Dry Creek). Twelve nodes have median reductions in *amax* of more than 5 days/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 Hunter River, the frequency of FD is reduced by 4 days/year at node 6 (Singleton) and by lesser amounts elsewhere.

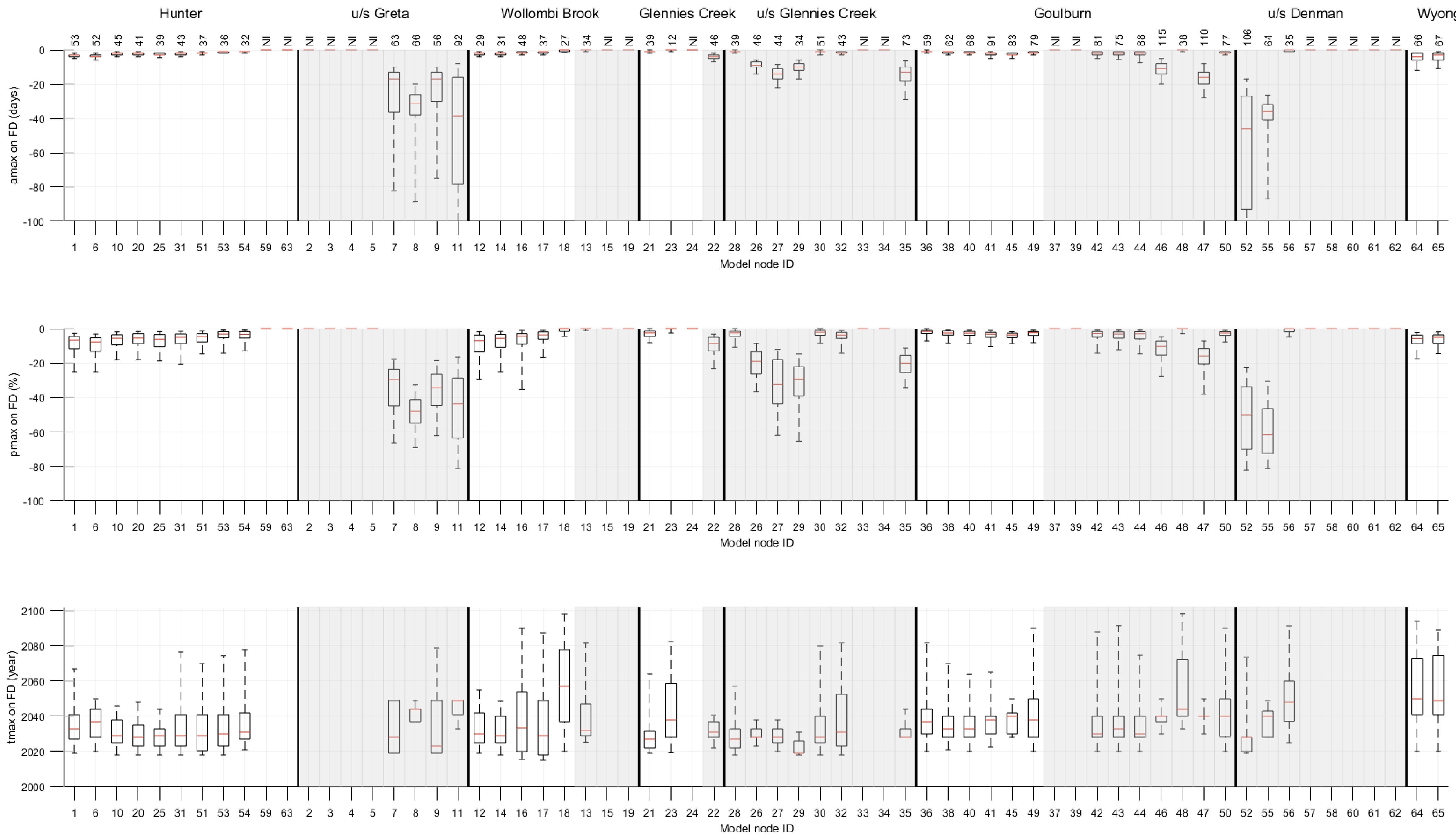

Figure 22 Hydrological changes due to additional coal resource development on high-flow days (FD) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.

Refer to Figure 4 in Section 2.6.1.3 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).

Figure 23 shows the changes to the daily streamflow rate at the 1st percentile (P01) at each model node. Reductions in median *pmax* of more than 10% are predicted in many of the tributary nodes with large reductions in high-flow characteristics, especially nodes 7, 8, 9, 11 and 55, including 100% reductions in median *pmax* at node 8 (Doctors Creek) and node 55 (unnamed). These cases are representative of a particular year in a replicate for which there is a nonzero 1st percentile of baseline flow, but the 1st percentile of CRDP flow is zero. Of particular note is that, despite showing little change to the high-flow characteristics, there are substantial predicted changes to 1st percentile flow in the two nodes in the Wyong river basin, where the *pmax* values show decreases of 51% (node 64) and 57% (node 65).

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 seven most heavily affected nodes.

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*.

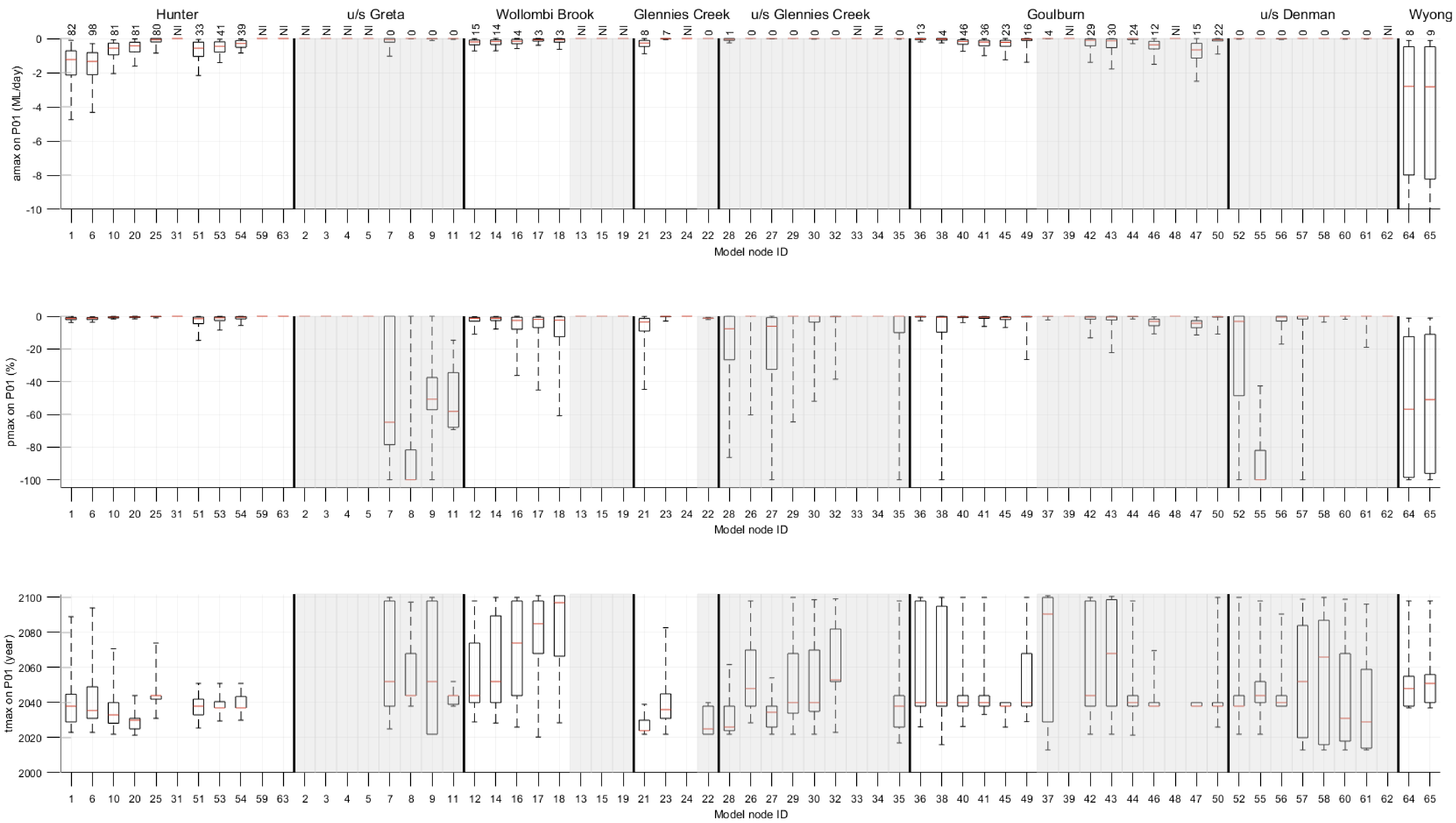

Figure 23 Hydrological changes due to additional coal resource development on daily streamflow at the 1st percentile (P01) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.

Refer to Figure 4 in Section 2.6.1.3 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).

Figure 24 shows the increases in the annual number of zero-flow days (ZFD) due to the additional coal resource development. Most of the nodes along the Hunter and Goulburn rivers, together with Glennies Creek and Wollombi Brook, are perennial in both the baseline and CRDP simulations and therefore show no effect on ZFD. Along the regulated part of the Hunter River, this reflects the fact that the river is managed to ensure that minimum environmental flows are met at key points along the river. This requirement is represented in the model, thus under the baseline and the CRDP, there are no zero-flow days. The only nodes with potentially large changes are on some of the small tributary nodes of the Hunter River and the nodes of the Wyong River. The largest predicted changes in ZFD are increases of 200 and 225 days/year at nodes 64 and 65 along the Wyong River. However, there is considerable uncertainty in these projections at all nine nodes where *amax* exceeds 15 days/year.

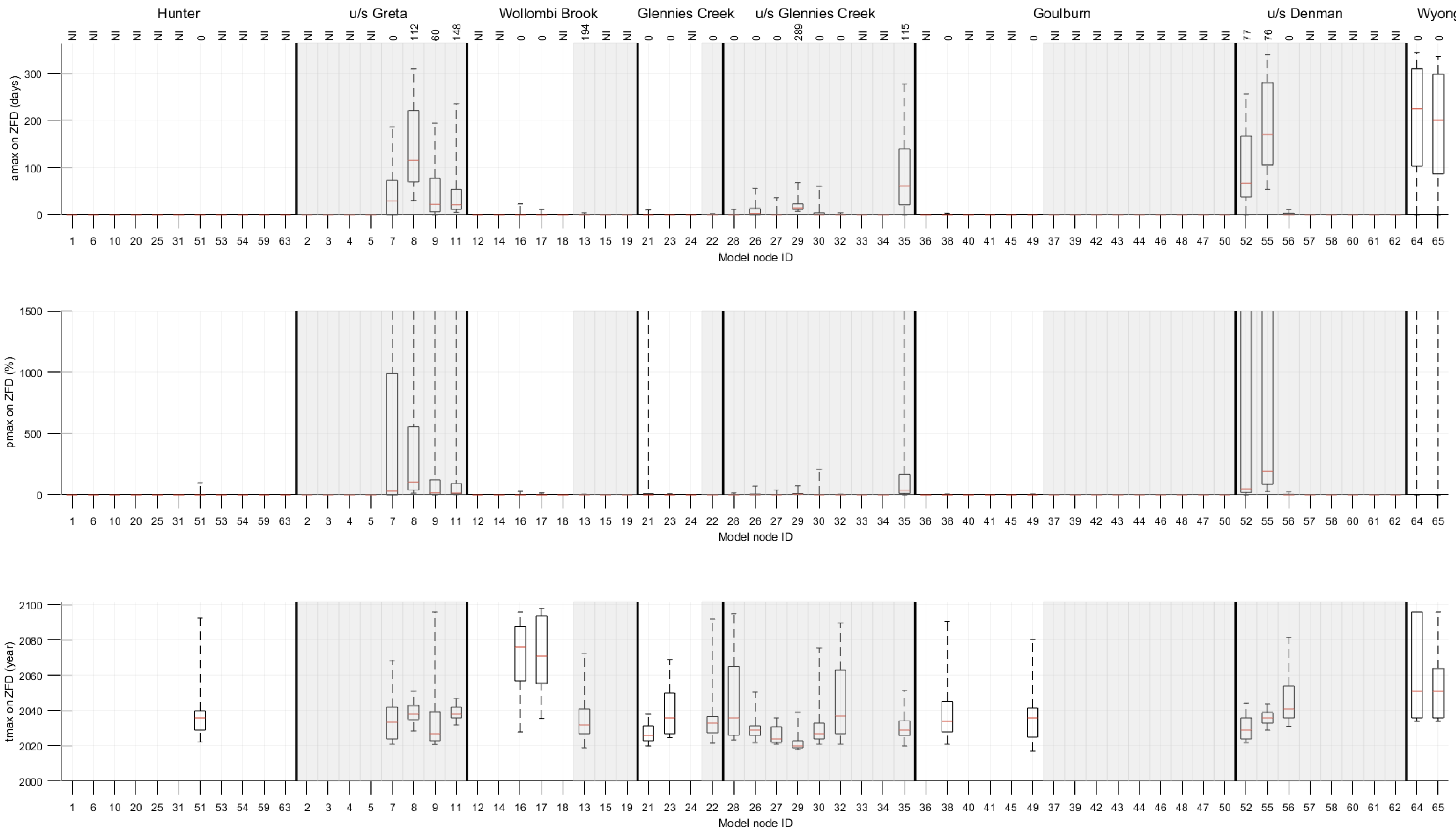

Figure 24 Hydrological changes due to the additional coal resource development on the number of zero-flow days (ZFD) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.
Refer to Figure 4 in Section 2.6.1.3 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).

Figure 25 shows the increases in the annual number of low-flow days (LFD) due to the additional coal resource development. There are substantial predicted increases in *amax* in many tributary nodes and in the Wyong river basin. The biggest effect is a median *amax* value of 295 days/year at node 55. The biggest change along the Hunter River is an increase of 5 days/year at node 6. There is considerable uncertainty in the corresponding *tmax* values for the heavily affected nodes, but the median *tmax* values typically occur between 2024 and 2036. Exceptions are node 50 (Goulburn River) where the median *tmax* is 2065 and the two nodes in the Wyong river basin where the median *tmax* values are 2051.

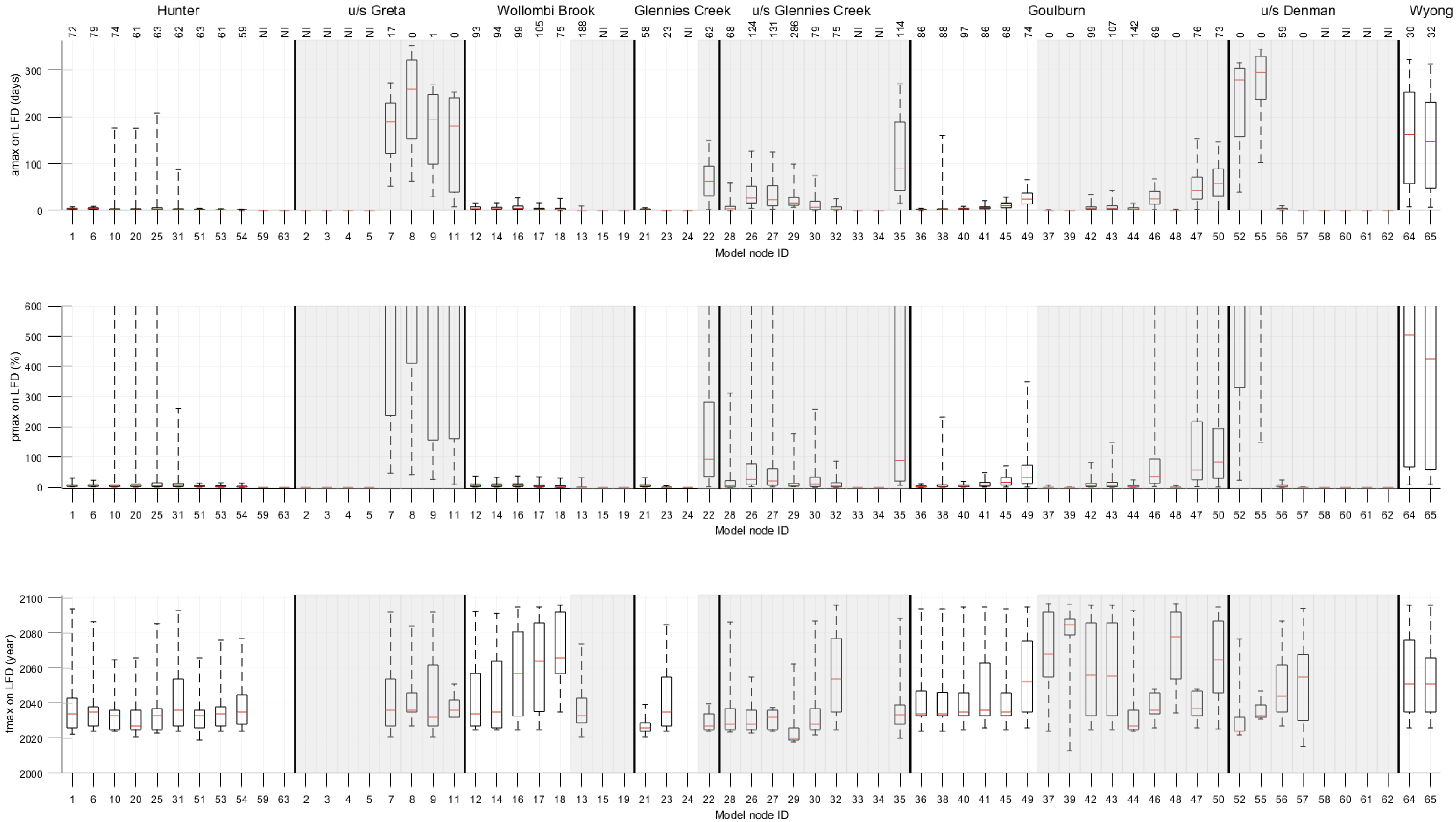

Figure 25 Hydrological changes due to the additional coal resource development on the number of low-flow days (LFD) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.

Refer to Figure 4 in Section 2.6.1.3 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).

Figure 26 shows the changes in low-flow spells (LFS) due to the additional coal resource development. Increases in median *amax* of more than three spells per year occur at tributary nodes 7, 8, 9, 52 and 55 as well as at nodes 64 and 65 in the Wyong river basin. The biggest changes are increases of 21 spells at nodes 8 and 55. However, there are also substantial increases in LFS at nodes 10, 20, 25 and 31 along the Hunter River, including a median change of 12 spells at node 31 (Liddell). Interestingly, there are two small tributary nodes (26 and 29) where median *amax* shows a decrease by two spells per year. These reductions in *amax* result when multiple spells coalesce into a single large spell.

There is considerable uncertainty in the projections of both *amax* and *tmax* in Figure 26.

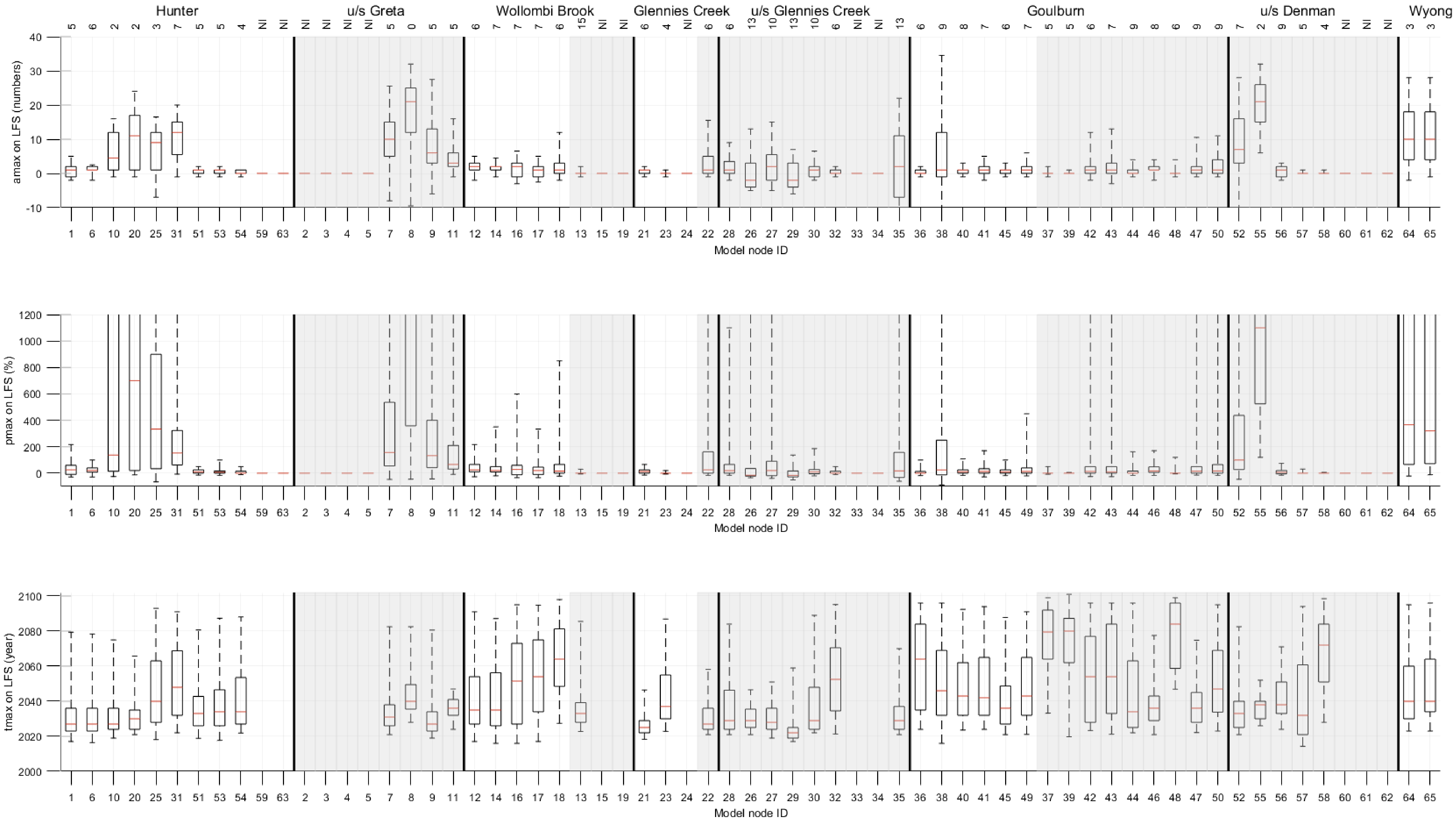

Figure 26 Hydrological changes due to the additional coal resource development on the number of low-flow spells (LFS) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.

Refer to Figure 4 in Section 2.6.1.3 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).

Figure 27 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. The LLFS is projected to increase by about 130 days at node 8 (Doctors Creek) and by more than 15 days at several other small tributary nodes. The LLFS is projected to increase by 32 and 37 days at the two nodes in the Wyong river basin.

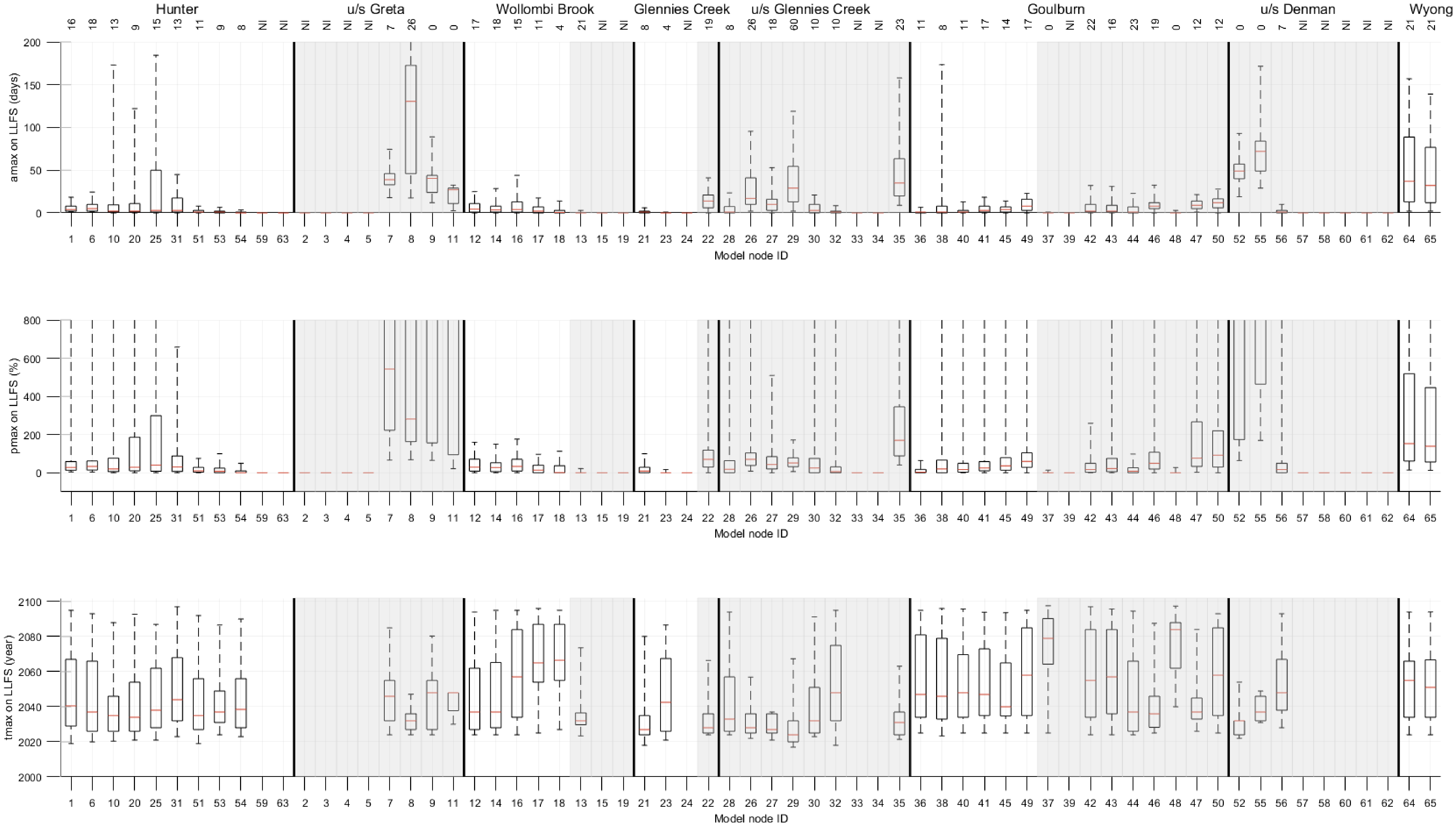

Figure 27 Hydrological changes due to the additional coal resource development on the length of longest low-flow spell (LLFS) at the 65 model nodes within the Hunter subregion

amax = maximum raw change; *pmax* = maximum percent change; *tmax* = year of maximum change; u/s = upstream of; NI = negligible 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. Within the groupings, small tributaries have a darker background shading.

Refer to Figure 4 in Section 2.6.1.3 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 Summary and discussion

The prediction results show that the additional coal resource development in the Hunter subregion can affect all of the hydrological response variables. Comparisons across the 65 model nodes show that the relative hydrological changes are larger for the nodes where the maximum footprint for the additional coal resource development affects a larger proportion of the catchment. For instance, the mine footprints in the catchments contributing to nodes 52 and 55 comprise 66% and 58% of the total contributing area, respectively (these areas are reported in Table 4 in Section 2.6.1.3). The resulting median *pmax* values for the high-flow flux-based variables, AF and P99, are around –68% and –59%, respectively. In general the median change in these variables is highly correlated and commensurate with the maximum proportion of the catchment that is included in the footprint for the additional coal resource development. Large changes are also predicted for node 8 for many hydrological response variables (–81% for AF and –65% for P99). Here the footprint for the additional coal resource development comprises 55% of the contributing area to this node, but since the node is also heavily affected by mining under the baseline, even larger hydrological changes are predicted relative to its proportional area.

The prediction results show that the additional coal resource development in the Hunter subregion has more noticeable effects on hydrological response variables in the small tributaries of the Hunter River, where the proportion of contributing area affected by mining is more likely to be high, than at the nodes along the Hunter River itself. This is particularly apparent in streamflow at nodes 7 to 9 (Loders Creek, including Doctors Creek), which enter the Hunter River just upstream of Singleton, and at nodes 52 (Dry Creek) and 55 (unnamed creek) in the vicinity of Muswellbrook. The catchments of nodes 7 to 9 include the Bulga and Mount Thorley–Warkworth additional coal resource developments, which affect 35–55% of the contributing areas (Table 4 in Section 2.6.1.3); the catchments of nodes 52 and 55 include the Bengalla and Mount Pleasant mines. Other nodes with substantial percentage changes in the high-streamflow hydrological response variables are nodes 26, 27, 29 and 35. The first three of these nodes are all located in the vicinity of the Glendell, Integra, Liddell and Mount Owen mines, while the catchment of node 35 includes parts of the Drayton South and Mount Arthur mines. All these nodes have relatively small contributing areas. While there are bigger predicted changes in *amax* at nodes further downstream, the proportional effects of these changes are diluted by relatively unaffected inflows. The prediction that the biggest effects occur downstream of multiple mine developments highlights the cumulative nature of potential hydrological changes, particularly on low-flow characteristics.

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, unlike for the high-streamflow hydrological response variables, there is also a substantial change in the low-streamflow hydrological response variables in the two nodes of the Wyong river basin. These nodes are located near the proposed Wallarah 2 and Mandalong underground mines. The effect of these reductions in baseflow is to turn what was previously a perennial stream into one that flows on only about 40% of days in the most heavily affected year. Although this is a large reduction, it must be remembered that the projections presented in Figure 19 to Figure 27 are for the worst-case year during the entire simulation period (2013 to 2102). There is no implication, particularly for the low-flow variables, that the changes will be this severe in every year.

Substantial increases in ZFD would be expected where the river connection with groundwater is broken – that is, if drawdown causes the watertable in the alluvium to drop below the channel bed. In such a situation, a perennial or intermittent stream would switch to an ephemeral system, which by definition only flows in response to rainfall-runoff events. As part of the Hunter subregion groundwater modelling (companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)) hydraulic property information from the Wallarah 2 environmental assessment (Mackie Environmental Research, 2013) was used to illustrate the process by which local information can be used to constrain the regional-scale predictions. The parameters from the environmental assessment indicated relatively poor connectivity through the overburden above the mine. The simulations informed by lower hydraulic conductivity parameters resulted in drawdowns towards the lower end of the range of predictions from the regional groundwater model (see Section 2.6.2.8.4 in Herron et al., 2018b). This suggests that the larger changes in baseflows from the set of regional groundwater parameters are over-estimates and that the Wyong River is unlikely to switch to an intermittent flow regime (i.e. a variable connection to groundwater). This is an area where more detailed investigation is needed to reduce the uncertainty around these predictions.

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). 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-flow variables.

For high-streamflow hydrological response variables, the *tmax* at nodes with noticeable changes occurs approximately when the maximum footprint for the additional coal resource development occurs. This indicates that the instantaneous streamflow reduction caused by the mine footprint for the additional coal resource development dominates *amax* and *pmax* in these hydrological response variables while the changes from the cumulative effect on baseflow over time caused by watertable drawdown are negligible. This conclusion is supported by the tightly constrained changes in *pmax* at most nodes which suggest that the biggest effect 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 low-streamflow hydrological response variables, the *tmax* at nodes with noticeable changes does not occur consistently with the time when the maximum footprint for the additional coal resource development occurs. 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 on the low-flow variables are controlled by a combination of the instantaneous change from the additional mine footprints and the cumulative effect on baseflow over time caused by watertable 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 response variables.

2.6.1.6.4 Defining thresholds of hydrological change

The consequences of the changes to streamflow characteristics described in this product on landscape classes and water-dependent assets are considered in companion product 3-4 for the Hunter subregion (as listed in Table 2). In order to rule out water-dependent landscape classes and assets that are unlikely to be impacted by changes in surface water hydrology, it is necessary to define the magnitude of change in hydrology below which reaches of the stream network are assumed to experience no significant hydrological change due to the additional coal resource development. A threshold has been defined conservatively for each of the nine hydrological response variables in Section 8.1.4 of Viney (2016). For:

- the flux-based hydrological response variables AF, P99 and IQR, this 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, this 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 negligible.
- the frequency-based metrics FD, LFD, LLFS and ZFD, this 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, this is a greater than 5% chance of there being a change in the variable of at least two spells in any year.

If results from the surface water modelling indicate that for all nine variables at a model node there is a less than a 5% probability the hydrological changes will exceed the thresholds, then landscape classes and assets that depend on streamflow at that location are very unlikely to be impacted due to the additional coal resource development.

Streams, predicted to experience changes that exceed these thresholds, will not necessarily be adversely impacted by these changes. Rather they are retained in the group of ‘potentially impacted’ streams for which more local information and analysis are needed to assess the implications of the changes on ecological, economic and sociocultural values. Thus these thresholds form the basis for defining the *zone of potential hydrological change* (see companion product 3-4), within which the potential for impacts cannot be ruled out.

Table 11 summarises for each surface water modelling node in the Hunter subregion whether the hydrological change due to the additional coal resource development exceeds the threshold for each hydrological response variable. At nodes 2–5, 15, 19, 23–24, 33–34, 39, 57–63, there are no significant hydrological changes due to the additional coal resource development; at nodes 7–9, 11, 26–27, 29, 35, 52 and 55, changes in all nine hydrological response variables exceed their respective thresholds; at all other nodes, there are above-threshold changes in some hydrological response variables, but not others. The last row in Table 11 gives the number of nodes for which the hydrological response variable was modelled to exceed its specified threshold. The majority of nodes (46) experience changes in three of the low-streamflow hydrological response variables (LFD, LFS and LLFS) and in the IQR hydrological response variable (43); less than a third exceed the specified threshold for the ZFD hydrological response variable; about half (33) exceed the specified threshold for AF.

Table 11 Change in hydrological response variable (column) relative to its threshold at each model node (row) due to additional coal resource development

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

	AF	P99	IQR	FD	P01	LFD	LFS	LLFS	ZFD
31	ET	ET	ET	ET	–	ET	ET	ET	–
32	–	–	ET	ET	–	ET	ET	ET	ET
33	–	–	–	–	–	–	–	–	–
34	–	–	–	–	–	–	–	–	–
35	ET	ET	ET	ET	ET	ET	ET	ET	ET
36	ET	ET	ET	–	–	ET	ET	ET	–
37	–	–	–	–	–	–	ET	–	–
38	ET	ET	ET	ET	–	ET	ET	ET	ET
39	–	–	–	–	–	–	–	–	–
40	ET	ET	ET	ET	–	ET	ET	ET	–
41	ET	ET	ET	ET	ET	ET	ET	ET	–
42	ET	ET	ET	ET	ET	ET	ET	ET	–
43	ET	ET	ET	ET	ET	ET	ET	ET	–
44	ET	ET	ET	ET	ET	ET	ET	ET	–
45	ET	ET	ET	ET	ET	ET	ET	ET	–
46	ET	ET	ET	ET	ET	ET	ET	ET	–
47	ET	ET	ET	ET	ET	ET	ET	ET	–
48	–	–	–	–	–	ET	ET	ET	–
49	–	–	ET	ET	ET	ET	ET	ET	–
50	–	–	–	ET	ET	ET	ET	ET	–
51	ET	ET	ET	ET	ET	ET	ET	ET	–
52	ET	ET	ET	ET	ET	ET	ET	ET	ET
53	–	ET	ET	–	ET	ET	ET	ET	–
54	–	ET	ET	–	ET	ET	–	ET	–
55	ET	ET	ET	ET	ET	ET	ET	ET	ET
56	–	–	ET	–	–	ET	ET	ET	ET
57	–	–	–	–	–	–	–	–	–
58	–	–	–	–	–	–	–	–	–
59	–	–	–	–	–	–	–	–	–
60	–	–	–	–	–	–	–	–	–
61	–	–	–	–	–	–	–	–	–
62	–	–	–	–	–	–	–	–	–
63	–	–	–	–	–	–	–	–	–
64	ET	–	ET	ET	ET	ET	ET	ET	ET

	AF	P99	IQR	FD	P01	LFD	LFS	LLFS	ZFD
65	ET	–	ET	ET	ET	ET	ET	ET	ET
Count	**33**	**36**	**43**	**37**	**35**	**46**	**46**	**46**	**21**

ET = exceeds threshold; – indicates not significant (see Viney (2016) and start of this section for definitions)

In Section 2.1.4.2.5 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a), the node to link mapping for the modelled Hunter River and Wyong River networks is defined. This mapping informs the extrapolation of results from model nodes to some length of reach upstream and downstream of the node, as appropriate to do so. The information in Table 11 and the node-link mapping in Section 2.1.4 of Herron et al. (2018a) have been used to identify the reaches of the Hunter blue line river network (Dataset 3) that have modelled hydrological changes from additional coal resource development. Figure 28 shows reaches predicted to experience a change in at least one hydrological response variable above its specified threshold due to additional coal resource development.

For some reaches (e.g. node 18 to node 19; node 55 to node 59), the change from an above threshold hydrological change to a non-significant hydrological change occurs somewhere between the two nodes. These reaches are shown as dashed pink lines and other information is needed to determine where to delineate the point of change. Similarly, upstream of the pink headwater model nodes in Figure 28 (i.e. those showing with a change exceeding a specified hydrological threshold), there will be some length of stream that is also potentially affected by the additional 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 a hydrological change exceeding at least one specified threshold. This final step is reported in companion product 3-4 (impact and risk analysis) for the Hunter 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 model node-link network and where hydrological changes from additional coal resource development could impact water-dependent landscapes and assets.

What these potential changes in hydrology from additional coal resource development might mean for Hunter subregion landscape classes and assets are covered in companion products 2.7 (receptor impact modelling) and 3-4 (impact and risk analysis) for the Hunter subregion (as listed in Table 2).

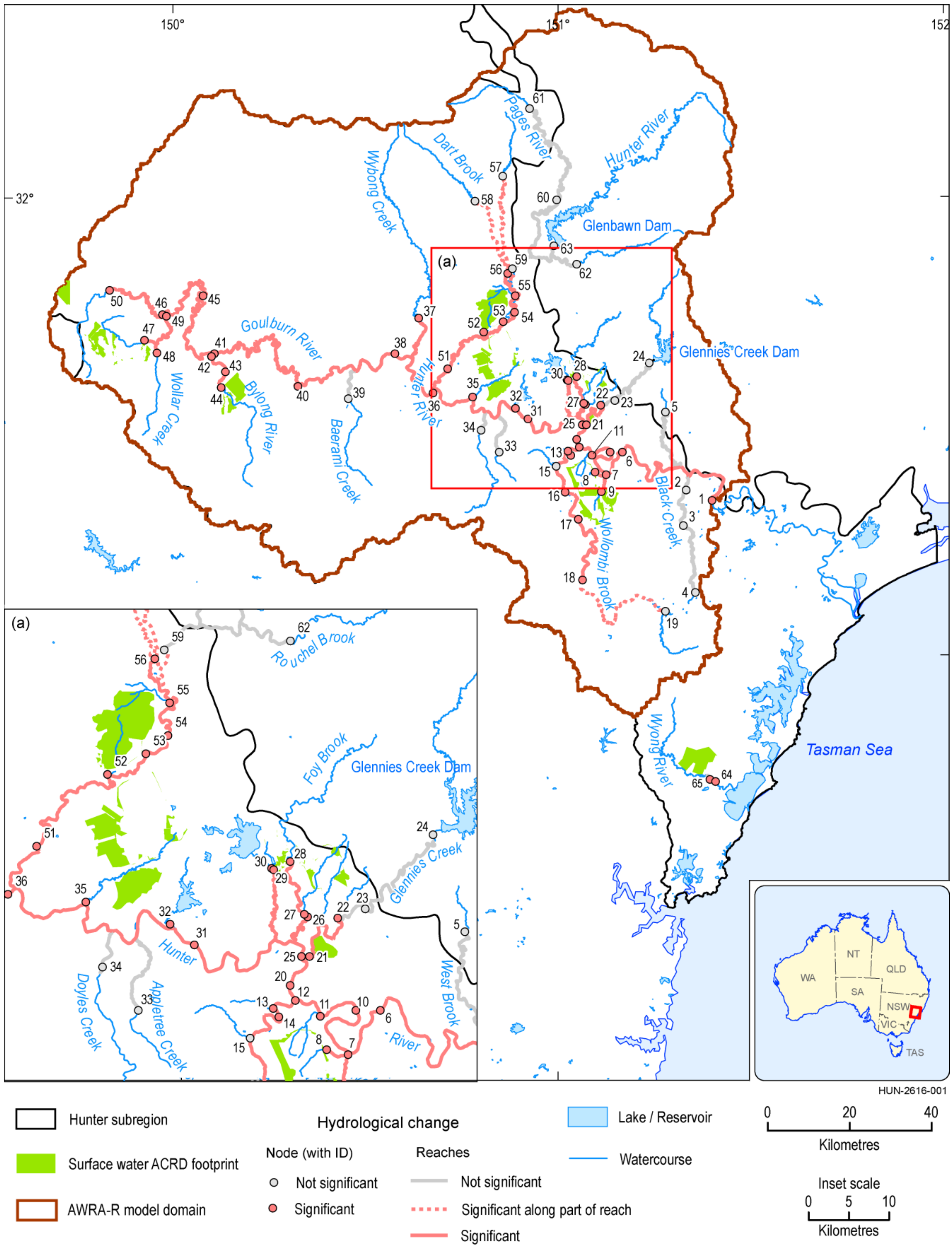

Figure 28 Model nodes and links with changes in at least one hydrological response variable due to additional coal resource development that exceed specified thresholds

ACRD = additional coal resource development; AWRA-R = Australian Water Resources Assessment river model
Data: Bioregional Assessment Programme (Dataset 2); Bureau of Meteorology (Dataset 3)

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Mackie Environmental Research (2013) Wallarah 2 Coal Project. Groundwater Impact Assessment. February 2013. Report No M7589/R6. Viewed 16 November 2016, https://majorprojects.affinitylive.com/public/4af1d9804380abfb6c9412514c24030f/10.%20Wallarah%202%20Coal%20Project%20EIS%20-%20Appendix%20I%20-%20Groundwater%20Impact%20Assessment.pdf.

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

Datasets

Dataset 1 Bioregional Assessment Programme (2016) HUN AWRA-LR Model v01. Bioregional Assessment Derived Dataset. Viewed 07 December 2016, http://data.bioregionalassessments.gov.au/dataset/670de516-30c5-4724-bd76-8ff4a42ca7a5.

Dataset 2 Bioregional Assessment Programme (2017) HUN SW Modelling Reaches and HRV lookup 20170106 v01. Bioregional Assessment Derived Dataset. Viewed 18 January 2017, http://data.bioregionalassessments.gov.au/dataset/a55000e4-4fb3-49ea-8c1c-ab6d12750a3e.

Dataset 3 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.

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

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

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

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

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

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

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

conceptual model: abstraction or simplification of reality

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

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

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

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

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

diversion: see extraction

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

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

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

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

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

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

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

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

impact: a change resulting from prior events, at any stage in a chain of events or a causal pathway. An impact might be equivalent to an effect (change in the quality 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

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.

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.

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

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.

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

source dataset: a pre-existing dataset sourced from outside the Bioregional Assessment Programme (including from Programme partner organisations) or a dataset created by the Programme based on analyses conducted by the Programme for use in the bioregional assessments (BAs) spring: a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water. Typically, it represents the point at which the watertable intersects ground level.

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

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

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

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

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

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

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

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