Australian Government

BIOREGIONAL ASSESSMENTS

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

Surface water numerical modelling for the Gloucester subregion

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

2018

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

The Bioregional Assessment Programme

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

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

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Authorship is listed in relative order of contribution.

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Cover photograph

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

Credit: Heinz Buettikofer, CSIRO

Australian Government
Department of the Environment and Energy
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Executive summary

Coal and coal seam gas (CSG) development can potentially affect water-dependent assets (either negatively or positively) through a direct impact on surface water hydrology. This product provides modelled estimates of the potential surface water impacts of likely coal resource developments in the Gloucester subregion.

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

Surface water modelling in the Gloucester subregion follows the companion submethodology M06 (as listed in Table 1) (Viney, 2016). No river modelling was carried out because the rivers in the subregion are unregulated and their catchments are relatively small. Instead, predicted streamflow is obtained by accumulating output from a spatially-explicit streamflow model (the Australia Water Resource Assessment Landscape model, AWRA-L).

The modelling domain comprises the Gloucester and Karuah river basins and includes 34 modelling nodes at which daily streamflow predictions are produced. The model simulation period is from 2013 to 2102. The conceptual model for the Gloucester subregion (in companion product 2.3 for the Gloucester subregion), indicates that CSG and large coal mining development have the potential to directly affect the regional groundwater system and that this direct effect can propagate through to the alluvia of the Gloucester and Karuah river systems. Any impact on the groundwater in the alluvium of those rivers in turn has the potential to affect streamflow and therefore surface water resources in the stream networks of the Gloucester and Karuah rivers. CSG development may impact streamflow if aquifer depressurisation reduces baseflow, while open-cut coal mines, in addition to reducing baseflow through groundwater drawdown, will intercept and retain surface runoff which has the potential to affect streamflow directly.

Surface water modelling results estimate hydrological changes arising from coal resource development by comparing the difference in predicted water levels between two possible futures – the baseline and the coal resource development pathway (CRDP) – to provide an estimate of changes that are attributable to the additional coal resource development (ACRD). Results are reported at 30 receptors, which are points in the landscape where water-related impacts on assets are estimated.

There are three open-cut coal mining operations in the Gloucester CRDP, as well as one coal seam gas (CSG) field. The Stratford Mining Complex and the Duralie Coal Mine are both baseline mines (i.e. in commercial production as of December 2012) that also have future expansion projects. The proposed open-cut mine at the Rocky Hill Coal Project is also in the CRDP, although it is not part of the baseline. The AGL Gloucester Gas Project is the proposed CSG field in the CRDP. Importantly, at the time the CRDP was finalised for the Gloucester subregion (October 2015), the proposed Rocky Hill Coal Mine was assumed to begin operations in 2015 and that starting time has been adopted for surface water modelling. Likewise, the AGL Gloucester Gas Project was included in the finalised CRDP, even though the development of this proposed CSG field was later abandoned by the proponent in late 2015.

The prediction results show that the ACRD in the Gloucester subregion has more noticeable impacts on hydrological response variables in northern receptors than in the southern receptors. They are particularly apparent in streamflows along the Avon River, a tributary of the Gloucester River, and where two of the three coal mines and most of the proposed Gloucester CSG field are located. Despite there being one coal mine with an ACRD footprint in the Karuah river basin, there is comparatively little hydrological impact on any response variables in the southern part of the subregion.

The comparison among the 30 receptors shows that the relative hydrological changes are larger for the receptors where the maximum ACRD percentage is larger. For every hydrological response variable, the biggest impacts are predicted to occur at node 14 on the Avon River. This node is located downstream of the ACRD expansions to the Stratford Mining Complex and within the proposed AGL Gloucester CSG field.

The ACRD impacts on the low streamflow hydrological response variables do not appear to be more noticeable than those on 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 flow variables.

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

Testing of the model provided confidence in predicting the impacts of coal resource development for each hydrological response variable in each receptor location in the Gloucester subregion. The model assumption that has the largest effect on predictions is the implementation of the CRDP. The numerical predictions are only valid for the mine footprints and CSG wells implemented in the model sequence.

Outputs from the surface water modelling are used for the receptor impact modelling (product 2.7) and in the impact and risk analysis (product 3-4).

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- Independent reviewers: Francis Chiew (CSIRO), Warwick McDonald (CSIRO), Richard Beecham (NSW Department of Primary Industries (Office of Water)).

Currency of scientific results

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

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

Introduction

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

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

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

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

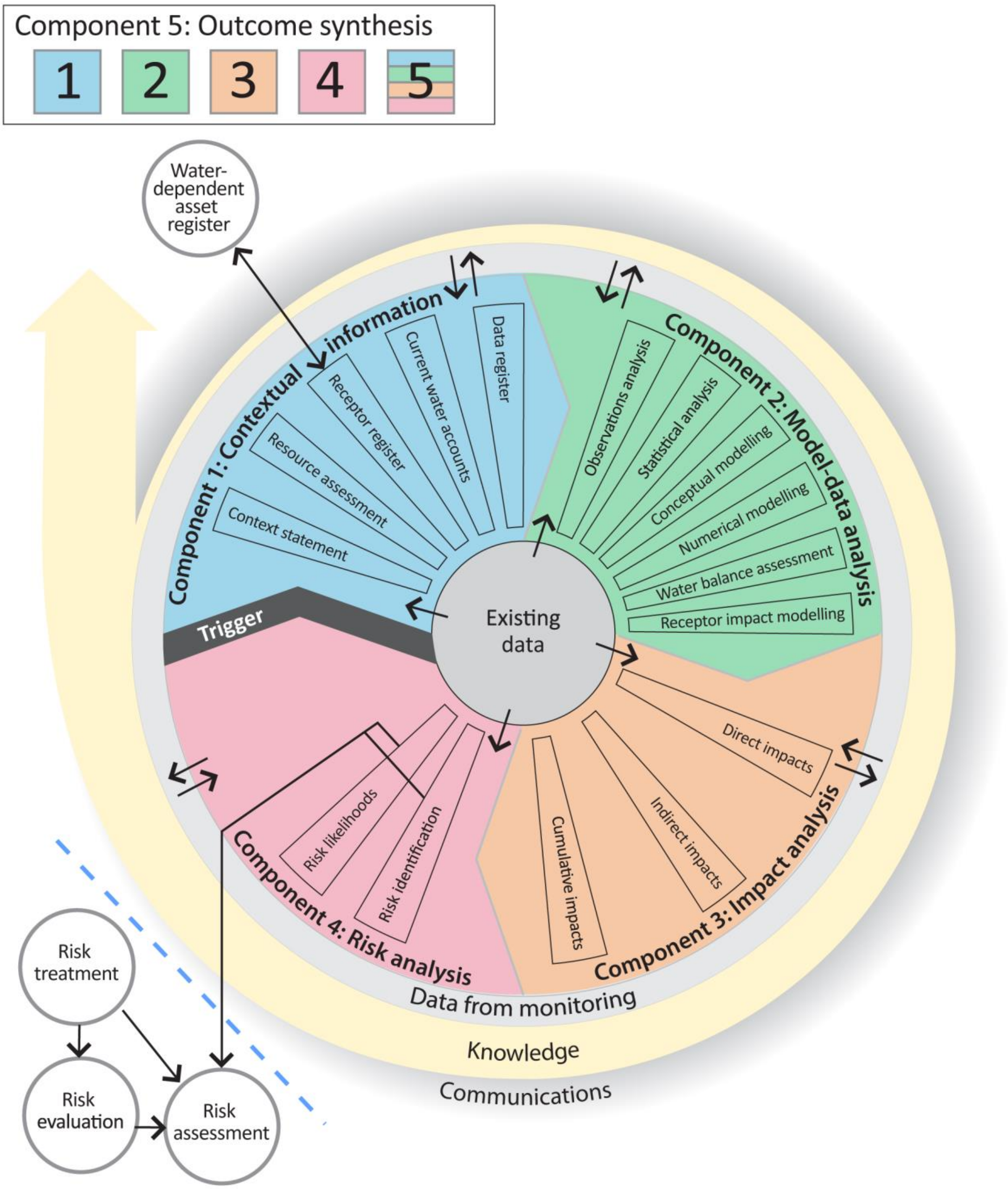

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

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

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

Table 1 Methodologies

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

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

Technical products

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

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

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

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

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

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

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

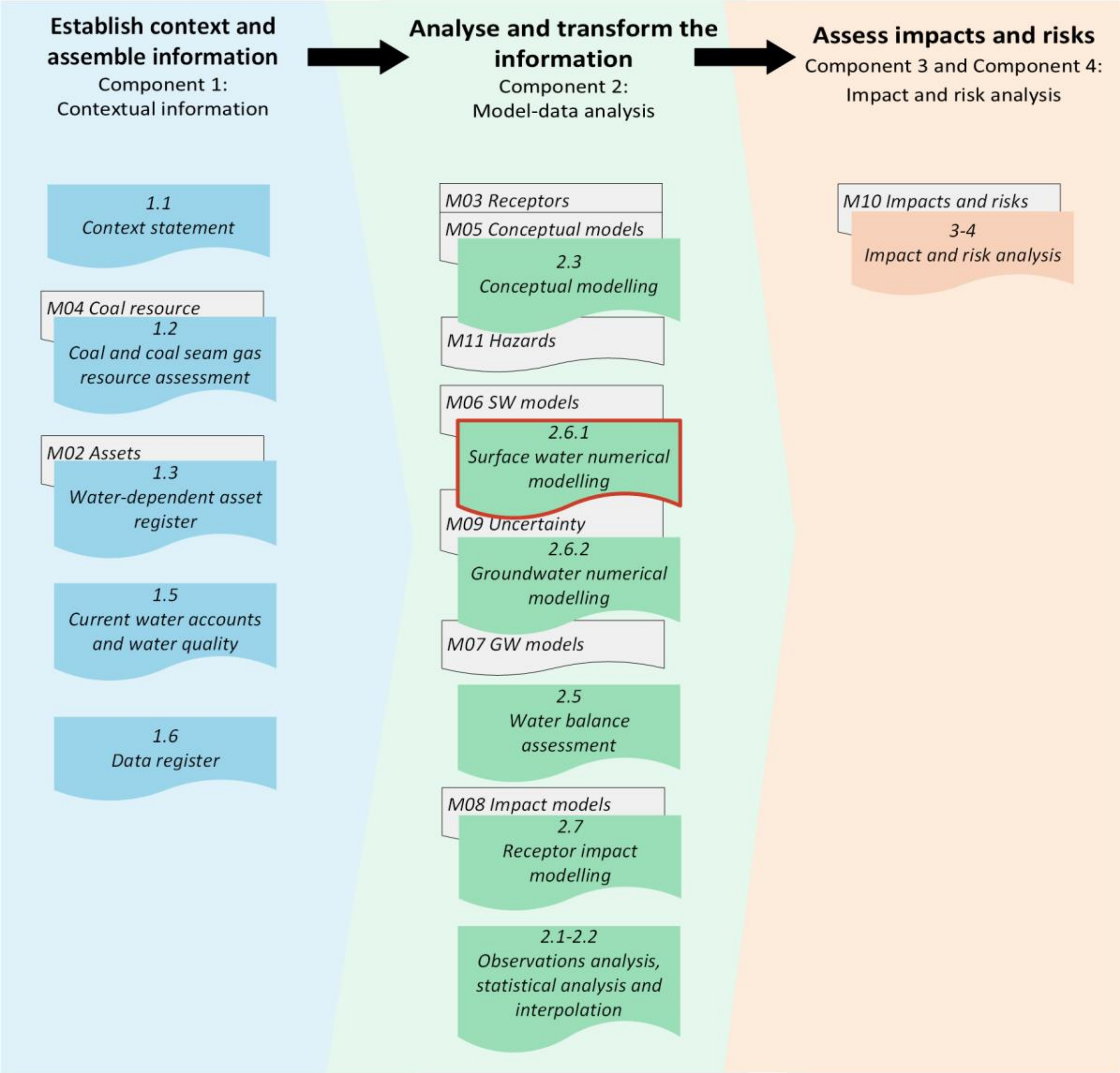

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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

Table 2 Technical products delivered for the Gloucester subregion

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

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

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

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

About this technical product

The following notes are relevant only for this technical product.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Northern Sydney Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Contact bioregionalassessments@bom.gov.au to access metadata (including copyright, attribution and licensing information) for all datasets cited or used to make figures in this product. At a later date, this information, as well as all unencumbered datasets, will be published online.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's 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 27 February 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 27 February 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 Gloucester 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 Gloucester 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 Gloucester subregion. The main difference is that in the Gloucester subregion, no river modelling is done because the rivers are unregulated and their catchments are relatively small. Instead, predicted streamflow is obtained by accumulating output from the Australian Water Resource Assessment Landscape model AWRA-L.

2.6.1.1.1 Surface water model choice

The conceptual model for the Gloucester subregion (see companion product 2.3 for the Gloucester subregion (Dawes et al., 2018)), indicates that coal seam gas (CSG) and large coal mining development has the potential to directly affect the regional groundwater system and that this direct effect can propagate through to the alluvium of the Avon and Karuah river systems. Any impact on the groundwater in the alluvium of those rivers in turn has the potential to affect streamflow (and therefore surface water resources) in the stream networks of the Avon and Karuah rivers. CSG development may impact streamflow if aquifer depressurisation reduces baseflow, while open-cut coal mines will intercept and retain surface runoff which has the potential to affect streamflow directly.

Both the Avon and Karuah rivers are unregulated, gaining streams (Section 2.1.5 in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)) with relatively small catchment areas. The simulation of river management or routing of streamflow through the river network with a river model is not necessary as the salient features of streamflow can be simulated solely with a rainfall-runoff model (see companion submethodology M06 for surface water modelling (Viney, 2016)).

For these reasons, surface water resources in the Gloucester subregion are modelled using the Australian Water Resource Assessment Landscape model AWRA-L (version 4.5; Viney et al., 2015) only. Gridded output from AWRA-L is accumulated to the model nodes without any lagged routing. That is, there is no explicit transmission delay algorithm.

In all other respects, the surface water modelling in the Gloucester subregion follows the methodology set out in companion submethodology M06 (Viney, 2016).

2.6.1.1.2 Model sequencing

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

The regional groundwater model is an analytic element model (referred to as GW AEM), designed to simulate the change in drawdown at the receptors associated with the groundwater bores in the Gloucester geological basin weathered zone, and to provide the change in groundwater level underneath the Avon and Karuah alluvia. The latter provides the lower boundary condition for the alluvial groundwater models. For both alluvial systems a MODFLOW model was developed (referred to as GW ALV) to simulate the change in drawdown on receptors associated with the alluvium and the change in surface water – groundwater flux. This flux is taken into account in the AWRA-L surface water model generated streamflow. The change in a number of hydrological response variables is modelled at the surface water receptor locations.

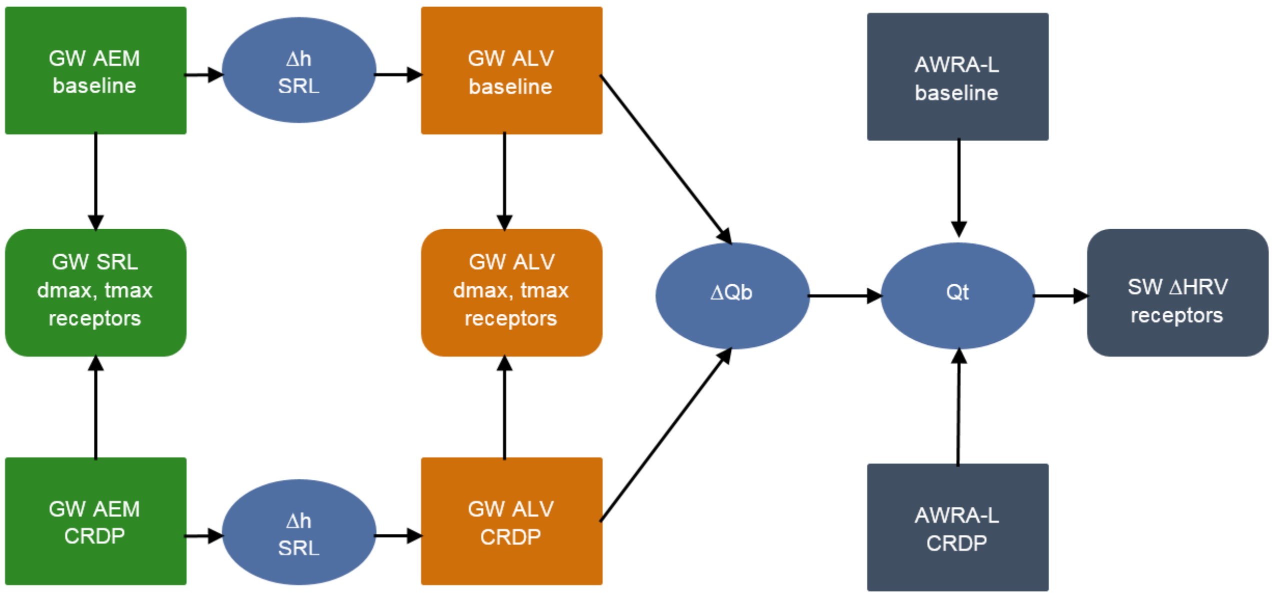

Figure 3 Model sequence for the Gloucester subregion

GW AEM = regional analytic element groundwater model; GW ALV = alluvial MODFLOW groundwater model; AWRA-L = rainfall-runoff model; SRL = surface weathered and fractured rock layer; dmax = maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures; tmax = year of maximum change; Δh = change in groundwater level; ΔQb = change in surface water – groundwater flux; Qt = total streamflow; ΔHRV = change in hydrological response variable

Figure 3 shows in more detail the sequencing of the different models. In the GW AEM baseline coal resource development model the impact of the historical coal mines and coal mines commercially producing coal as of December 2012 are simulated. The GW AEM CRDP simulates the impact of the coal resource development pathway (CRDP), which is the impact of the baseline as well as those developments that are expected to begin commercial production after 2012. The difference in simulated drawdown of those two runs will be the simulated impact of the additional coal resource development on the groundwater receptors in the shallow weathered and fractured rock layer of the Gloucester geological basin.

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

$$\Delta\, Qb(t) = Qb_b(t) - Qb_c(t) \tag{1}$$

where $Qb_b(t)$ and $Qb_c(t)$ are the baseflows under baseline and CRDP, respectively, at time t.

The AWRA-L baseline run simulates streamflow at surface water receptors incorporating the effect of commercially-producing open-cut coal mines at December 2012. The AWRA-L CRDP run simulates streamflow at the surface water receptors incorporating the effect of the baseline open-cut coal mines plus the additional coal resource development. The difference in total streamflow, $\Delta\, Qt(t)$, is obtained as:

$$\Delta\, Qt(t) = Qt_b(t) - Qt_c(t) - \Delta\, Qb(t) \tag{2}$$

where $Qt_b(t)$ and $Qt_c(t)$ are the total streamflows under baseline and CRDP, respectively. The time series of $\Delta Qt(t)$ are summarised in the nine hydrological response variables to highlight different aspects of the hydrograph. These hydrological response variables will inform the receptor impact models for the surface water receptors.

2.6.1.1.3 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 receptor, an ensemble of the predicted maximum absolute and relative change and time to this change.

To generate these ensembles, a very large number of parameter combinations of the combined groundwater and surface water model are evaluated. For each hydrological response variable, only those parameter combinations are accepted in the posterior ensemble of parameter combinations for which the goodness of fit between observed annual hydrological response variables and their simulated equivalent meet a predefined threshold.

While the Approximate Bayesian Computation methodology outlined in companion submethodology M09 (as listed in Table 1) (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 uncertainty methodology proposes the development of numerical emulators to mimic the relationship between parameter values and the response of hydrological variables 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 where 10,000 model evaluations are available, 1000 (i.e. 10%) will be accepted in the posterior ensemble of predictions. This number is considered large enough to estimate 5th, 50th and 95th percentiles robustly.

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2.6.1.2 Review of existing models

Summary

There are no suitable surface water models for use in bioregional assessments that have been applied previously in the Gloucester subregion.

There are no suitable surface water models for use in bioregional assessments that have been applied previously in the Gloucester subregion. For a discussion of the reasons for the choice of the Australian Water Resource Assessment Landscape (AWRA-L) model in the Bioregional Assessment Programme, readers are referred to the surface water modelling methodology document (companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

References

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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 the hydrological impacts of coal resource development in the Gloucester subregion. It includes discussion of the spatial and temporal modelling domains, the spatial resolution of the modelling, the development of a future climate trend, the development of time series of open-cut coal mine footprints, and the estimation of additional coal resource development (ACRD) impacts on streamflow.

The modelling domain comprises the Gloucester and Karuah river basins and includes 34 model nodes at which daily streamflow predictions are produced. The model simulation period is from 2013 to 2102.

Seasonal climate scaling factors from the CSIRO-Mk3.0 global climate model are chosen to provide a trended climate input over the course of the simulation period. These result in a reduction in mean annual precipitation of 0.4% per degree of global warming.

2.6.1.3.1 Spatial and temporal modelling domains

The Gloucester subregion contains two distinct river systems. The Gloucester river basin drains the northern half of the Gloucester subregion and discharges into the Manning River near Bundook. The Karuah river basin drains the southern half of the Gloucester subregion and discharges into Port Stephens (Figure 4). The surface water modelling domain adopted in the bioregional assessment includes the entire basin of the Gloucester River above its junction with the Manning River and the entire basin of the Karuah River above Karuah.

The tidal limit of the Karuah River extends almost up to the town of Booral, which is more than 20 km upstream of the town of Karuah and Port Stephens. The modelling domain therefore extends well below the tidal limit of the Karuah River. The streamflow below the tidal limit is modelled as if tidal effects were non-existent. In effect, we are modelling only the river inflows into the tidal zone.

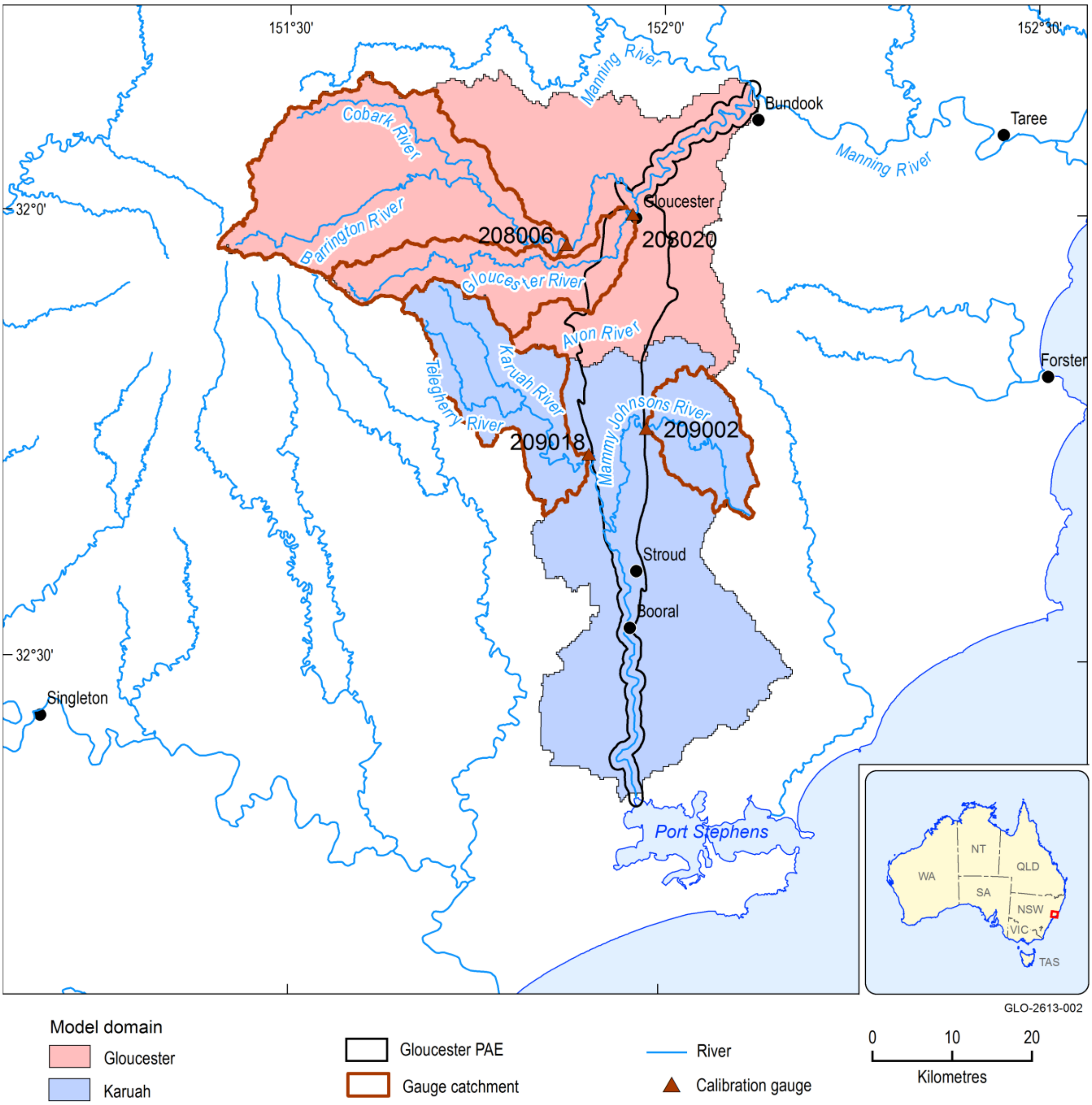

Figure 4 The surface water modelling domain for the Gloucester subregion

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

Both the baseline and coal resource development pathway (CRDP) include simulations from 2013 to 2102. However, for both futures, the period from 1983 to 2012 is also modelled and acts as an extended spin-up period (the period of time in which the model is allowed to run prior to the period for which predictions are required – it allows the initial values of any model stores to converge (or equilibrate) towards natural conditions before the prediction period begins).

2.6.1.3.2 Location of model nodes

The surface water model nodes represent those locations at which streamflow predictions are made. In the Gloucester subregion these nodes correspond with the 30 surface water receptor locations and are shown in Figure 5.

In general, these nodes are located either:

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

Nodes 1 to 17 are located within the Gloucester river basin. They are numbered approximately north to south such that node 1 represents the junction of the Gloucester River with the Manning River.

Nodes 18 to 30 are located within the Karuah river basin. They are numbered approximately north to south such that node 30 represents the southernmost extent of the modelling domain.

A further four model nodes (nodes 31–34) are located at key gauging sites within the modelling domain. These are on the Barrington, Gloucester, Mammy Johnsons and Karuah rivers, respectively. Predicted streamflow at these locations is used in model validation.

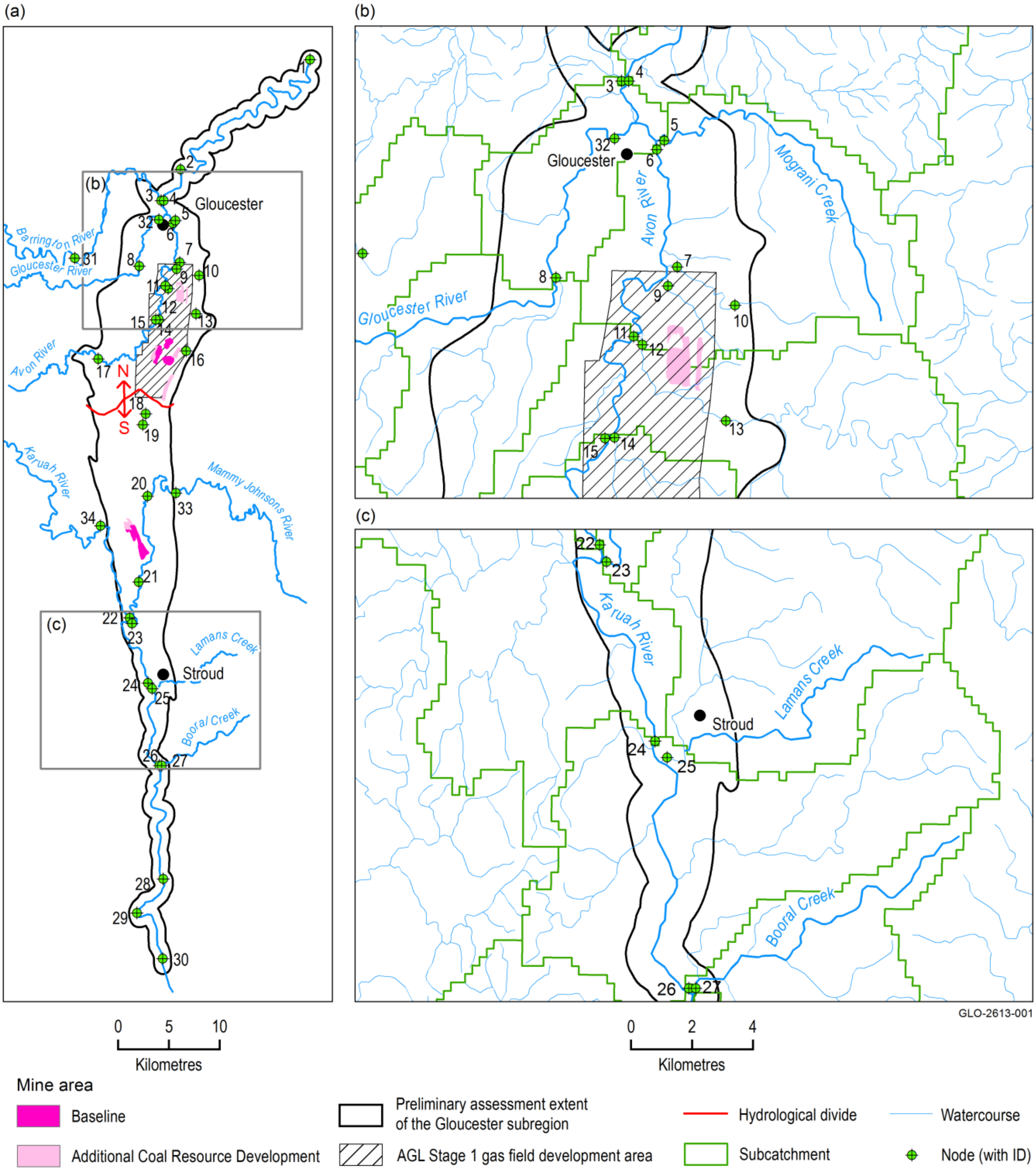

Figure 5 Location of hydrological nodes within the Gloucester subregion

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

2.6.1.3.3 Choice of seasonal scaling factors for climate trend

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 Gloucester subregion. There are 15 available GCMs 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. Scaling factors for the AR4 emissions scenario A1B (IPCC, 2007) are used.

The resulting changes in mean annual precipitation for a 1 °C global warming in the Gloucester subregion are shown in Table 3 for each GCM. The 15 GCMs predict changes in mean annual precipitation ranging from –5.4% (i.e. a reduction in mean annual precipitation) to 6.7% (i.e. an increase in mean annual precipitation). The GCM with the median change is CSIRO-Mk3.0. The corresponding projected change in mean annual precipitation per degree of global warming is a reduction of 0.4%, or about 4.5 mm. The seasonal scaling factors for CSIRO-Mk3.0 are +4.5%, –2.1%, –4.5% and –2.8% 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 (GCM) and their predicted change in mean annual precipitation across the Gloucester subregion per degree of global warming

GCM	Modelling group and country	Change in mean annual precipitation (%)
CCCMA T47	Canadian Climate Centre, Canada	6.7%
MIUB	Meteorological Institute of the University of Bonn, Germany Meteorological Research Institute of KMA, Korea	4.8%
MIROC3	Centre for Climate Research, Japan	4.0%
CCCMA T63	Canadian Climate Centre, Canada	2.7%
NCAR-PCM	National Center for Atmospheric Research, USA	2.0%
NCAR-CCSM	National Center for Atmospheric Research, USA	1.1%
INMCM	Institute of Numerical Mathematics, Russia	0.8%
CSIRO-MK3.0	**CSIRO, Australia**	**–0.4%**
MRI	Meteorological Research Institute, Japan	–1.0%
GFDL2.0	Geophysical Fluid, Dynamics Lab, USA	–1.4%
IAP	LASG/Institute of Atmospheric Physics, China	–2.3%
MPI-ECHAM5	Max Planck Institute for Meteorology DKRZ, Germany	–3.1%
GISS-AOM	NASA/Goddard Institute for Space Studies, USA	–5.1%
IPSL	Institut Pierre Simon Laplace, France	–5.1%
CNRM	Meteo-France, France	–5.4%

Data: CSIRO (Dataset 5)

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

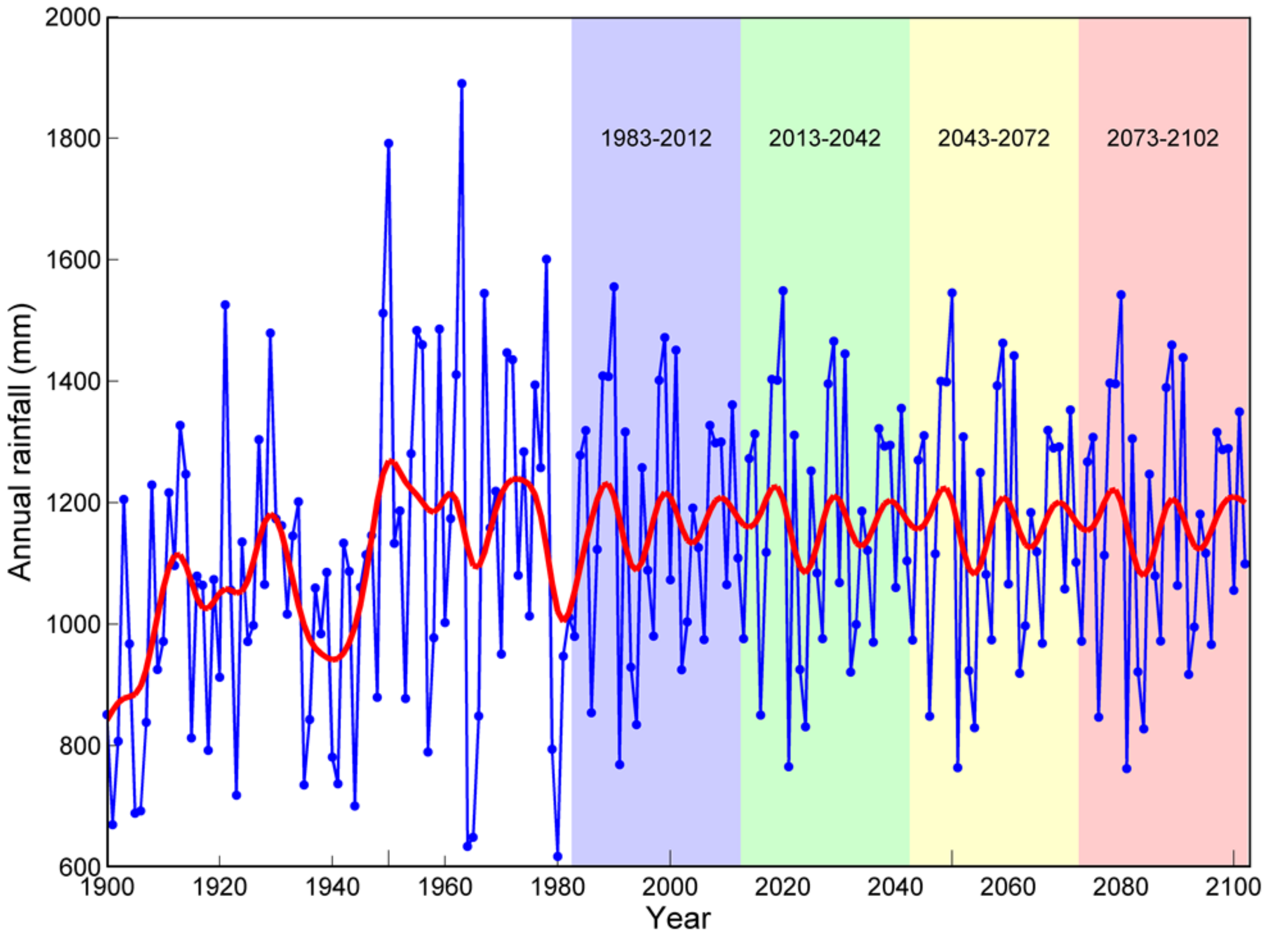

Figure 6 Time series of observed and projected annual precipitation averaged over the Gloucester subregion (blue line). The red line is a centrally-weighted moving average

Data: Bioregional Assessment Programme (Dataset 6)

2.6.1.3.4 Mine footprints

One of the key ways in which coal mines affect water resources is the direct impact of the mine footprint areas on detaining surface runoff and preventing its entry to the natural stream network. It is important, therefore, to know how much land surface area is intercepting natural surface runoff. This area is termed the footprint of the mine. For the purposes of bioregional assessments, the footprint includes the entire area disturbed by mine operations, pits, road, spoil dumps, water storages and infrastructure. It may also include otherwise undisturbed parts of the landscape from which natural runoff is retained in reservoirs. The footprint does not include rehabilitated areas whose surface drainage is allowed to enter the natural drainage network. Nor does it include catchment areas upstream of drainage channels that divert water around a mine site but do not retain it.

Coal seam gas developments are assumed to have negligible impact on surface drainage, hence surface water impacts of the Gloucester Gas Project stage 1 are not modelled. The water management plans for this development included using co-produced water for nearby irrigation, using existing storages to store water (see Section 2.1.6.4). As the storages pre-date the mining development, they were also not modelled as part of the ACRD.

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 may decrease.

Mine footprint areas are obtained from two sources: digitisation of remotely sensed images of historical mine disturbance, and digitisation of projected mine water management plans in environmental impact statements and similar documents.

The temporal evolution of footprint areas for the three mines in the Gloucester subregion is shown in Figure 7. Each panel shows footprints for both the baseline and the CRDP.

The Stratford Mining Complex started operations in 1995 and its baseline footprint increases to a maximum of 3.58 km^2 by 2012. In the baseline, the footprint stays at this level until rehabilitation commences in 2035, leading to an ongoing footprint area of 2.15 km^2. However, in the CRDP, proposed mine expansion means that the footprint continues to increase after 2013, reaching a maximum of 10.97 km^2 by 2026 before mine site rehabilitation reduces the footprint to 4.53 km^2 by 2035.

The Duralie Coal Mine commenced operations in 2003 and under the baseline its footprint area increases to a maximum of 3.33 km^2 by 2012. The baseline footprint remains at this level after 2012. In the CRDP, the footprint area continues to increase beyond 2013, reaching a peak of 4.09 km^2 by 2018. A large proportion of both the baseline and CRDP footprints is comprised of the catchments of several water management dams which are to be retained indefinitely beyond the mine's productive lifetime. For this reason, the assumed mine footprints remain high for the remainder of the modelling period.

The proposed open-cut at the Rocky Hill Coal Project was not in production before the end of 2012. As a consequence, it does not have a baseline footprint. At the time the Gloucester subregion CRDP was finalised Rocky Hill was assumed to begin operations in 2015 and that starting time has been adopted here. The proposed mine's footprint reaches a peak of 1.69 km^2 by 2019 before decreasing under rehabilitation to an ongoing base level of 0.10 km^2 by 2038.

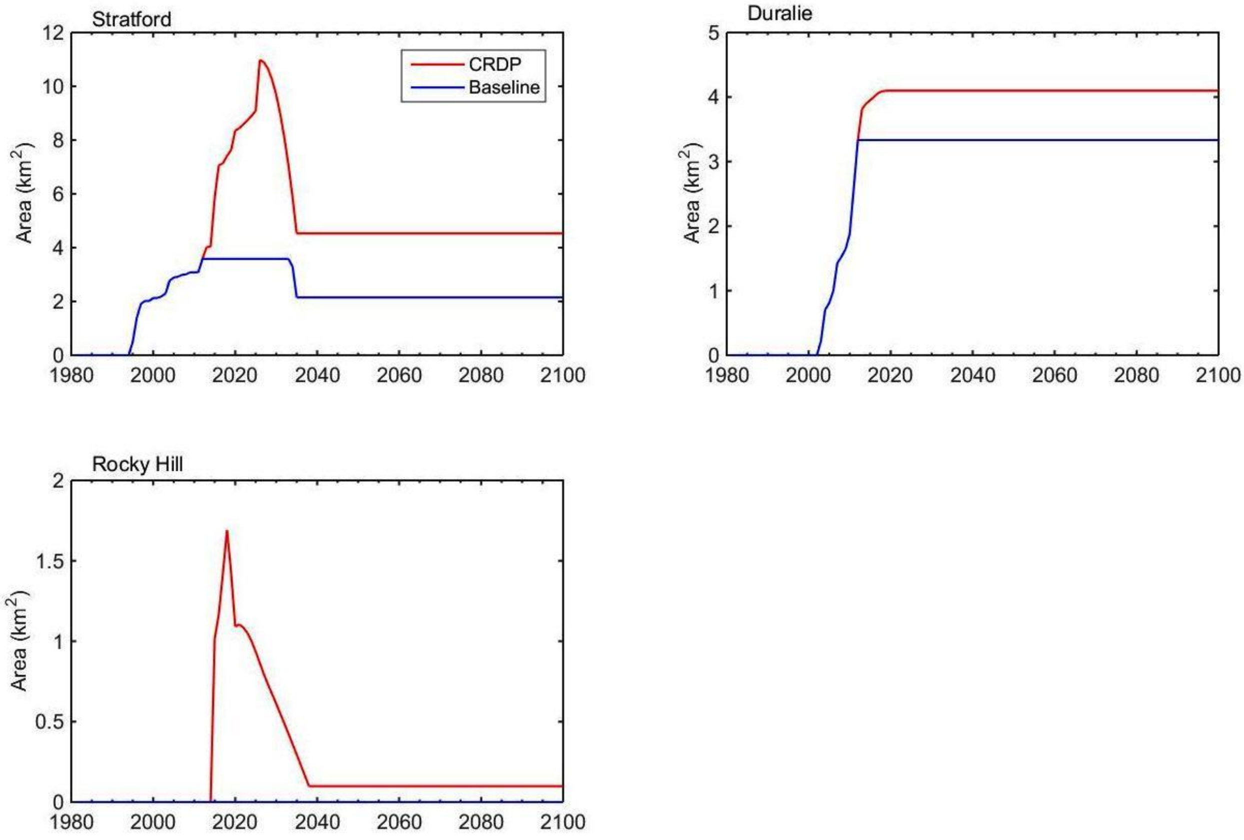

Figure 7 Temporal variation of footprint area under the baseline and coal resource development pathway (CRDP) for the Stratford Mining Complex and Duralie Coal Mine and proposed Rocky Hill Coal Mine

Data: Bioregional Assessment Programme (Dataset 7)

The location, contribution area and maximum additional coal resource development (ACRD) footprint percentage for each receptor is summarised in Table 4 (refer to Figure 5 for location of the receptors – also known as 'nodes' – within the subregion). The receptors with the largest upstream mine footprint are those located at and below node 6 in the Avon River, for which the maximum CRDP footprint is 11.7 km^2. In the southern part of the subregion, the maximum CRDP footprint is 4.3 km^2, which occurs at and below node 21. The node with the largest proportion of its contributing area taken up by ACRD footprint is node 14 on Dog Trap Creek, where 18.4% of the catchment is disturbed by the ACRD.

Table 4 Summary of the 30 surface hydrological receptors selected in the Gloucester subregion

Receptor ID	Longitude	Latitude	River	Contribution Area (km^2)	Maximum baseline footprint (km^2)	Maximum CRDP footprint (km^2)	Maximum ACRD footprint percentage (%)	Time for the maximum ACRD footprint (year)
001	152.116	–31.861	Gloucester River	1650	3.2	11.7	0.51%	2026
002	151.981	–31.959	Gloucester River	1268	3.2	11.7	0.66%	2026
003	151.961	–31.986	Barrington River	715	0.0	0.0	0.00%	NA
004	151.964	–31.986	Gloucester River	546	3.2	11.7	1.54%	2026
005	151.976	–32.004	Mograni Creek	33	0.0	0.0	0.00%	NA

Receptor ID	Longitude	Latitude	River	Contribution Area (km²)	Maximum baseline footprint (km²)	Maximum CRDP footprint (km²)	Maximum ACRD footprint percentage (%)	Time for the maximum ACRD footprint (year)
006	151.974	–32.006	Avon River	256	3.2	11.7	3.29%	2026
007	151.981	–32.041	Oaky Creek	10	0.0	0.0	0.16%	2028
008	151.939	–32.044	Gloucester River	233	0.0	0.0	0.00%	NA
009	151.978	–32.046	Unnamed Avon River tributary	3	0.0	0.1	3.22%	2017
010	152.002	–32.052	Oaky Creek	7	0.0	0.0	0.00%	NA
011	151.966	–32.061	Avon River	132	3.2	10.8	5.74%	2026
012	151.969	–32.064	Waukivory Creek	88	0.0	0.8	0.96%	2018
013	151.999	–32.086	Waukivory Creek	78	0.0	0.0	0.00%	NA
014	151.960	–32.091	Dog Trap Creek	41	3.2	10.8	18.39%	2026
015	151.956	–32.091	Avon River	75	0.0	0.0	0.00%	NA
016	151.989	–32.118	Dog Trap Creek	9	0.0	0.1	1.54%	2035
017	151.896	–32.126	Avon River	43	0.0	0.0	0.00%	NA
018	151.947	–32.174	Wards River	46	0.0	0.2	0.42%	2026
019	151.944	–32.184	Wards River	65	0.0	0.2	0.29%	2026
020	151.949	–32.247	Mammy Johnsons River	275	0.0	0.2	0.07%	2026
021	151.940	–32.322	Mammy Johnsons River	309	3.3	4.3	0.31%	2026
022	151.931	–32.354	Karuah River	339	0.0	0.0	0.00%	2015
023	151.934	–32.359	Mammy Johnsons River	319	3.3	4.3	0.30%	2026
024	151.951	–32.411	Karuah River	760	3.3	4.3	0.13%	2026
025	151.956	–32.416	Mill Creek	131	0.0	0.0	0.00%	NA
026	151.964	–32.484	Karuah River	975	3.3	4.3	0.10%	2026
027	151.966	–32.484	Booral Creek	41	0.0	0.0	0.00%	NA
028	151.969	–32.584	Karuah River	1100	3.3	4.3	0.09%	2026
029	151.941	–32.614	Karuah River	1361	3.3	4.3	0.07%	2026
030	151.969	–32.654	Karuah River	1450	3.3	4.3	0.07%	2026

NA = data not available, ACRD = additional coal resource development, CRDP = coal resource development pathway, the maximum ACRD percentage is calculated from the maximum ACRD divided by contribution area
Data: Bioregional Assessment Programme (Dataset 4, Dataset 8)

2.6.1.3.5 Estimation of additional coal resource development impacts on streamflow

The ACRD impacts on daily streamflow at each model node are estimated as the total of two impacts: direct open-cut mine footprints and baseflow impact. Section 2.6.1.3.4 describes how the open-cut mine footprints are obtained. Their direct impact is the streamflow detained in the mine footprint areas, simulated from the Australian Water Resource Assessment Landscape model (AWRA-L) daily streamflow multiplied by the ratio of the ACRD area to each node's contribution area. This means that there will be no impact on streamflow if there is no ACRD, and the reduction in streamflow will be 100% if the ACRD area covers 100% of the node's contribution area.

The hydrological changes to baseflow are estimated using the MODFLOW groundwater model, which is described in detail in Section 2.6.2.3 of companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018). The MODFLOW model estimates monthly baseflow for each model node under the baseline and CRDP. The difference between CRDP and baseline simulations is taken as the monthly hydrological change in baseflow, which is then equally partitioned to obtain the daily changes.

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Datasets

Dataset 1 Bioregional Assessment Programme (2015). GLO Surface water calibration catchments. Bioregional Assessment Derived Dataset. Viewed 6 June 2016, http://data.bioregionalassessments.gov.au/dataset/f6864619-e6d4-4355-a7c6-ad09dce87b0d.

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Dataset 5 CSIRO (2016) SEACI GCM Scaling. Bioregional Assessment Source Dataset. Viewed 03 February 2017, https://data.bioregionalassessments.gov.au/datastore/dataset/bde1e7b7-5bb3-483c-8616-c4176fde8818

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2.6.1.4 Calibration

Summary

The Australian Water Resource Assessment Landscape (AWRA-L) model was regionally calibrated at 16 unregulated catchments using two calibration schemes: one biased towards high streamflow and another towards low streamflow. Two parameter sets obtained from the two model calibrations are used as starting points to generate 10,000 parameter sets used for uncertainty analysis (Section 2.6.1.5).

Both model calibrations result in predictions that perform well across a wide range of streamflow conditions. The high-streamflow calibration predicts reasonable hydrological response variables related to high-flow characteristics (indicated by very narrow interquartile ranges in model bias, and the median bias approaching zero), including P99 (streamflow at the 99th percentile), flood days, annual flow and interquartile range. In contrast, the low-streamflow calibration predicts reasonable hydrological response variables for low-streamflow metrics including P01 (streamflow at the first percentile), low-flow days, low-flow spells, and length of the longest low-flow spell. Neither calibration scheme predicts zero-flow days well, but this is unsurprising since most streams are perennial.

The regional calibration procedure employed in BA is characterised by minimal degradation in prediction performance between calibration catchments and other parts of the modelling domain. The good performance of the model in calibration therefore provides confidence that it will also apply well to each receptor location where there are no streamflow observations.

2.6.1.4.1 Data

Input climate data: daily time series of maximum temperature, minimum temperature, incoming solar radiation and precipitation from 1981 to 2012 at 0.05 x 0.05 degrees (~5 x 5 km) grid cells from the gridded data generated by the Bioregional Assessment Programme (Dataset 1).

Streamflow: daily streamflow data from 16 unregulated catchments collated by the Bioregional Assessment Programme (Dataset 2) were used for model calibration (Figure 8). Out of the 16, four contribute to the Gloucester or Karuah river basins, including the Barrington River at Forbesdale (calibration gauge 208006), Gloucester River at Gloucester (208020), Mammy Johnsons River at Pikes Crossing (209002) and Karuah River at Dam site (209018). Of the remaining catchments, five are in the Manning river basin, six are in the Hunter river basin and one is in the Wallis Lake river basin.

Criteria for selecting the calibration catchments include that they:

- have long-term measurements (>20 years from 1980)
- are not impacted by coal mining or coal seam gas extraction
- have no significant flow regulation (e.g. dams)
- are not nested

- are close to the Gloucester subregion and have similar catchment sizes and climate regimes.

Boundaries for the 16 catchments were delineated using the Geofabric (Bioregional Assessment Programme, Dataset 1).

Figure 8 Location of the 16 catchments used for Australian Water Resource Assessment Landscape (AWRA-L) model calibration for the Gloucester subregion

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

2.6.1.4.2 Model calibration results

Figure 9 summarises regional model calibration results for the 16 catchments. The bottom, middle and top of each box represent the 25th, 50th and 75th percentiles, and the bottom and top whiskers represent the 10th and 90th percentiles. For both high-streamflow and low-streamflow calibrations, three metrics (F value, daily efficiency and model bias) are shown and their details are introduced in the Figure 9 notes. The high-streamflow calibration yields a good Nash–Sutcliffe efficiency of daily streamflow (E_d(1.0)) and low model bias, indicated by a median E_d(1.0) of 0.67 and a median bias of –0.04.

Table 5 shows the E_d(1.0) and bias for each catchment. For the four catchments contributing surface water to the Gloucester subregion, the E_d(1.0) is 0.67, 0.57, 0.59 and 0.67 for the catchments 208006, 208020, 209002 and 209018 respectively; their respective biases are –0.31, 0.15, 0.07 and 0.08.

The low-streamflow calibration is evaluated against the daily streamflow data transformed with a power of 0.1, or a Box-Cox lambda value of 0.1 (Box and Cox, 1964), which allows the calibration to put more weight on low streamflows than would occur with a higher Box-Cox lambda. The low-streamflow calibration yields overall good efficiency with the Box-Cox lambda value of 0.1, indicated by a median E_d(0.1) of 0.65. The E_d(0.1) is 0.73, 0.75, 0.27 and 0.78 for the catchments 208006, 208020, 209002 and 209018 respectively; their respective biases are –0.27, 0.16, 0.20 and 0.08.

It is noted that the 16 calibration catchments cover a wide range of climatic and topographic conditions, where mean annual streamflow varies from 100 mm/year at catchment 210080 to 507 mm/year at catchment 208006 (Table 5). The good performance for both high-streamflow and low-streamflow calibrations indicates that the AWRA-L model can predict streamflow well in the Gloucester subregion and its surrounding areas where climate conditions vary widely.

The performance of the high-streamflow calibration for the 16 catchments appears to be independent of catchment wetness, as it does not perform better with a wetter climate. However, the performance of the low-streamflow calibration becomes significantly ($p < 0.1$) better when the catchment becomes wetter, as indicated by a coefficient of determination of 0.18 between mean annual streamflow and E_d(0.1) for the 16 catchments.

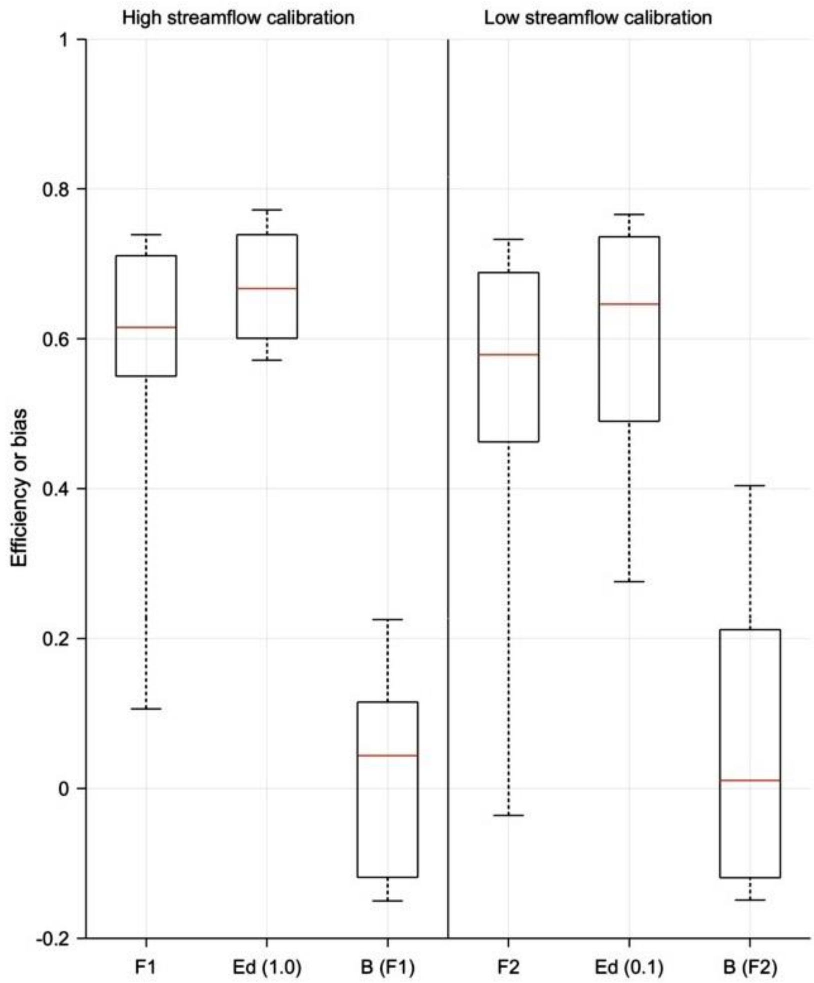

Figure 9 Summary of two AWRA-L model calibrations for the Gloucester subregion

Left: high-streamflow calibration; right: low-streamflow calibration. In each boxplot, the bottom, middle and top of the box are the 25th, 50th and 75th percentiles, and the bottom and top whiskers are the 10th and 90th percentiles. F1 is the F value for high-streamflow calibration; F2 is the F value for the low-streamflow calibration; 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 (Viney, 2016).
AWRA-L = Australian Water Resource Assessment Landscape
Data: Bioregional Assessment Programme (Dataset 1); NSW Office of Water (Dataset 3)

Table 5 Summary of model calibration for the 16 catchments for the Gloucester subregion

Streamflow gauge ID	Mean annual streamflow (mm/y)	F1[a]	E_d(1.0)[a]	Bias (F1)[a]	F2[b]	E_d(0.1)[b]	Bias (F2)[b]
208005	168	0.70	0.74	0.14	0.63	0.73	0.23
208006	507	0.26	0.67	–0.31	0.44	0.73	–0.27
208015	477	0.71	0.71	–0.01	0.54	0.54	–0.04
208019	314	0.71	0.76	–0.15	0.69	0.72	–0.12
208020	319	0.53	0.57	0.15	0.71	0.75	0.16
208026	177	0.59	0.64	–0.15	0.73	0.77	–0.12
208027	115	0.57	0.59	–0.11	0.62	0.64	–0.11
209002	254	0.58	0.59	0.07	0.21	0.27	0.20
209006	201	0.09	0.68	0.53	–0.06	0.30	0.42
209018	327	0.66	0.67	0.08	0.77	0.78	0.08
210011	386	0.79	0.81	–0.10	0.63	0.66	–0.12
210014	102	0.74	0.74	0.05	0.50	0.50	0.03
210017	237	–0.03	0.07	0.23	0.49	0.63	0.27
210022	383	0.74	0.77	–0.13	0.69	0.74	–0.15
210080	100	0.62	0.63	0.09	–0.49	–0.05	0.46
210123	116	0.61	0.61	0.03	0.48	0.48	–0.01
Median	245	0.62	0.67	0.04	0.58	0.65	0.01

[a]*F1* is the F value for high-streamflow calibration (see Viney, 2016).
[b]*F2* is the F value for low-streamflow calibration (see Viney, 2016).
Data: Bioregional Assessment Programme (Dataset 1); NSW Office of Water (Dataset 3)

Figure 10 shows the performance of the two calibration schemes (high-streamflow calibration and low-streamflow calibration) for predicting the nine hydrological response variables (their details shown in Table 4). The high-streamflow calibration yields very good predictions on high-streamflow metrics – annual flow and interquartile range – indicated by very narrow interquartile ranges in model bias and by the median bias approaching zero. The high-streamflow calibration predicts P01 poorly, with an overestimate in the majority of catchments (see annual streamflow boxplot). It predicts other low-streamflow metrics even worse, such as zero-flow days, low-flow days, low-flow spells, and the longest low-flow spell for most catchments, and the bias for these hydrological response variables is –1 for the majority of catchments. This indicates the high-streamflow calibration almost always overestimates low streamflow. This is expected as the high-streamflow calibration puts more weight for simulating high streamflow and less weight for simulating low streamflow.

Table 6 Summary of nine hydrological response variables (HRVs)

Abbreviation of HRVs	Meaning	Unit
P01	Daily streamflow at the 1st percentile	ML/day
ZFD	Zero-flow days (less than 0.01 ML/day)	Days
LFD	Low-flow days (less than 10th percentile)	Days
LFS	Low-flow spells	Times/year
LLFS	Longest low-flow spell	Days
P99	Daily streamflow at the 99th percentile	ML/day
FD	Flood days (greater than 90th percentile)	Days
AF	Annual flow	GL/year
IQR	Interquartile range	ML/day

Compared to the high-streamflow calibration, the low-streamflow calibration noticeably improves predictions on P01 and other low-streamflow metrics. It estimates P01 with a median bias of 0.06. It slightly underestimates low-flow days, low-flow spells, and length of the longest low-flow spells, with the median biases being –0.27, –0.33 and –0.16 respectively.

The low-streamflow calibration yields slightly poorer predictions on P99 and flood days, with the median bias being –0.15 and 0.30, respectively. The low-streamflow calibration, however, is slightly better than the high-streamflow calibration, with a median bias approaching zero. A slight overestimate on interquartile range is obtained from the low-streamflow calibration, in contrast to the underestimate obtained from the high-streamflow calibration.

Neither model calibration scheme predicts zero-flow days well. This is because streamflow at the gauge sites in most of the catchments is perennial and the observed annual number of zero-flow days (ZFD) is zero. As stated by Viney (2016), it is expected that for most receptors, the variables P01 and ZFD will be mutually exclusive in that one or the other will produce useful information, but not both. In the Gloucester subregion, ZFD is unlikely to provide useful predictions in most receptors and is not carried forward as an hydrological response variable into the predictions and uncertainty sections.

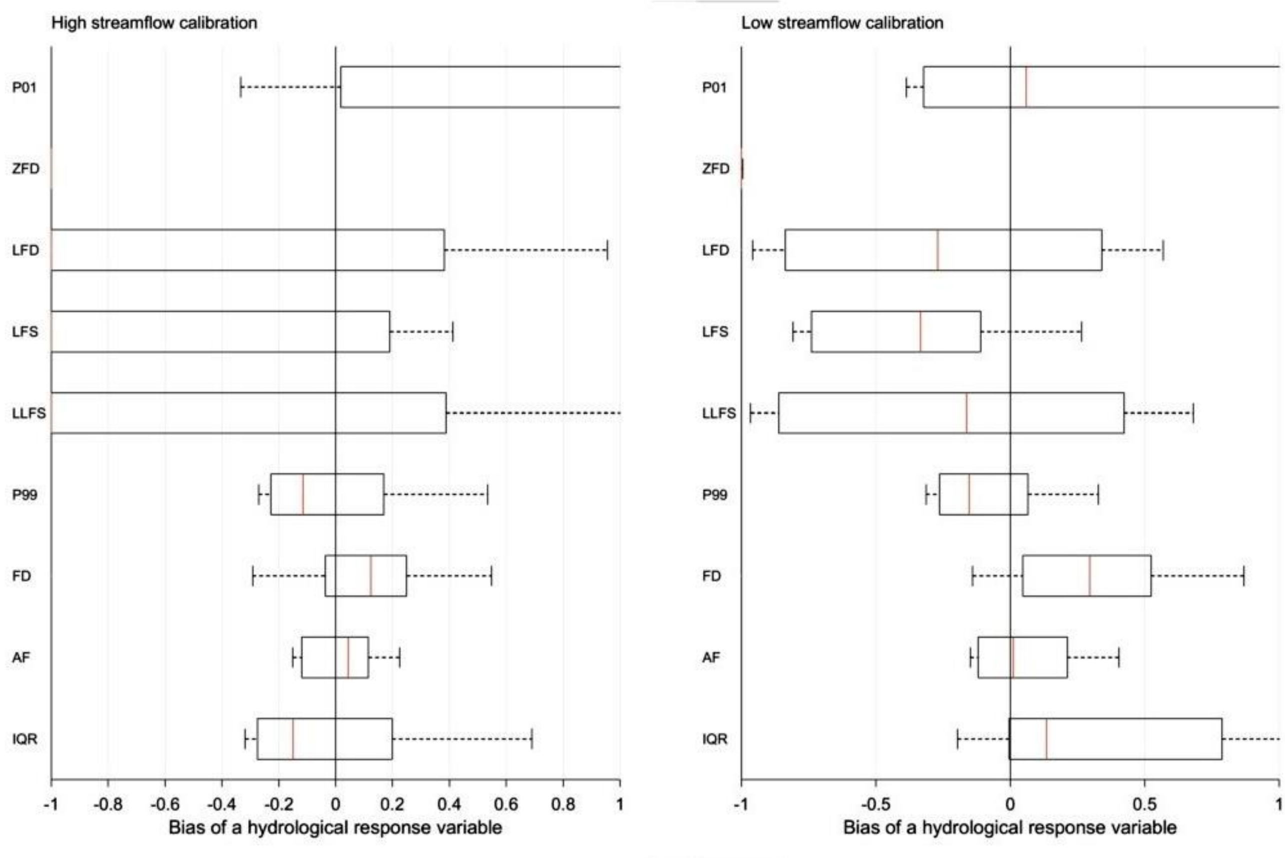

Figure 10 Summary of performance of the nine simulated hydrological response variables obtained using the two AWRA-L model calibrations (left: high-streamflow calibration; right: low-streamflow calibration)

Boxplots are obtained from the statistics (Nash–Sutcliffe efficiency and bias) results at the 16 calibration catchments. 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.
AWRA-L = Australian Water Resource Assessment Landscape
Data: Bioregional Assessment Programme (Dataset 1); NSW Office of Water (Dataset 3)

The calibration results obtained from Figure 9 and Figure 10 indicate that the high-streamflow calibration is sufficient for predicting P99, annual flow and interquartile range, and the low-streamflow calibration is suitable for predicting P01. The low-streamflow calibration, however, is much better than the high-streamflow calibration for predicting the hydrological response variables reflecting low-streamflow metrics, including low-flow days, low-flow spells, and length of the longest low-flow spells.

2.6.1.4.3 Implications for model predictions

The regional model calibration results (Table 5 and Figure 9) suggest that the AWRA-L model performs well in estimating high streamflow and low streamflow in the Gloucester subregion and its surrounding area when it is calibrated against in situ high streamflow and low streamflow, respectively.

The Nash–Sutcliffe efficiency (NSE) of daily streamflow obtained in this study is about 0.10 to 0.15 better than the predicted NSE obtained from traditional hydrological modelling carried out in south-east Australia (Zhang and Chiew, 2009; Chiew et al., 2009), which first calibrates a hydrological model against streamflow observation at each catchment, then regionalises the model parameters from a nearby catchment to a target ungauged catchment for streamflow prediction. The median $E_d(0.1)$ is about 0.07 to 0.15 higher than the predicted NSE of log-transformed daily streamflow obtained in south-east Australia (Zhang et al., 2015; Pena-Arancibia et al., 2015).

It is noted that when the regional model is calibrated against observations from the 16 streamflow gauges it does not generate a uniform model performance. Though the AWRA-L model performs well overall, its performance is modest in some catchments. For instance, the high-streamflow model calibration reproduces daily streamflows poorly at catchment 210017 and the low-streamflow model calibration exhibits a poor model performance at catchment 210080 (Table 5). Both are tributaries of the Hunter River (Figure 8) and the model noticeably overestimates at the two catchments. For the four calibration catchments contributing surface water to the Gloucester subregion (208005, 208020, 209002 and 209018), the model performs well in terms of model efficiency and shows a slight tendency toward overestimation.

A key characteristic of a regional calibration approach is that, unlike with local calibration, there is little degradation in prediction performance between model calibration and model prediction (Viney et al., 2014; Zhang et al., 2011). This means that prediction performance in calibration provides a good guide to the expected performance in ungauged parts of the modelling domain. In other words, it is reasonable to expect that at all receptors the $E_d(1.0)$ values will be of the order of 0.55 to 0.75 and the biases will be of the order of –0.17 to 0.22. This, therefore provides confidence in the prediction quality of the AWRA-L model outputs in each receptor location where there are no streamflow observations.

The results from the simulated hydrological response variables (Figure 10) show that in the Gloucester subregion the AWRA-L model, calibrated against high streamflow, performs well for estimating hydrological response variables reflecting high-streamflow metrics, and the AWRA-L model, calibrated against low streamflow, performs well for estimating most hydrological response variables reflecting low-streamflow metrics (except for zero-flow days).

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Datasets

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2.6.1.5 Uncertainty

Summary

The uncertainty analysis includes quantitative uncertainty analysis to provide ensembles of the predicted change in hydrological response variables at the receptors as well as qualitative assessment of the effect of model assumptions on the prediction.

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

This ensemble of parameter combinations is used to calculate the absolute change, the relative change and the time to absolute change for each hydrological variable at each receptor.

A comprehensive sensitivity analysis is carried out to ensure that the parameters that can be constrained by the historical observations are ones the predictions are sensitive to.

In the qualitative uncertainty analysis the rationale behind the major assumptions and their effect on predictions is discussed and scored. The assumption deemed to have the largest effect on predictions is the implementation of the coal resource development pathway (CRDP). The numerical predictions are only valid for the open-cut coal mine footprints implemented in the model sequence, as modelling of impacts of coal seam gas (CSG) infrastructure on surface water were not modelled.

2.6.1.5.1 Quantitative uncertainty analysis

The aim of the quantitative uncertainty analysis is to provide a probabilistic estimate of the change in the hydrological response variables due to coal resource development at the receptors. 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 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.

Design of experiment

The parameters included in the uncertainty analysis are the same as those used in the calibration, with the exception that in the uncertainty analysis parameter *ne_scale* is included.

Table 7 lists the parameters used in the uncertainty analysis and the range uniformly sampled in the design of experiment. The AWRA-L parameters in Table 7 are explained in the AWRA-L v4.5 documentation (Viney et al., 2015).

Table 7 Summary of AWRA-L parameters for uncertainty analysis

Parameter name	Units	Transformation	Min	Max
cGsmax_hruDR	na	none	0.02	0.05
cGsmax_hruSR	na	none	0.001	0.05
ER_frac_ref_hruDR	na	none	0.04	0.25
FsoilEmax_hruDR	na	none	0.2	1
FsoilEmax_hruSR	na	none	0.2	1
K_gw_scale	na	log10	0.001	1
K_rout_int	na	none	0.05	3
K_rout_scale	na	none	0.05	3
K0sat_scale	na	log10	0.1	10
Kdsat_scale	na	log10	0.01	1
Kr_coeff	na	log10	0.01	1
Kssat_scale	na	log10	0.0001	0.1
ne_scale	na	none	0.1	1
Pref_gridscale	na	none	0.1	5
S_sls_hruDR	mm	none	0.03	0.8
S_sls_hruSR	mm	none	0.03	0.8
S0max_scale	na	none	0.5	5
Sdmax_scale	na	none	0.5	1
slope_coeff	na	log10	0.01	1
Ssmax_scale	na	none	0.5	3
Ud0_hruDR	mm/d	log10	0.001	10

AWRA-L = Australian Water Resource Assessment Landscape, na = data not applicable

Through a space filling Latin Hypercube sampling (Santer et al., 2003), 10,000 parameter combinations are generated from the AWRA-L parameters, with the ranges and transform in Table 7. These ranges and transforms are chosen by the modelling team based on previous experience in regional and continental calibration of AWRA-L (Vaze et al., 2013). These mostly correspond to the upper and lower limits of each parameter during calibration.

The parameter combinations are generated together with the parameter combinations for the regional analytic element groundwater model and the alluvial groundwater model (see companion product 2.6.2 for the Gloucester subregion (Peeters 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 10,000 parameter sets is used to drive AWRA-L to generate streamflow time series at each 0.05 x 0.05 degree (~5 x 5 km) grid cell (Jones et al., 2009).

Observations

Four catchments used for the calibration contribute flow to the river systems in the Gloucester subregion. For these catchments the historical observations of streamflow are summarised into eight of the nine hydrological response variables for all years with a full observational record (ZFD is not used because it is not a meaningful HRV in rivers with perennial flow (Section 2.6.1.4)). The equivalent historical simulated hydrological response variable values are computed from the 10,000 design of experiment runs. The goodness of fit between these observed and simulated historical hydrological response variable values is used to constrain the 10,000 parameter combinations and select the best 10% replicates (i.e. 1000 replicates) that are used for predictions in Section 2.6.1.6.

Predictions

For each of the 30 receptor catchment nodes the post-processing of design of experiment results in 10,000 time series with a length of 90 years of hydrological response variable values for baseline, $HRV_{base}(t)$, and coal resource development conditions, $HRV_{CRDP}(t)$.

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

$$pmax = \frac{amax}{HRV_{base}(tmax)} * 100 \tag{3}$$

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

Sensitivity analysis

Figure 11 shows the sensitivity indices of the absolute change in the 1st percentile of flow in all receptor catchment nodes to all parameter values for both surface water and groundwater models. These are computed with the density based algorithm described in Plischke et al. (2013) from the results of the design of experiment. It is very clear from this plot that there are only a handful of AWRA-L parameters that control the change in the 1st percentile of flow. These are consistent across catchments. None of the parameters of the groundwater models have a sizeable impact, mainly because of the limited size of the change in baseflow due to coal resource development, compared to the total streamflow.

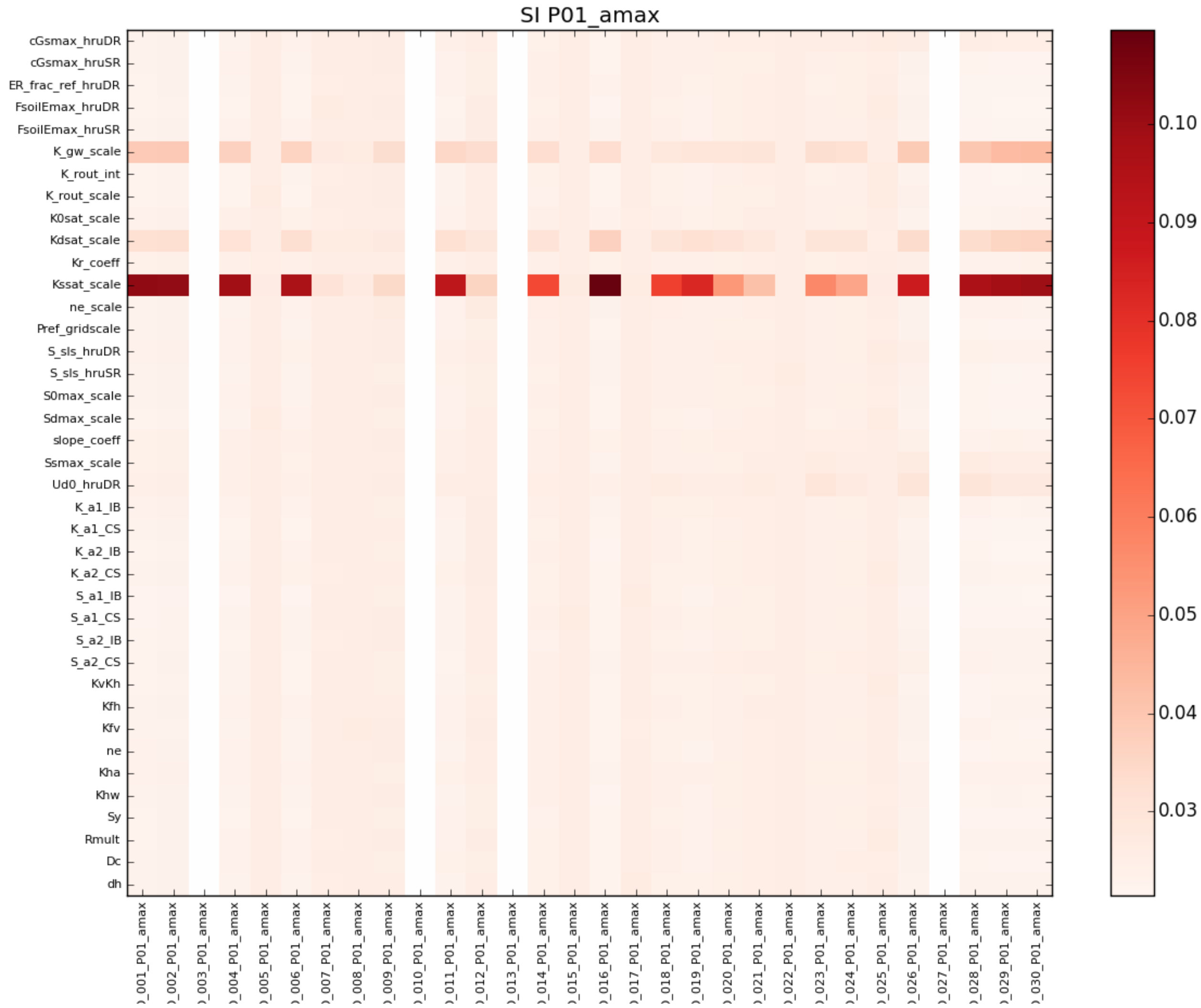

Figure 11 Sensitivity indices and parameter values for the surface water and groundwater models

The figure shows sensitivity indices of the absolute change in the 1st percentile of flow in all receptor catchment nodes (x axis) to all parameter values for both surface water and groundwater models (y axis). High values indicate high sensitivity of the prediction to a parameter.
See Section 2.6.2.6 in companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018) for explanations of the parameter names.

Selection of behavioural 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 four gauges. This means that out of the 10,000 model replicates, the 1000 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 to that obtained from the high-streamflow and low-streamflow model calibrations. Furthermore, it is expected that the full 10,000 replicates contain many with infeasible parameter combinations and that these are likely to be filtered out by sampling only the best 10% of replicates. Nevertheless, selecting the 10% best replicates is determined arbitrarily, and its strength and weakness 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 Gloucester subregion surface water model are listed in Table 8. The goal of the table is to provide a non-technical audience with a systematic overview of the model assumptions, their justification and effect on predictions, as judged by the modelling team. This table will also assist in an open and transparent review of the modelling.

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

A detailed discussion of each of the assumptions, including the rationale for the scoring, follows Table 8.

Table 8 Qualitative uncertainty analysis as used for the Gloucester subregion surface water model

Assumption / model choice	Data	Resources	Technical	Effect on predictions
Selection of calibration catchments	medium	low	low	low
High-flow and low-flow objective function	low	low	high	low
Selection of goodness-of-fit function for each hydrological response variable	low	low	low	low
Selection of acceptance threshold for uncertainty analysis	medium	high	medium	medium
Interaction with the groundwater model	medium	medium	high	low
Implementation of the coal resource development pathway	high	medium	low	high
No streamflow routing	low	low	low	low

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

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 small.

High-flow and low-flow objective function

The AWRA-L landscape model 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 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 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 (NSE) 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 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 NSE transformed by a Box-Cox power of 0.1 and bias, which again represent the trade-off between daily and mean annual accuracy.

The choice of the weights between both terms in both objective functions is based on the experience of the modelling team (Viney et al., 2009). The choice is not constrained by data, technical issues or available resources. While different choices of the weights will result in a different set of optimised parameter values, experience in the Water Information Research And

Development Alliance (WIRADA) Project in which the AWRA-L is calibrated on a continental scale, has shown the calibration to be fairly robust against the weights in the objective function (Vaze et al., 2013).

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' scoring.

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 focusses 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 BA, the calibration aims at providing a parameter set that performs well at a daily resolution, while the uncertainty analysis focusses on specific aspects of the yearly hydrograph.

The goodness-of-fit function is tailored to each hydrological response variable and averaged over the four calibration catchments that contribute to flow in the Gloucester subregion. 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' score for these attributes.

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 receptor locations. There are limited rating curve data available, hence the 'medium' score. Even if this information were to be available, the operational constraints within the bioregional assessment (BA) prevent such a detailed analysis – although it is technically feasible. The resources column therefore receives a 'high' score while the technical column receives a 'medium' score.

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 modelling team learned that this threshold is an acceptable trade-off between guaranteeing enough prediction samples and overall good model performance. While relaxing the threshold will lead to larger uncertainty intervals for the predictions, the median predicted values are considered robust to this change. A formal test of this hypothesis has not yet been carried out. The effect on predictions is therefore scored ‘medium’.

Interaction with the groundwater model

The coupling between the results of the groundwater models and the surface water model, described in the model sequence section (Section 2.6.1.1), represents a pragmatic solution to account for surface water – groundwater interactions at a regional scale. Like the majority of rainfall-runoff models, the current version of AWRA-L does not allow an integrated exchange of groundwater related fluxes during runtime. Even if this capability were available, the differences in spatial and temporal resolution would require non-trivial up- and downscaling of spatio-temporal distributions of fluxes.

The choice of the coupling methodology is therefore mostly a technical choice, hence the ‘high’ score for this attribute. The data and resources columns are scored ‘medium’ as even when it is technically possible to couple both models in an integrated fashion, the implementation would be constrained by the available data and the operational constraints. This warrants the ‘medium’ score for both resources and data.

The integration of a change in baseflow from the groundwater model into AWRA-L does mean that the overall water balance is no longer closed in AWRA-L. This method of coupling both models is therefore only valid if the exchange flux is small compared to the other components of the water balance. The exchange flux (see companion product 2.5 for the Gloucester subregion (Herron et al., 2018)) does show that for the Gloucester subregion the change in baseflow under baseline and under CRDP is much smaller than the other components of the surface water balance.

Another risk in this methodology is that consistency between both models is not guaranteed. In the Gloucester subregion, the major river reaches represented in the groundwater model are all considered to be gaining. The implementation of these in the MODFLOW model as drainage boundary conditions ensures these reaches will always be simulated to be gaining. By design in the current version of AWRA-L, all simulated reaches are gaining. This means the construction of both models in this subregion guarantees consistency. The groundwater modelling results presented in companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018) show that it is very unlikely that the river system will change from gaining to losing as a result of coal resource development.

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

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 of the catchment that is intercepted by the mine footprint from the total catchment runoff.

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, the effect of precise delineation of mine footprint spatial extent does become very important.

Similarly, the temporal evolution of the 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 Gloucester subregion, the accuracy with which mine footprints are represented, depends fully on the resolution of the planned mine footprints 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 score ‘low’. The effect on predictions is scored ‘high’.

No streamflow routing

Streamflow routing is not taken into account in the Gloucester subregion as the system is unregulated and sufficiently small that lags in streamflow due to routing will be within a daily time-step. The effect of not incorporating routing is therefore minimal on the prediction. Seeing the small potential for impact, resourcing the development of a river routing model for this region was not warranted. All attributes are scored ‘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 impacts on eight hydrological response variables caused by additional coal resource development. The impacts on each receptor were generated from 10,000 replicates of the model runs using randomly selected parameter sets.

The prediction results show that the additional coal resource development in the Gloucester subregion has more noticeable impacts on hydrological response variables in receptors in the northern part of the subregion than those in the southern part. They are particularly apparent in streamflows along the Avon River, a tributary of the Gloucester River, and where two of the three coal mines and most of the coal seam gas (CSG) field are located. Despite there being one coal mine with an additional coal resource development footprint in the Karuah river basin, there is comparatively little hydrological impact on any response variables in the southern part of the subregion.

The comparison among the 30 receptors shows that the relative hydrological changes are larger for the receptors where the maximum additional coal resource development percentage is larger. For every hydrological response variable, the biggest impacts are predicted to occur at node 14 on the Avon River. This node is located downstream of the expansions to the Stratford Mining Complex and within the proposed Gloucester CSG field.

The impacts due to the additional coal resource development on the low-streamflow hydrological response variables do not appear to be more noticeable than those on 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-flow variables.

These results suggest that changes to low-flow 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, 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 30 surface hydrological receptors (see Table 4) and the eight hydrological response variables:

- P01 – the daily streamflow rate at the first percentile (ML/day)
- 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 (perennial streams only). A spell is defined as a period of contiguous days of streamflow below the 10th percentile threshold
- LLFS – the length (days) of the longest low-flow spell each year
- P99 – the daily streamflow rate at the 99th percentile (ML/day)

- FD – flood days, the number of days with streamflow greater than the 90th percentile from the simulated 90-year period (2013 to 2102)
- AF – the annual flow volume (GL/year)
- IQR – the interquartile range in daily streamflow (ML/day). That is, the difference between the daily streamflow rate at the 75th percentile and at the 25th percentile.

A ninth hydrological response variable defined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) – the annual number of zero-flow days (ZFD) – is not reported here because most of the streams in the Gloucester subregion are perennial (see Section 2.6.1.4).

For each of these hydrological response variables a time series of annual values is constructed.

For each receptor, 10,000 sets of randomly selected parameter values were used to generate 10,000 replicates of development impact. From these, the best 1000 replicates for each hydrological response variable, as assessed by their ability to predict that hydrological response variable at the four observation sites, were chosen for further analysis. Each boxplot was generated from the resulting 1000 samples. The boxplots show the distributions over the 1000 replicates of the maximum raw change (*amax*) in each metric between the baseline and 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 and FD) will be *amax*.

2.6.1.6.2 Results analysis

Figure 12 shows the hydrological changes to the annual flow (AF) at each receptor. For the receptors in the northern part of the subregion, the biggest impact occurs at node 14 (Dog Trap Creek), where the median *pmax* is –15%. That is, of the reductions in streamflow between the baseline and CRDP from the 1000 replicates, the median (~500th) of the predicted maximum changes is 15%. There is a tightly constrained distribution of *pmax* values around this median value. The year in which this maximum change occurs is 2030 for almost all replicates. The 15% median reduction in streamflow corresponds with a reduction of about 3.2 GL below the median baseline streamflow of 22 GL for that year. This raw change propagates downstream through nodes 11 and 6 on the Avon River and nodes 4 and 2 on the Gloucester River, all of which have median *tmax* values in the same year. However, the median *pmax* reductions get smaller downstream as the change from node 11 is diluted by further tributary inflows. There are also smaller reductions in *pmax* of less than 2% at nodes 16, 12 and 9, but negligible or no impact at nodes 3, 5, 7, 8, 10, 13, 15 and 17.

For all the receptors in the southern part of the subregion, the maximum impact is less than 1% of baseline flow. Node 21 has an absolute reduction in annual flow of 0.6 GL with a median *tmax* of 2079. This reduction is maintained at a similar order of magnitude in all nodes downstream of node 21. There is substantial variability in predicted *tmax* throughout the southern nodes, but for those nodes downstream of node 21, the median typically occurs around 2050, reflecting the lagged groundwater response and different climate conditions.

Node 14 is immediately downstream of the Stratford Mining Complex (Figure 5 in Section 2.6.1.3), which has the largest additional coal resource development footprint in the Gloucester subregion (Figure 7 in Section 2.6.1.3). The percentage increase in additional coal resource development footprint (18%) and year of maximum additional coal resource development footprint (2026) in Table 4 in Section 2.6.1.3 are commensurate with the predicted impact and timing of maximum AF change. Nodes 9 and 12 are downstream of the proposed Rocky Hill Coal Mine and their early median *tmax* values reflect the early peak in additional coal resource development footprint at that mine.

The uncertainty in *tmax* in nodes in the Karuah river basin result from the Duralie Coal Mine maintaining its maximum additional coal resource development footprint throughout the period 2018 to 2102.

The tightly constrained changes in *pmax* at most nodes suggests that the biggest impact on AF is caused by interception and retention of surface runoff at the mine sites, rather than by reduced baseflows associated with groundwater drawdown. The impact of any drawdown associated with the Gloucester CSG field is not readily discernible, though most nodes nearby are either affected by mine impacts or are only on the fringes of the CSG field.

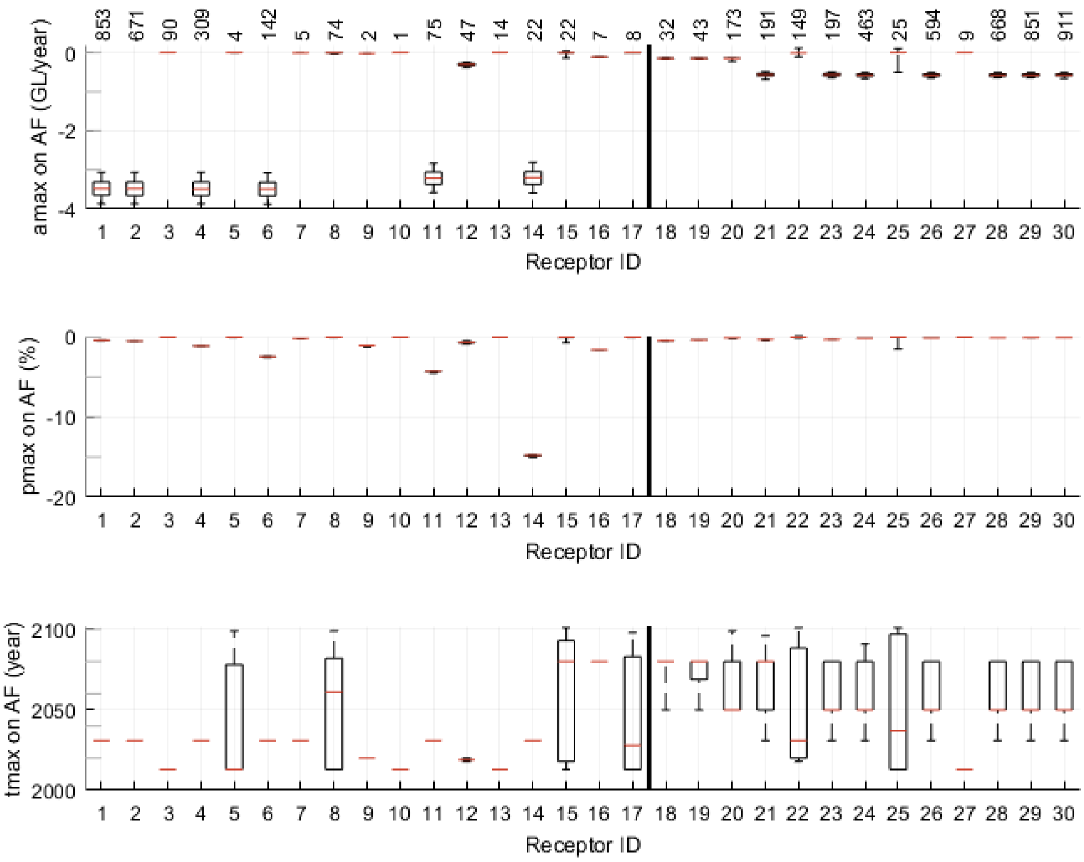


Figure 12 Hydrological changes from additional coal resource development on annual flow (AF) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

Figure 13 shows the hydrological changes to P99 at each receptor. Again, the biggest change in *pmax* occurs at node 14, where there is a reduction of about 15%, which corresponds to a median *amax* reduction of about 300 ML/day. The median *tmax* occurs in 2030. In most respects, the pattern of change in P99 is the same as that in AF, with small impacts at nodes 9, 12 and 16, and with the impacts from these three and node 14 being translated through downstream nodes. There is negligible percentage change in the nodes in the southern part of the subregion.

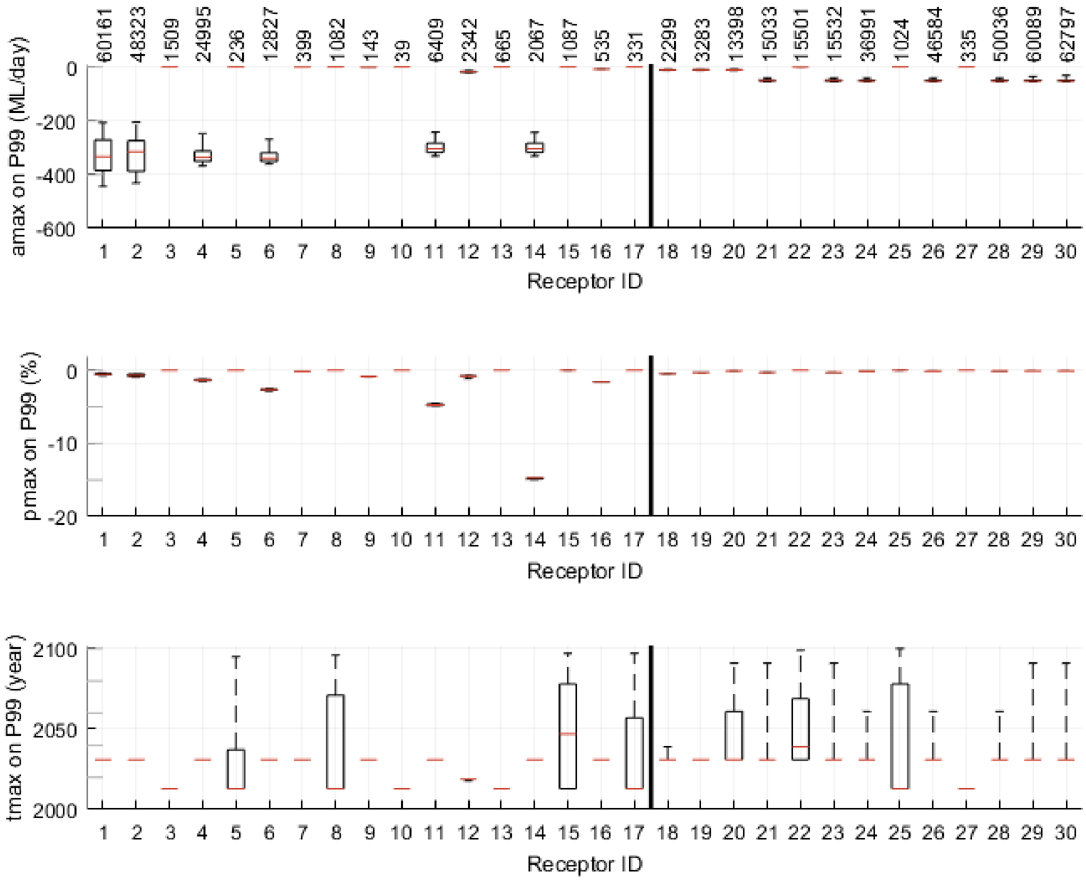


Figure 13 Hydrological changes from additional coal resource development on streamflow at the 99th percentile (P99) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

Figure 14 shows the hydrological changes to the interquartile range (IQR) at each receptor. The patterns of change are similar to those of AF (Figure 12) and P99 (Figure 13). The biggest percentage change in IQR is a median reduction of 17% in 2027 at node 14.

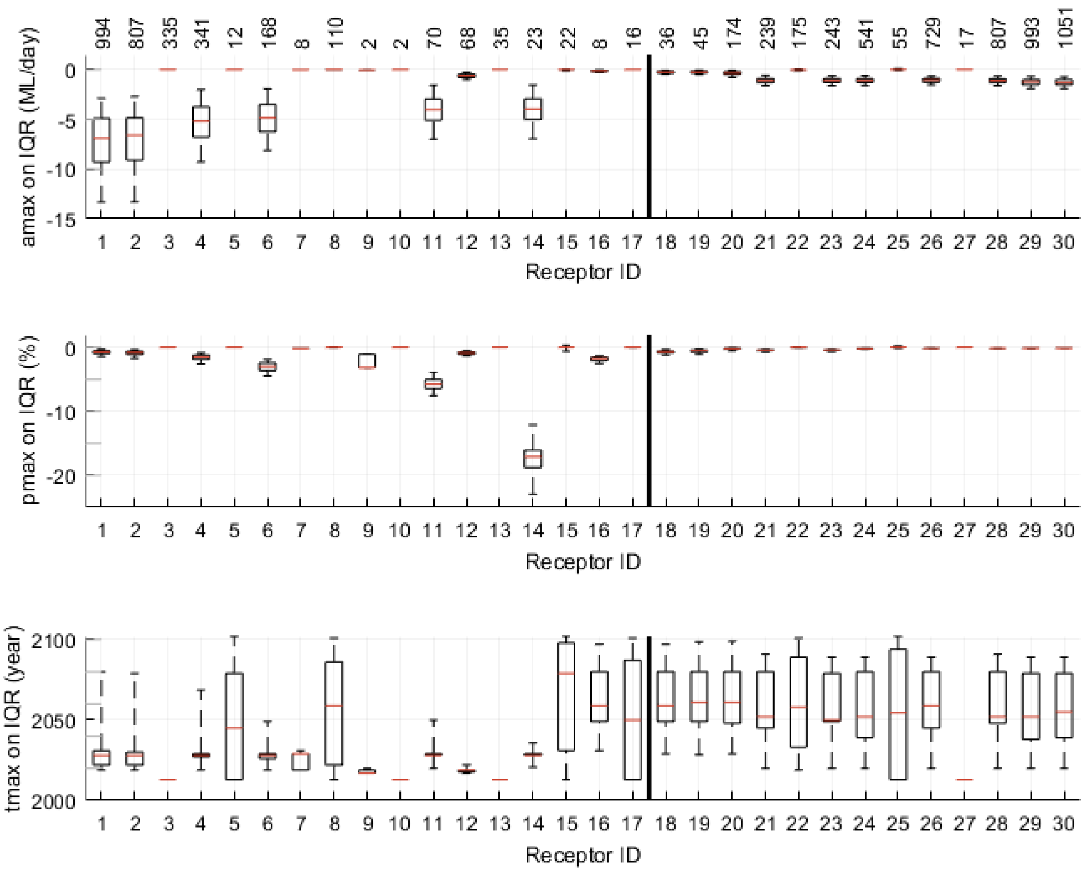


Figure 14 Hydrological changes from additional coal resource development on interquartile range (IQR) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

Figure 15 shows the hydrological changes to FD at each receptor. There is a noticeable decrease (>1 day) for the maximum change in FD at some northern receptors. The largest decrease is predicted at receptor 14 where the *amax* on FD at the median of the 1000 replicates and at the maximum impact time is nine days. This change propagates downstream but with reduced impact. At node 1, the predicted decrease in FD is just one day. There are median reductions in amax of three and four days at nodes 9 and 16, respectively. Compared to AF, P99 and IQR, there is greater uncertainty in *tmax* for FD at the nodes with significant impact. The median *tmax* remains in the period around 2030 or earlier at and downstream of node 14, but occurs in 2049 at node 16.

The *amax* on FD for all southern receptors is less than two days, with tmax values being very uncertain.

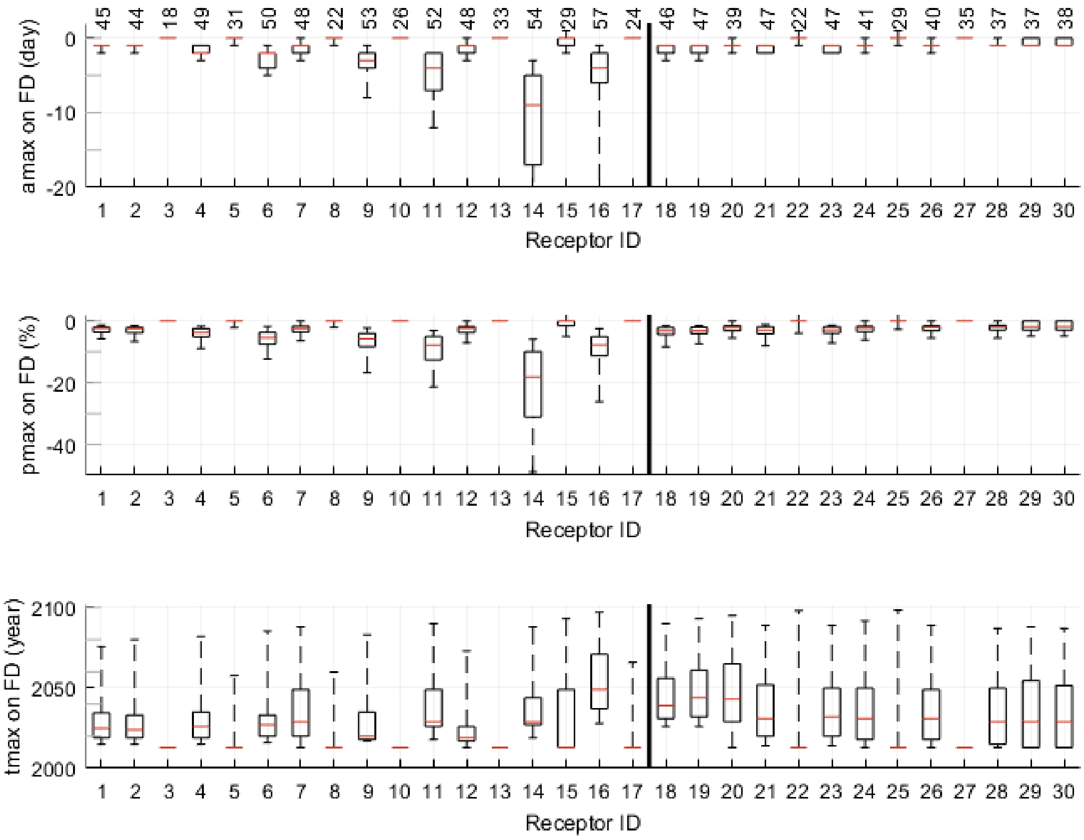


Figure 15 Hydrological changes from additional coal resource development on flood (high-flow) days (FD) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

The remaining boxplots characterise the changes for the low-streamflow hydrological response variables. Figure 16 shows the hydrological changes to daily streamflow at P01 at each receptor. At the 25th percentile, the most significant reductions occur at nodes 9, 12 and 14, which are all on small tributaries of the Avon River. The respective 25th percentile *pmax* values are –27%, –47% and –41%. However, in each case these large percentage changes are generated from already quite small values of baseline P01 and only node 14 shows significant impact at the median (–17%). A small minority of replicates at some nodes (e.g. node 14) predict small increases in P01. The *tmax* values for the most heavily impacted nodes vary greatly, but for node 14, the median *tmax* is as late as 2069.

The *amax* and *pmax* at receptors located within the southern part of the subregion are negligible. The additional coal resource development causes reductions at P01 of less than 1% in all southern receptors.

By comparison to the three flux-based high-flow 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*.

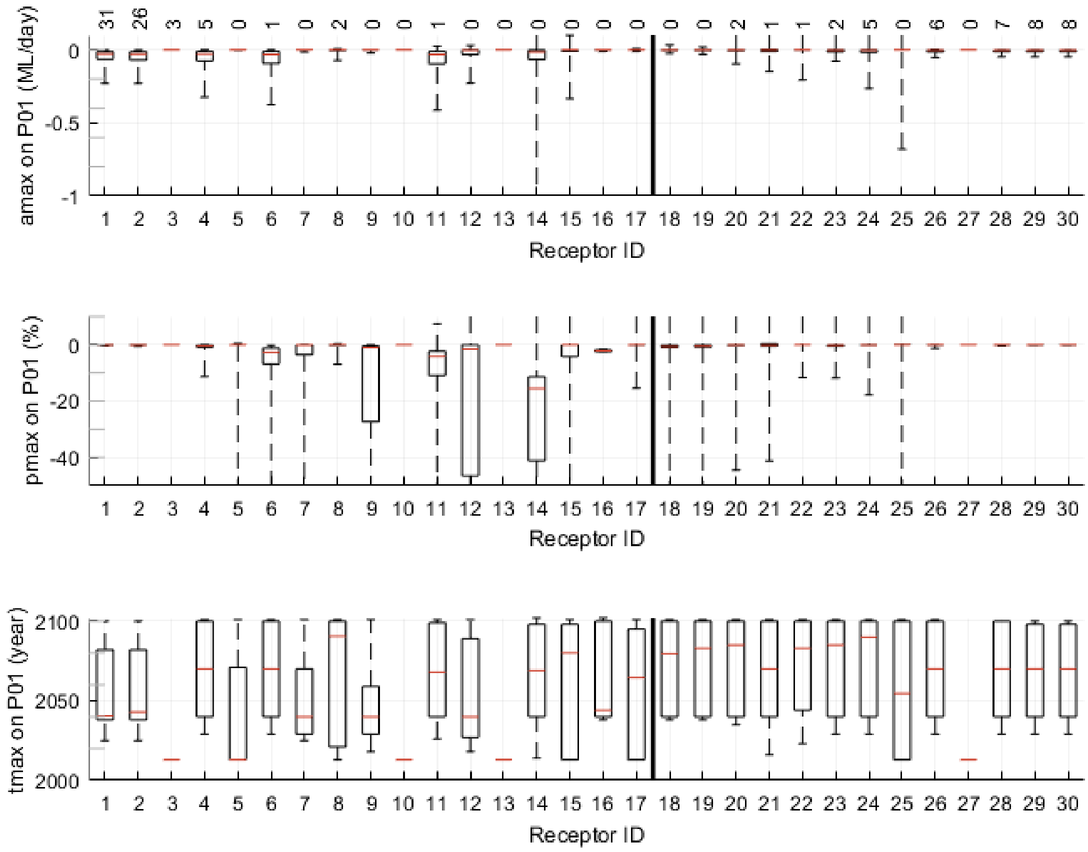


Figure 16 Hydrological changes from additional coal resource development on streamflow at the first percentile (P01) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

Figure 17 shows the increases in LFD caused by the additional coal resource development. In the northern part of the subregion, the median *amax* on LFD is predicted to increase by 12 days at receptor 14 and by at least four days at receptors 11 and 16. There is considerable uncertainty in the corresponding *tmax* values, but the median *tmax* values at node 14 occurs in 2032. Only nodes 3, 10 and 13 are unaffected in the northern part of the subregion.

In the southern part of the subregion, the changes on LFD are smaller, with the biggest impacts occurring at receptor 18, with a median *amax* value of two days. This node is not downstream of any coal mines, so the changes in LFD must be associated with reduced baseflow from groundwater drawdown generated from either the expansion of the Stratford Mining Complex or the proposed Gloucester Gas Project stage 1.

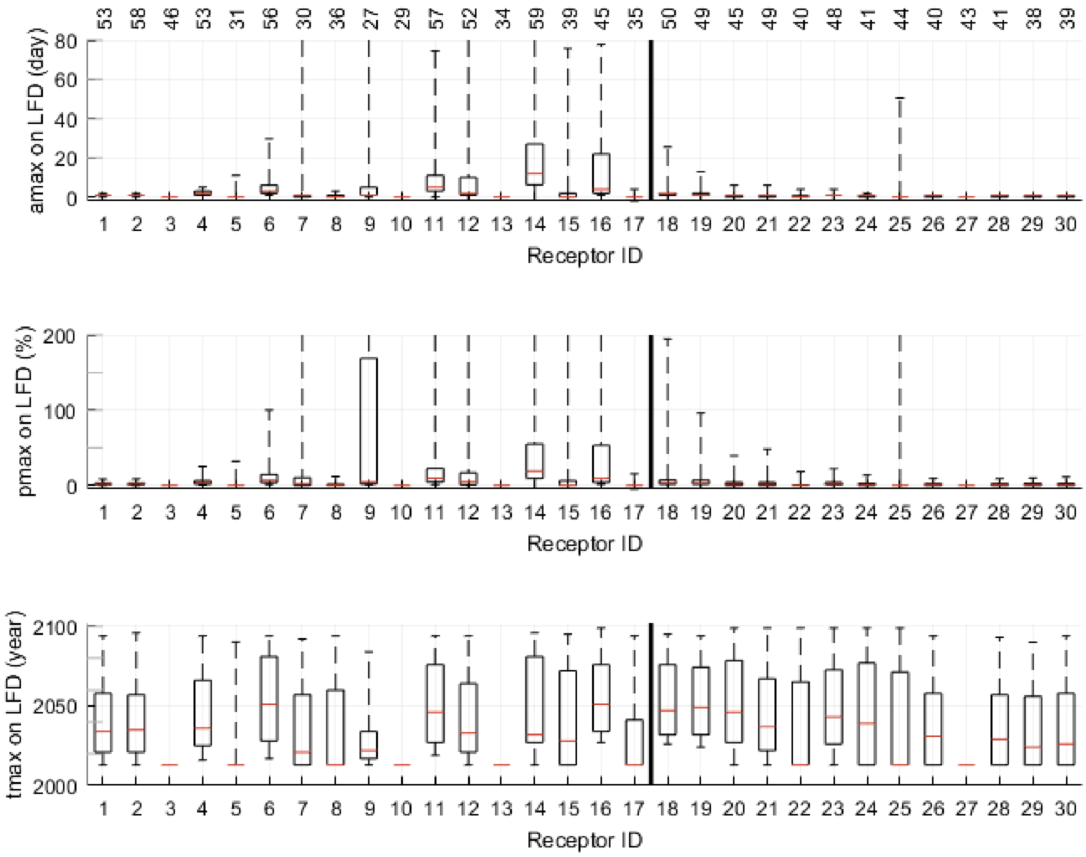


Figure 17 Hydrological changes from additional coal resource development on low-flow days (LFD) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

Figure 18 shows the hydrological changes on LFS. The patterns of change in LFS are similar to those for LFD. In the northern part of the subregion, there is a median increase in low-flow spells of up to two spells per year (node 14). There are median increases of one spell per year at nodes 6, 11 and 16. At the 50th percentile, there are no changes to the number of low-flow spells per year in the southern part of the subregion.

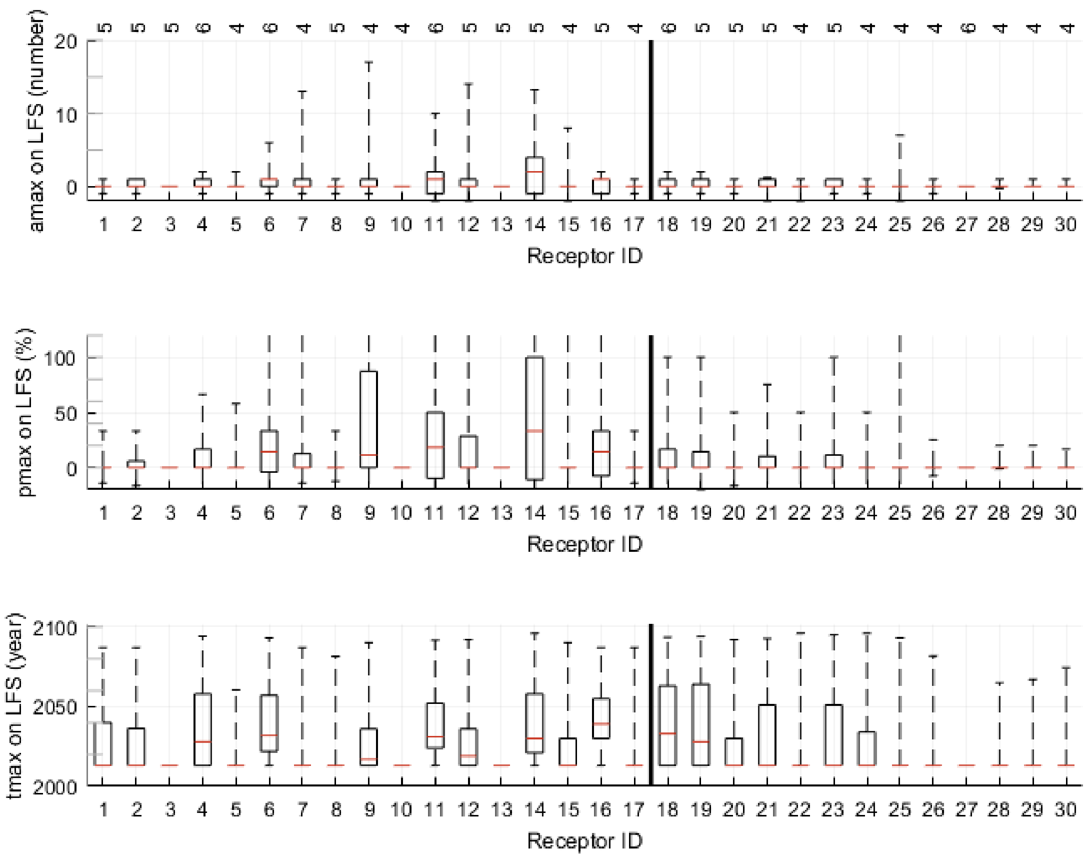


Figure 18 Hydrological changes from additional coal resource development on the number of low-flow spells (LFS) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

Figure 19 shows the maximum changes to the length of the longest annual low-flow spell (LLFS). The changes in LLFS are very similar to those in LFS and those in LFD. In the northern part of the subregion, the median increase in LLFS is 11 days at node 14, six days at node 11 and three days at node 16. There is a 25% chance that the maximum LLFS will increase by 19 days at node 14. The median *tmax* occurs in 2041. The median LLFS increases by no more than one day at any node in the southern part of the subregion.

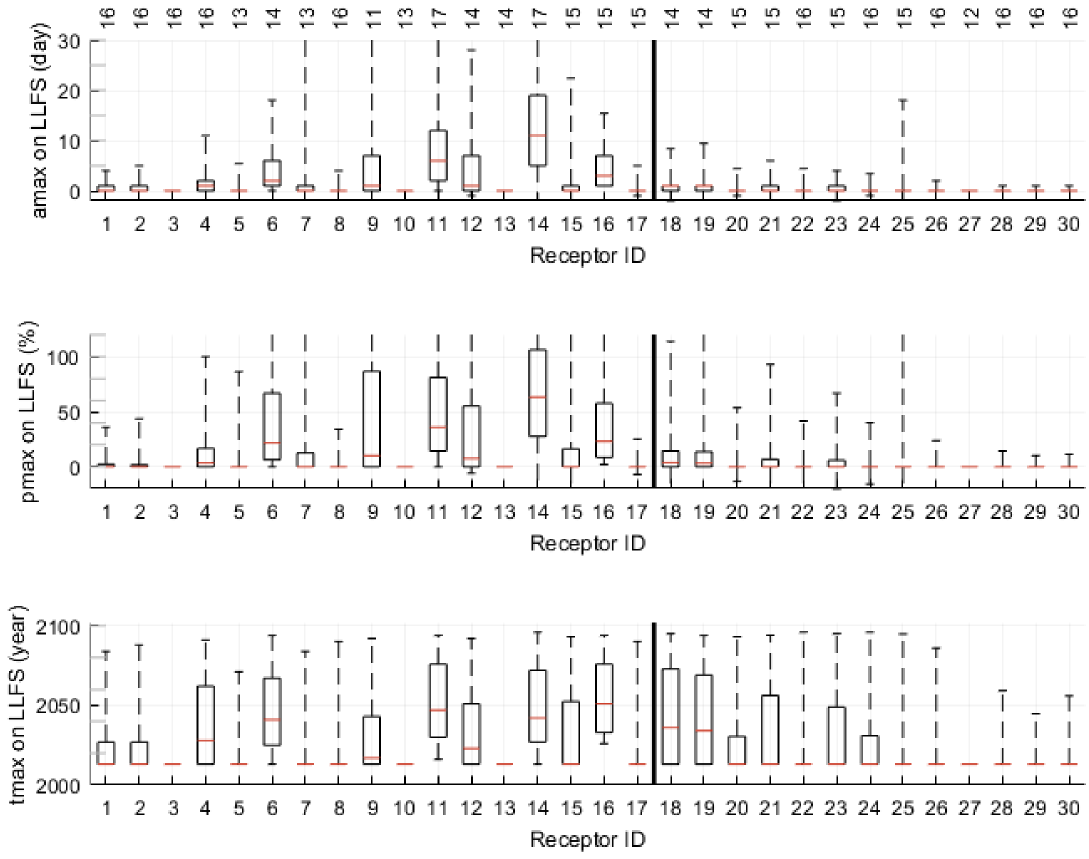


Figure 19 Hydrological changes from additional coal resource development on the length of longest low-flow spell (LLFS) at the 30 receptors within the Gloucester subregion

Numbers above the top panel are the median of the best 1000 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. The thick black line divides receptors in the northern part of the subregion (receptors 1–17) from those in the southern part (receptors 18–30).
amax = maximum raw change, *pmax* = maximum percent change and *tmax* = year of maximum change
Data: Bioregional Assessment Programme (Dataset 1)

2.6.1.6.3 Summary and discussion

The prediction results show that the additional coal resource development in the Gloucester subregion has more noticeable impacts on hydrological response variables in northern receptors than in the southern receptors. They are particularly apparent in streamflows along the Avon River, a tributary of the Gloucester River, and where two of the three coal mines and most of the proposed CSG field are located. Despite there being one coal mine with an additional coal resource development footprint in the Karuah river basin, there is comparatively little hydrological impact on any response variables in the southern part of the subregion.

The comparison among the 30 receptors shows that the relative hydrological changes are larger for the receptors where the maximum additional coal resource development percentage is larger. For instance, the receptors with the two largest additional coal resource development footprints are receptors 14 and 11, where the percentage increases in footprint are 18% and 6%, respectively. The resulting median *pmax* values for the three high-flow flux-based variables (AF, P99 and IQR) are in the range between –15% and –17% for node 14 and in the range –4% to –6% for node 11.

For every hydrological response variable, the biggest impacts (in terms of *pmax* for the flux-based variables and in terms of *amax* for the frequency-based variables) are predicted to occur at node 14. This node is located downstream of the expansions to the Stratford Mining Complex and within the proposed Gloucester Gas Project stage 1 field. There are bigger predicted changes in *amax* at nodes further downstream, but the proportional impacts of these changes are diluted by relatively unaffected inflows from the Upper Gloucester (node 8) and Barrington (node 3) rivers.

The impacts due to additional coal resource development on the low-streamflow hydrological response variables (daily streamflow at the first percentile, low-flow days, number of low-flow spells and the longest low-flow spell) do not appear to be more noticeable than those on the high-streamflow hydrological response variables (annual flow, daily streamflow at the 99th percentile and flood days). The flux-based variables (AF, IQR, P99 and P01) have similar median *pmax* values at the most heavily impacted nodes. Similarly, the two frequency-based variables that are most directly comparable – FD and LFD – have roughly commensurate changes in median *amax* values. However, the uncertainty in predicted *pmax* (for the flux-based variables) and *amax* (for the frequency-based variables), and in predicted *tmax* is greater for the low-flow variables.

For high-streamflow hydrological response variables, the *tmax* at receptors with noticeable changes occurs approximately when the maximum additional coal resource development occurs. This indicates that the instantaneous streamflow reduction caused by the additional mine footprint dominates *amax* and *pmax* in these hydrological response variables while the changes from the cumulative impact on baseflow over time caused by watertable drawdown are negligible.

For low-streamflow hydrological response variables, the *tmax* at receptors with noticeable changes does not occur consistently with the time when the maximum additional coal resource development footprint occurs. Furthermore, at the most heavily impacted node (node 14), the predicted median *tmax* values tend to be a little later for two of the low-flow hydrological response variables, P01 and LLFS. This indicates that the causes of the impacts on the low-flow variables are controlled by a combination of the instantaneous impact from the additional mine footprints and the cumulative impact 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.

References

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). GLO AWRA HRVs v02. Bioregional Assessment Source Dataset. Viewed 7 June 2016, http://data.bioregionalassessments.gov.au/dataset/20784922-036f-4aae-a22f-9498c8050073.

Glossary

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

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

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

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

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

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

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

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

coal resource development pathway: a future that includes all coal mines and coal seam gas (CSG) fields that are in the baseline as well as those that are expected to begin commercial production after December 2012 component: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a coal seam gas (CSG) operation or coal mine. For example, components during the development life-cycle stage of a coal mine include developing the mine infrastructure, the open pit, surface facilities and underground facilities. Components are grouped into life-cycle stages.

conceptual model: abstraction or simplification of reality

consequence: synonym of impact

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

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

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

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

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

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

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

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

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

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

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

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

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

groundwater system: see water system

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

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

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

impact cause: an activity (or aspect of an activity) that initiates a hazardous chain of events

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

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

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.

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

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

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)

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

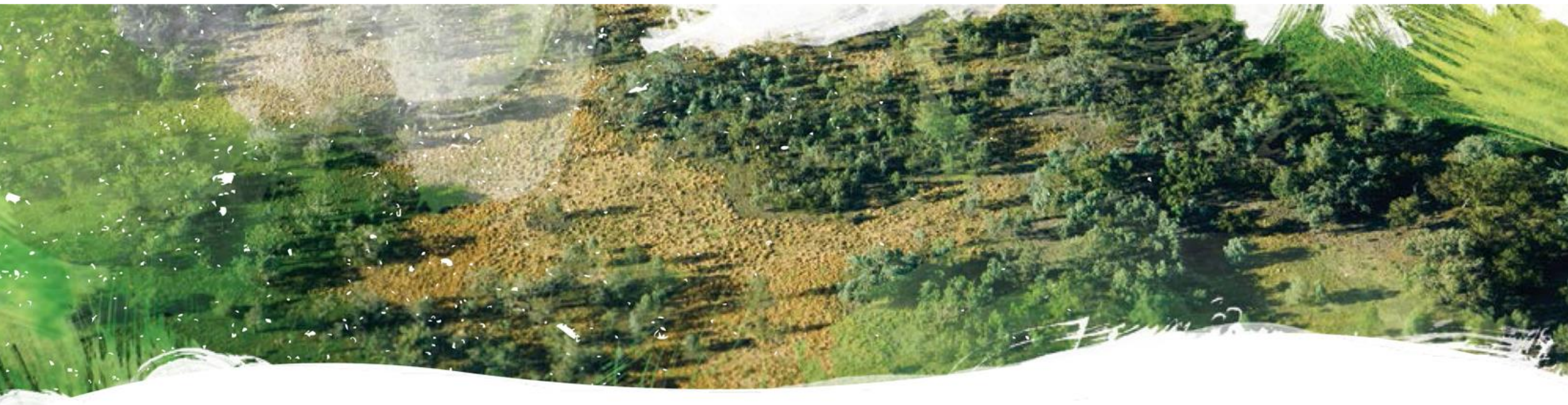
uncertainty: the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence, or likelihood. For the purposes of bioregional assessments, uncertainty includes: the variation caused by natural fluctuations or heterogeneity; the incomplete knowledge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

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

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

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

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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