Australian Government

BIOREGIONAL ASSESSMENTS

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

Surface water numerical modelling for the Galilee subregion

Product 2.6.1 for the Galilee subregion from the Lake Eyre Basin Bioregional Assessment

2018

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

The Bioregional Assessment Programme

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

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

Department of the Environment and Energy

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Artesian Spring Wetland at Doongmabulla Nature Refuge, Queensland, 2013

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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 potential surface water changes due to likely coal resource development in the Galilee subregion. The methods are summarised, followed by details regarding the development of the model. The product concludes with predictions of the hydrological response variables, the hydrological characteristics of the system that potentially changes due to coal resource development (for example, drawdown or the annual flow volume). The uncertainty and limitations of the models are also reported.

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

- *baseline coal resource development* (baseline): a future that includes all coal mines and CSG fields that are commercially producing as of December 2012 (if any)
- *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 baseline and the CRDP is the change that is primarily reported in a BA. This change is due to the additional coal resource development – all coal mines and CSG fields, including expansions of baseline operations that are expected to begin commercial production after December 2012.

There are no coal or CSG developments in operation as of the last quarter of 2012 for the Galilee subregion for the baseline. There are 17 proposed new developments in the Galilee subregion for the CRDP. There is enough information available to include seven of these developments in the numerical modelling for the Galilee subregion.

The seven development projects being modelled are the open-cut coal mines Alpha Coal Project and Hyde Park Coal Project, and the combined open-cut and underground coal mines Carmichael Coal Mine Project, China First Coal Project, China Stone Coal Project, Kevin’s Corner Coal Project and South Galilee Coal Project.

A generic methodology for surface water numerical modelling in BA is presented in companion submethodology M06 (as listed in Table 1). This product describes how the methodology has been applied in the Galilee subregion. Numerical simulation of the likely changes in surface water due to coal resource development requires a model or model sequence that can simulate change in the: regional groundwater system, the alluvial groundwater system, and the stream network. In the BA for the Galilee subregion an indirectly coupled model sequence of two models – consisting of a regional groundwater analytical element model (referred to as GW AEM) and a rainfall-runoff model (the Australia Water Resources Assessment landscape model, referred to as AWRA-L) – is used to simulate the hydrological changes on the surface water systems of the subregion.

Development of a single coupled and integrated surface water and groundwater model is beyond the resources and data available for this assessment of the Galilee subregion.

The surface water modelling domain comprises the Belyando, Cape and Suttor river basins and includes 61 model nodes at which daily streamflow is predicted. The model simulation period is from 2013 to 2102.

The comparison among the 61 model nodes shows that for the hydrological response variables that characterise high-streamflow conditions, the relative hydrological changes are largest for the model nodes where the maximum additional coal resource development percentage is largest. In general, the biggest changes (flow reductions of up to 20%) occur immediately downstream of additional coal resource development and are particularly evident in model nodes where the mine footprint forms a large proportion of the node catchment. For every high-streamflow hydrological response variable, the biggest changes are predicted to occur at a model node with a small upstream catchment on Sandy Creek. This node is located downstream of the South Galilee Coal Project.

The changes due to additional coal resource development on the low-streamflow hydrological response variables are more substantial than those on the high-streamflow hydrological response variables. However, they are also associated with greater uncertainty in both the predicted change and the year of maximum change. For the low-streamflow variables the biggest impacts occur in the middle reaches of the Belyando River and reflect an accumulation of impacts from multiple developments. These results also indicate that changes to low-streamflow characteristics are caused by a combination of the instantaneous impact of interception from the mine footprints of the additional coal resource development and the cumulative impact on baseflow over time caused by drawdown of the watertable, while the changes to high-streamflow characteristics are dominated by direct interception of runoff.

The change in baseflow due to changes in surface water – groundwater interactions under the CRDP is small compared to other components of the water balance and the effect of rainfall interception by mine sites. In the Galilee 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.

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

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Contributors to the Technical Programme

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

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

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

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This technical product was reviewed by several groups:

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

Currency of scientific results

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

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

Introduction

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

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

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

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

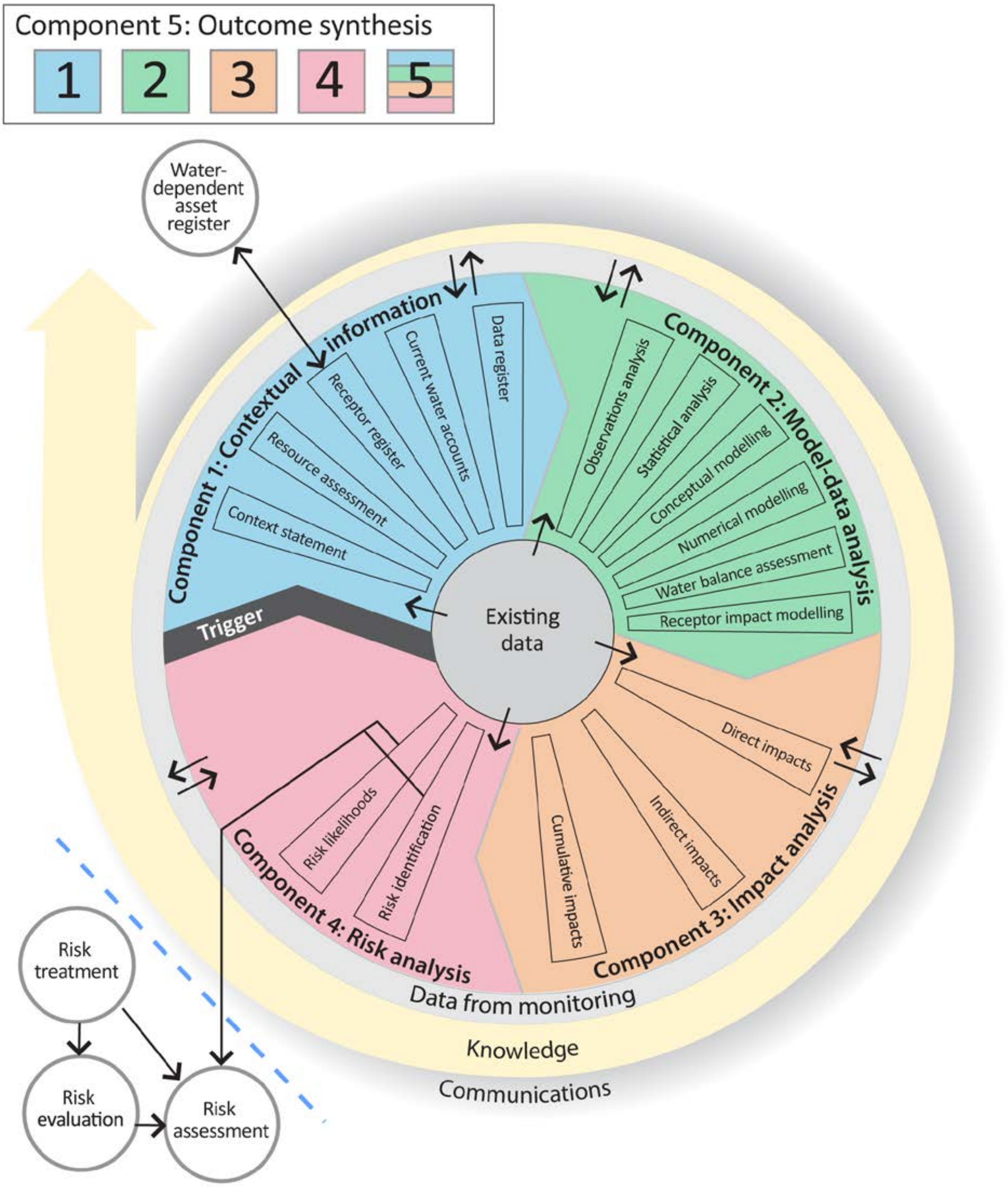

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

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

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

Table 1 Methodologies

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

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

Technical products

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

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

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

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

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

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

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

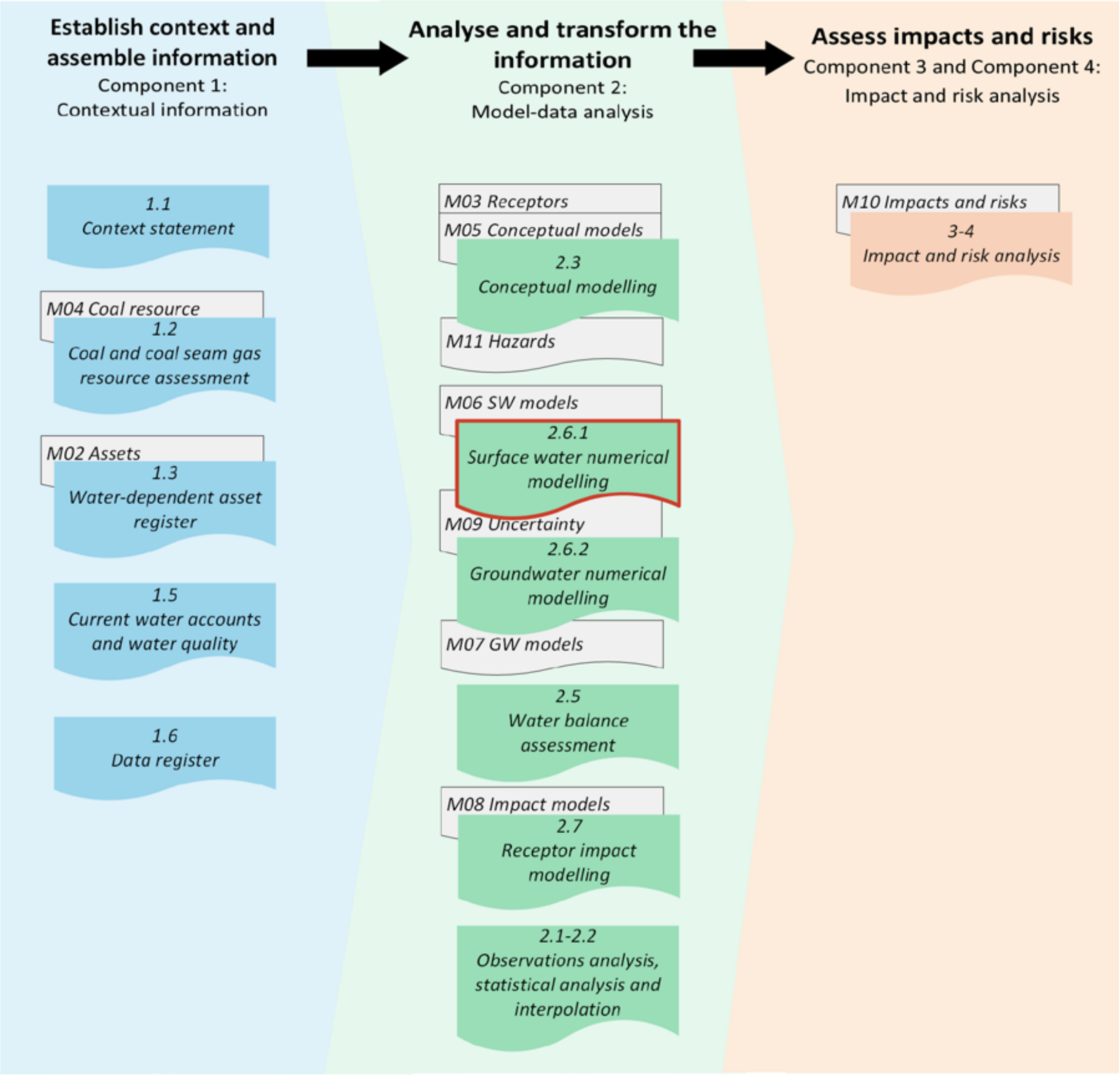

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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

Table 2 Technical products delivered for the Galilee subregion

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

Component	Product code	Title	Section in the BA methodology[b]	Type[a]
Component 1: Contextual information for the Galilee 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 Galilee 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 Galilee subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Galilee 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 Lake Eyre 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 140.0° East for the Lake Eyre Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://www.bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset’s published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived Datasets, the created date is used.

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 22 June 2018, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 22 June 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

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

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

This product reports results for only those developments in the baseline and CRDP that can be modelled. Results generated at model nodes are interpolated to estimate potential hydrological changes for surface water. Similarly, potential hydrological changes are estimated for groundwater in product 2.6.2 (groundwater numerical modelling). Product 3-4 (impact and risk analysis) then reports impacts on landscape classes and water-dependent assets arising from these hydrological changes.

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

2.6.1.1 Methods

Summary

A generic methodology for surface water numerical modelling in the Bioregional Assessment Programme is presented in companion submethodology M06 (as listed in Table 1) (Viney, 2016). This section describes the methodology that has been applied in the Galilee subregion and highlights the differences from the generic methodology. The main difference is that no river modelling is done for the Galilee subregion. Instead, predicted streamflow is obtained by accumulating output from the Australian Water Resources Assessment landscape model (AWRA-L).

2.6.1.1.1 Selection of surface water model

Surface water flow is influenced by coal mining directly through interception and flow diversion and indirectly by changes in groundwater level. Companion product 2.3 for the Galilee subregion (Evans et al., 2018b) indicates that 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 Belyando River and its tributaries via a change to baseflow. 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 Belyando river basin.

The Belyando is an unregulated and variably losing–gaining river, where it loses water at high flows and gains water at low flows (see Section 2.1.5 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)). 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 (as listed in Table 1) for surface water modelling (Viney, 2016)).

For these reasons, surface water resources in the Galilee subregion are modelled using the Australian Water Resources Assessment landscape model (AWRA-L) 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 Galilee subregion follows the methodology set out in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

2.6.1.1.2 Model sequencing

The numerical simulation of the hydrological changes due to the coal resource development pathway (CRDP) at the identified model nodes necessitates the development of an integrated surface water – groundwater modelling approach. The groundwater and surface water, however, operate at very different spatial and temporal scales. The surface water obviously is bound to river channels and floodplains. Streamflow is very responsive to individual rainfall events, requiring at least a daily temporal resolution to capture its ephemeral nature. Groundwater dynamics in the alluvial and Cenozoic deposits are mostly local and controlled through interactions with surface events, such as high rainfall or flooding (see Section 2.1.5 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)). Capturing this dynamic in a numerical groundwater model requires at a minimum a monthly resolution.

The deeper hydrogeological units hosted in the Eromanga and Galilee basins are much more extensive, both horizontally and vertically. The groundwater dynamics are very slow. In the outcrop zones of the units, there are indications that groundwater levels are influenced by recharge events. In the deeper, confined parts of the hydrogeological units there is no indication that groundwater dynamics are affected by recharge and discharge processes. Simulating groundwater flow in the deeper hydrogeological units requires a spatially extensive model, but a high temporal resolution is not essential.

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

For this Assessment, a pragmatic coupling of two models was developed. The models consist of a regional groundwater model to simulate the change to the groundwater systems of the subregion and a rainfall-runoff model to simulate the change to the surface water systems of the subregion (Figure 3). The individual models have different spatial and temporal resolution which requires a set of customised processing steps to upscale or downscale model data to allow the models to be linked.

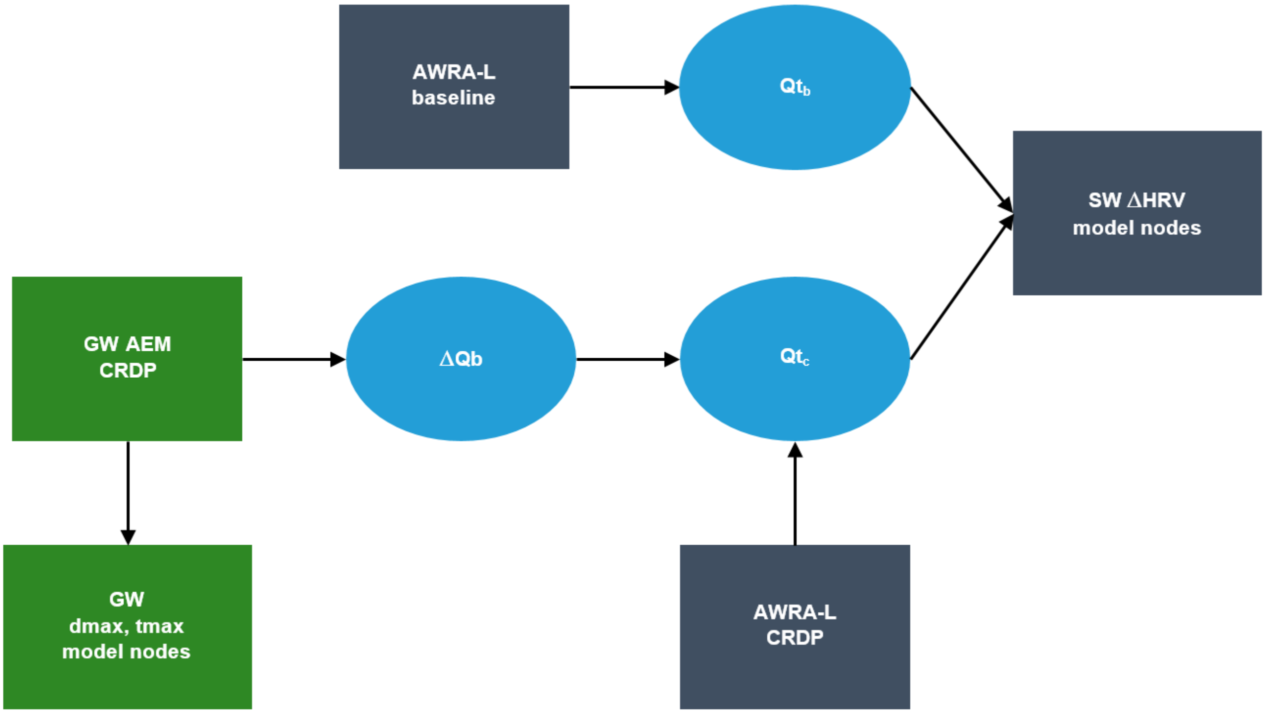

Figure 3 Model sequence for the Galilee subregion

GW AEM = regional groundwater analytic element model; AWRA-L = rainfall-runoff model; 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 to maximum change; ΔQb = change in surface water – groundwater flux; Qt_b = total streamflow baseline; Qt_c = total streamflow CRDP; ΔHRV = change in hydrological response variable; CRDP = coal resource development pathway; GW = groundwater; SW = surface water

The regional groundwater model is an analytic element model (referred to as GW AEM), designed to simulate the change in drawdown at the groundwater model nodes shown in Figure 3 and the change in surface water – groundwater flux. This model is explained in detail in companion product 2.6.2 for the Galilee subregion (Peeters et al., 2018). As there is no coal resource development under baseline conditions, the drawdown and change in surface water – groundwater flux due to baseline coal resource development is zero. There is therefore no need for a separate baseline conditions run for the groundwater model. The change in surface water – groundwater flux simulated with the CRDP run of the analytic element model, ΔQb, 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 model nodes. The modelling of river management or routing of streamflow through the river network with a river model is not necessary as the salient features of streamflow can be simulated solely with a rainfall-runoff model (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

The AWRA-L baseline run simulates streamflow at surface water model nodes without any active mines. The AWRA-L CRDP run simulates streamflow at the surface water model nodes incorporating the effect of modelled open-cut and underground coal mines in the CRDP. The time series of baseline and CRDP streamflows are summarised in the nine hydrological response variables to highlight different aspects of the hydrograph. The differences between baseline and CRDP of these hydrological response variables will inform the receptor impact models for the surface water model nodes.

2.6.1.1.3 Integration with sensitivity and uncertainty analysis workflow

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

To generate these ensembles, a very large number of parameter combinations of the combined groundwater and surface water model is 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) for propagating uncertainty through models (Peeters et al., 2016) requires that this acceptance threshold be specified independently, preferably based on assessment of the observational uncertainty, this is generally not possible for the various surface water response variables. A pragmatic choice is made to set the acceptance threshold to the 90th percentile of goodness of fit for the large number of model evaluations. The ensemble of predictions for each hydrological response variable is thus based on the top 10% of parameter combinations for that hydrological response variable.

The 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 groundwater 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, 1,000 (i.e. 10%) will be accepted in the posterior ensemble of predictions. Preliminary investigation (not shown) has demonstrated that this number is large enough to estimate the 5th, 50th and 95th percentiles robustly.

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2.6.1.2 Review of existing models

Summary

This section provides a review of existing surface water models in the Galilee subregion and discusses the suitability of existing models for use in the bioregional assessment (BA). There are purpose-oriented surface water models for the Burdekin river basin where all seven proposed coal mines are located. These models were developed by the Queensland Government and are primarily used to estimate water availability for domestic, agricultural and environmental usages. None of these models takes coal mine and coal seam gas (CSG) developments into account. A number of surface water models have been prepared by mining companies for surface water impact assessment required for the seven proposed coal mines that are selected for this BA. As of November 2015, a surface water model exists for six out of the seven proposed mines. However, there are no existing surface water models that are suitable to use for the Galilee subregion.

2.6.1.2.1 Review of surface water models in the Galilee subregion

Review of existing surface water models was undertaken only for the Burdekin river basin because all seven proposed coal mines selected for impact assessment are located in this basin. There are several purpose-oriented surface water models developed by the Queensland Government (e.g. DNR, 1999; Dougall et al., 2014) for water resource assessment and management. Surface water models are also available for the Burdekin river basin as a case study for hydrological model calibration and validation (e.g. Post and Croke, 2002). None of these models takes coal mine and coal seam gas (CSG) developments into account.

As a part of environmental impact statements (EISs), mining companies have prepared surface water models to assess the changes in flow regimes due to coal mine developments in the Galilee subregion. As of November 2015, a surface water model exists for six of the seven proposed coal mines (China Stone Coal Project, Carmichael Coal Mine Project, Kevin's Corner Coal Project, Alpha Coal Project, China First Coal Project and South Galilee Coal Project).

Changes in peak flow and flood inundation for the proposed Carmichael Mine were investigated by GHD (2012) using the XP-RAFTS hydrologic model (XP-Solution, 2013) and the TUFLOW hydraulic model (BMT WBM, 2010). A surface water model has been prepared by URS (2011a, 2011b) to investigate changes in flood inundation in the vicinity of Alpha and Kevin's Corner coal projects using a suite of hydrologic (RORB) and hydrodynamic models (one-dimensional HEC-RAS and two-dimensional TUFLOW). Hansen Bailey (2015) used XP-RAFTS to estimate changes in flow regimes for the proposed China Stone Coal Project. Engeny (2011) investigated the changes in peak flow due to the China First Coal Project using XP-RAFTS and conducted hydraulic modelling using TUFLOW. WRM (2012) used the operational simulation solution software (OPSIM) program to estimate the changes in flow regimes due to the South Galilee Coal Project development (Water Solutions, 2010).

Except for the models for mine EISs, none used coal mine development scenarios for long-term flow simulation. While surface water models developed for EIS studies included the mine impacts, they are calibrated locally and may not be suitable for regional flow prediction. Moreover, none of the models have been used for investigating low-flow metrics.

No existing surface water models were found to be suitable to use in the Galilee subregion.

For a discussion of the reasons for the choice of the Australian Water Resources Assessment landscape model (AWRA-L) in this bioregional assessment, readers are referred to companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

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2.6.1.3 Model development

Summary

This section summarises the steps taken in developing surface water models for predicting the hydrological impacts of coal resource development in the Galilee subregion. It describes the modelling domains, the spatial resolution and temporal resolutions, the development of future climate trends and time series of mine footprints for the period of mine operation. It includes discussion on the estimation of coal resource development pathway (CRDP) impacts on streamflow.

The surface water modelling domain comprises the Belyando, Cape and Suttor river basins and includes 61 model nodes at which daily streamflow predictions are produced. The model simulation period is from 2013 to 2102.

Seasonal climate scaling factors from the GFDL2.0 global climate model are chosen to provide a trended climate input over the course of the simulation period. This results in a reduction in mean annual precipitation of 3.1% per degree of global warming.

2.6.1.3.1 Spatial and temporal modelling domains

The hydrological modelling for the Galilee subregion is limited to the Burdekin river basin where all seven proposed coal mines identified for impact assessment are located (Figure 4). The Belyando River, which is a tributary of the Burdekin River, receives surface water runoff from the seven proposed mining sites and discharges via the Suttor River into the Burdekin River (Figure 4). The surface water modelling domain adopted in the bioregional assessment for the Galilee subregion includes the portion of the Burdekin river basin upstream of the junction of the Suttor and Cape rivers just above the Burdekin Falls Dam. The spatial boundary of the modelling domain was selected in accordance with the conceptual modelling for the Galilee subregion (see companion product 2.3 for the Galilee subregion (Evans et al., 2018)). Streamflow in this part of the Burdekin river basin is predominantly unregulated.

The surface water model operates on a daily time step and at a spatial resolution of 0.05 by 0.05 degrees. Model output from these grid cells are accumulated, in an areally weighted fashion, to provide daily streamflow predictions at the locations of interest.

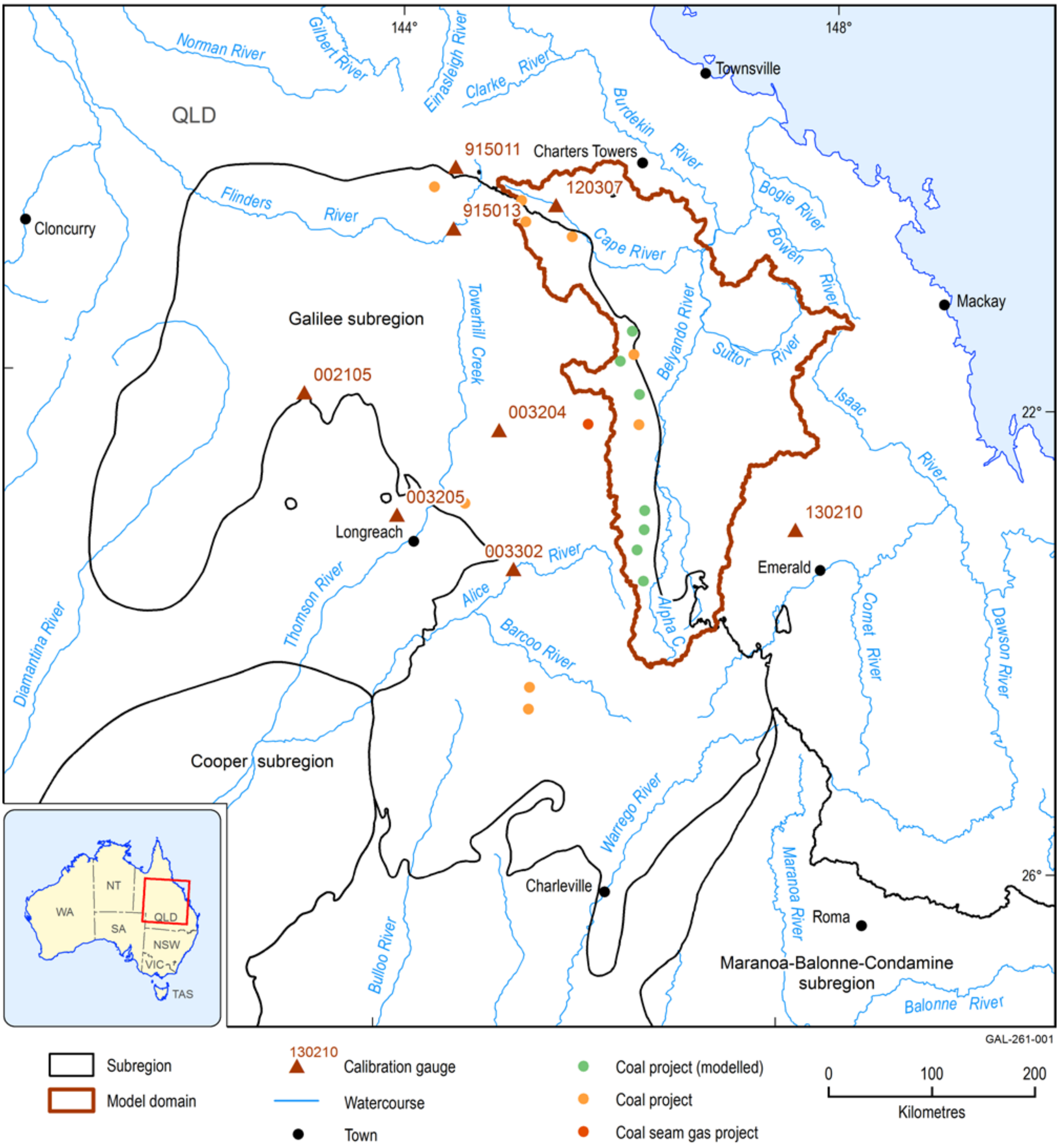

Figure 4 Surface water modelling domain for the Galilee subregion showing location of proposed coal and coal seam gas projects

Data: Bureau of Meteorology (Dataset 1); Bioregional Assessment Programme (Dataset 2, Dataset 3)

There are no coal or coal seam gas (CSG) developments in operation as of the last quarter of 2012 for the Galilee subregion for the baseline coal resource development. There are 17 proposed new developments in the Galilee subregion for additional coal resource development. There is enough available information to include seven of these coal resource developments in the numerical modelling for the Galilee subregion.

The seven development projects being modelled are the open-cut coal mines Alpha Coal Project and Hyde Park Coal Project, and the combined open-cut and underground coal mines Carmichael

Coal Mine Project, China First Coal Project, China Stone Coal Project, Kevin’s Corner Coal Project and South Galilee Coal Project.

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

Surface water model nodes represent those locations at which streamflow predictions are made. In the Galilee subregion these model nodes correspond with the 61 model node locations as shown in Figure 5.

In general, these nodes are located either:

- above major confluences
- immediately below proposed mines
- along major flow paths
- at an existing stream gauge location
- at other locations deemed appropriate for receptor impact analysis.

Out of 61 model nodes, 3 are on the Cape River and the remaining 58 are on the Belyando and Suttor rivers and their tributaries. Nodes 23, 26, 36, 49, 50, 51, 52 and 53 are located at existing stream gauge sites within the modelling domain. Predicted streamflow at these locations is used in model validation.

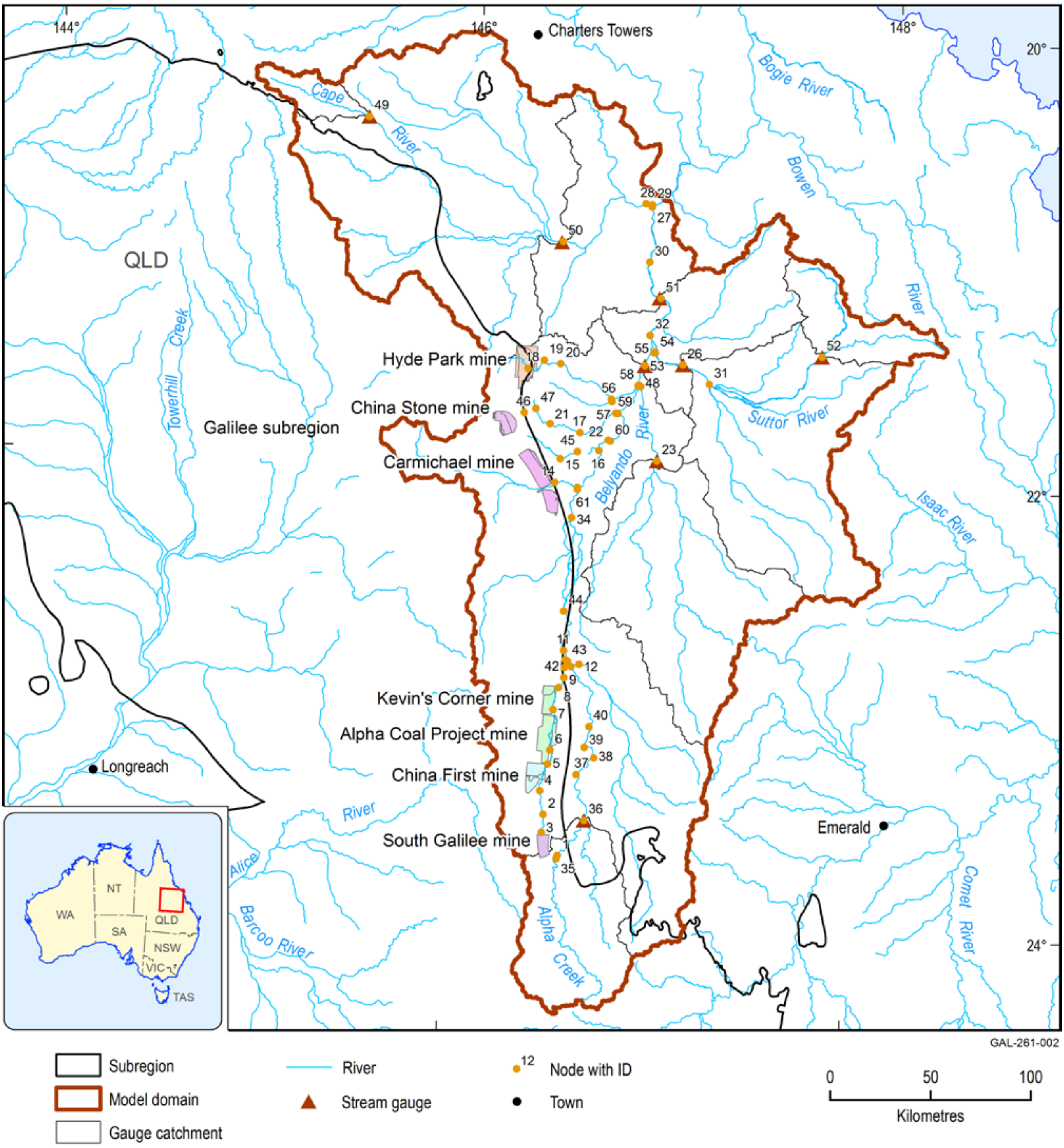

Figure 5 Location of model nodes within the Galilee surface water modelling domain

Data: Bioregional Assessment Programme (Dataset 2, Dataset 3, Dataset 4, Dataset 5)

2.6.1.3.3 Choice of seasonal scaling factors for climate trend

The objective in developing a future climate series is to choose the set of global climate model (GCM) seasonal scaling factors that give the median change in mean annual precipitation in the Galilee subregion. There are 15 available GCMs as presented in Table 3 with seasonal scaling factors for each of the four seasons: summer (December–February), autumn (March–May), winter (June–August) and spring (September–November).

For each GCM the change in mean seasonal precipitation that is associated with a 1 degree global warming is calculated. These seasonal changes are then summed to give a change in mean annual precipitation.

The resulting changes in mean annual precipitation for a 1 degree global warming in the Galilee subregion are shown in Table 3 for each GCM. The 15 GCMs predict changes in mean annual precipitation ranging from –7.3% (i.e. a reduction in mean annual precipitation) to 6.4% (i.e. an increase in mean annual precipitation). The GCM with the median change is GFDL2.0. The corresponding projected change in mean annual precipitation per degree of global warming is a reduction of 3.1%, or about 17 mm. The seasonal scaling factors for GFDL2.0 are +6.0%, –10.4%, – 13.0% and –13.8% for summer, autumn, winter and spring, respectively. In other words, projected increases in precipitation in the wettest season, summer, are offset by projected decreases in the other three seasons.

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

Global climate model	Modelling group and country	Change in mean annual precipitation (%)
MIUB	Meteorological Institute of the University of Bonn, Germany and Meteorological Research Institute of KMA, Korea	6.4%
NCAR-PCM	National Center for Atmospheric Research, USA	6.3%
MIROC3	Centre for Climate Research, Japan	5.6%
CCCMA T47	Canadian Climate Centre, Canada	3.8%
CCCMA T63	Canadian Climate Centre, Canada	3.4%
INMCM	Institute of Numerical Mathematics, Russia	1.3%
NCAR-CCSM	National Center for Atmospheric Research, USA	1.3%
GFDL2.0	Geophysical Fluid Dynamics Lab, USA	–3.1%
IAP	LASG/Institute of Atmospheric Physics, China	–3.2%
MPI-ECHAM5	Max Planck Institute for Meteorology DKRZ, Germany	–4.2%
MRI	Meteorological Research Institute, Japan	–4.4%
CNRM	Meteo-France, France	–5.7%
IPSL	Institut Pierre Simon Laplace, France	–5.9%
CSIRO-MK3.0	CSIRO, Australia	–6.2%
GISS-AOM	NASA/Goddard Institute for Space Studies, USA	–7.3%

The seasonal scaling factors associated with GFDL2.0 are used to generate trended climate inputs for the years 2013 to 2102. The trends assume global warming of 1 degree for the period 2013 to 2042, compared to 1983 to 2012. The global warming for 2043 to 2072 is assumed to be 1.5 degrees 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 degrees.

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 Galilee subregion is shown in Figure 6. It depicts a cycle of 1983–2012 climate that is repeated a further three times but with increasingly trended climate change scalars. It can be seen that the decrease in precipitation from 2013 to 2102 is less than the typical interannual variability (Figure 6).

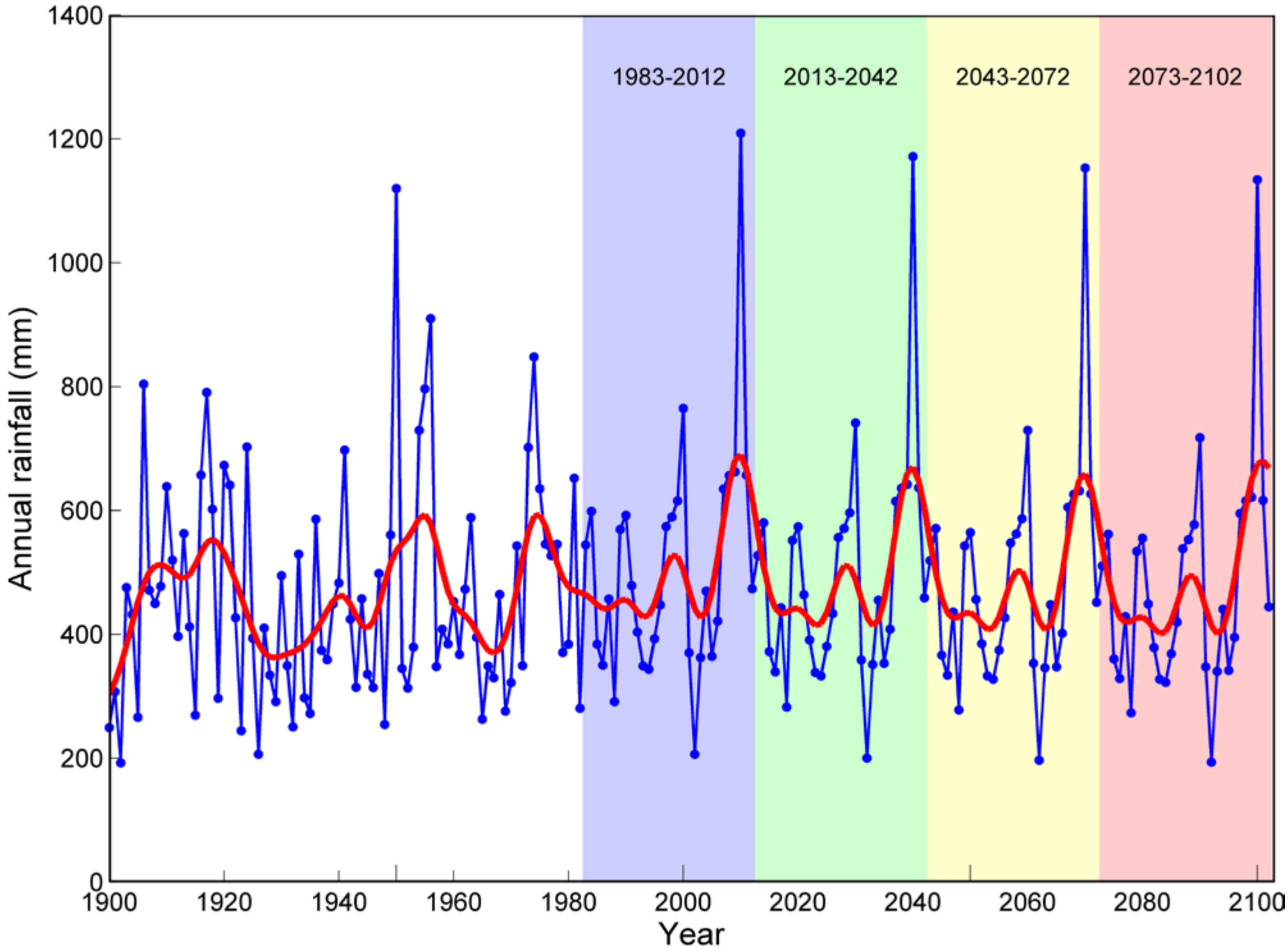

Figure 6 Time series of observed and projected annual precipitation averaged over the Galilee subregion (blue line); the red line is a centrally weighted moving average

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, roads, spoil dumps, water storages and infrastructure. It may also include otherwise undisturbed parts of the landscape from which natural runoff is retained in reservoirs. The footprint does not include rehabilitated areas 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.

Mine footprint areas change over the lifetime of a mine’s operations (Figure 7). 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.

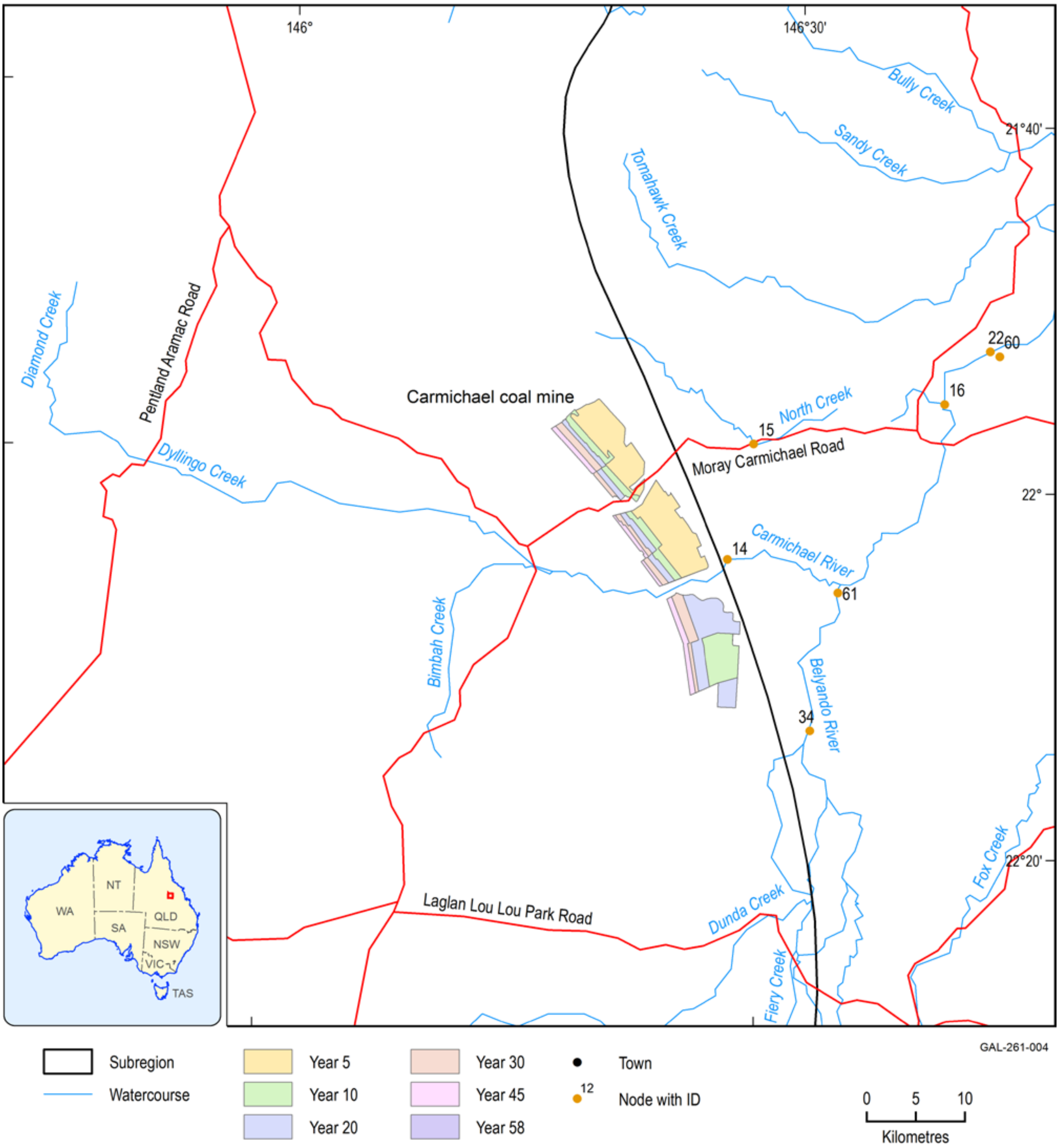

Figure 7 An example of the evolution of an open-cut footprint area over time for the proposed Carmichael Coal Mine Project in the Galilee subregion

This map shows the open-cut footprint only, not the entire mine footprint that includes pits, roads, spoil dumps, water storage, infrastructure and any other areas disturbed by the mine operation.
Data: Bioregional Assessment Programme (Dataset 4, Dataset 6)

For underground mines, the impact on surface runoff is through subsidence of the land surface associated with the progressive collapse of mined longwall panels. This impact is assumed to continue indefinitely. However, it should be noted that on a per unit area basis, the impact of an underground mine footprint on surface runoff is much less than that of an open-cut mine footprint.

Mine footprint areas are obtained from the mine environmental impact statement (EIS) and supplementary environmental impact statement (SEIS) reports published by the mining companies. Time sequences of mine footprint (i.e. the total area affected by mining operation) areas were estimated using the ArcGIS tool based on publicly available mine plan information.

The temporal evolution of footprint areas for the seven proposed coal resource developments in the Galilee subregion is shown in Figure 8. Each panel shows footprints for open-cut and underground mines. None of the mines is currently operational in the Galilee subregion. Therefore, no footprint area is shown for the baseline condition. The starting and ending dates of individual mines was assumed to be the same as reported in Section 2.3.4 of companion product 2.3 for the Galilee subregion (Evans et al., 2018). It was assumed that any infrastructure – including dams, levee banks and roads – which has beneficial future use by post-mine landowners will be left in place. Areas of these features were included in the residual footprint area after final rehabilitation.

Table 4 details the maximum footprint extent for each model node and the year in which that maximum occurs. In Table 4, the footprint is taken as the open-cut footprint plus 5% of the area of the underground footprint. Since subsidence-related ponding is assumed to occur in 5% of the landscape above a collapsed underground panel, the footprint percentages in Table 4 are likely to be directly relatable to the hydrological impacts presented in Section 2.6.1.6.

Table 4 also indicates whether nodes interact with the groundwater model. In the groundwater model (see companion product 2.6.2 for the Galilee subregion (Peeters et al., 2018)) only the main channel of the Belyando River is considered to be perennially in hydrological contact. Only the prediction nodes on this channel can potentially interact with the groundwater model.

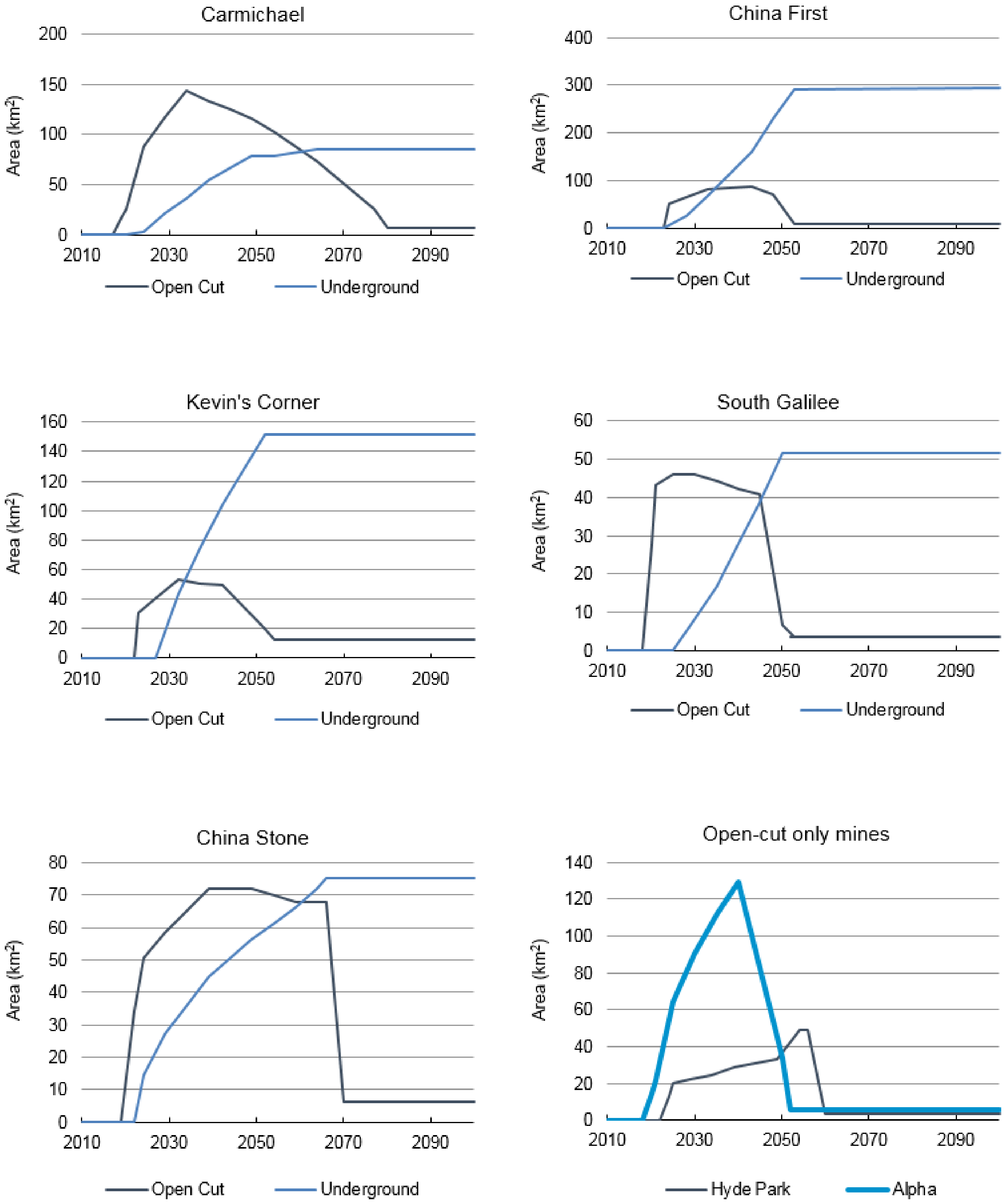

Figure 8 Temporal variation of footprint areas of the seven additional coal resource developments included in the surface water modelling for the coal resource development pathway (CRDP) for the Galilee subregion

Table 4 Summary of prediction model nodes with the catchment area, the maximum extent of the coal resource development pathway (CRDP) as percentage of the catchment area, the time of this maximum extent and whether or not the node incorporates groundwater model results

Model node	Longitude	Latitude	Tributary number	River	Contributing area (km^2)	Maximum CRDP (percentage of contributing area)	Year of maximum extent	Interaction with groundwater model
001	146.555	−23.738	11	Alpha Creek tributary 1	68	10.0	2043	No
002	146.476	−23.559	10	Tallarenha Creek	253	17.3	2026	No
003	146.471	−23.639	10	Tallarenha Creek	182	24.0	2026	No
004	146.454	−23.454	10	Tallarenha Creek	339	12.9	2026	No
005	146.486	−23.334	10	Lagoon Creek	1,066	5.0	2034	No
006	146.494	−23.271	10	Lagoon Creek	1,383	6.1	2040	No
007	146.499	−23.089	10	Sandy Creek	2,218	8.0	2040	No
008	146.521	−22.989	10	Sandy Creek	2,797	8.4	2040	No
009	146.544	−22.899	10	Sandy Creek	3,056	7.7	2040	No
010	146.546	−22.864	10	Sandy Creek	3,066	7.6	2040	No
011	146.536	−22.824	2	Belyando River	14,509	1.7	2040	Yes
012	146.614	−22.881	2	Belyando River	5,824	0.0	–	No
013	146.563	−22.093	9	Carmichael River	2,632	1.0	2034	No
014	146.451	−22.075	9	Carmichael River	2,562	1.0	2022	No
015	146.471	−21.969	8	North Creek	639	19.0	2033	No
016	146.659	−21.924	8	North Creek	1,146	12.9	2033	No
017	146.561	−21.846	7	Tomahawk Creek	553	0.0	–	No
018	146.294	−21.571	5	Bully Creek	208	7.1	2054	No
019	146.371	−21.531	5	Bully Creek	333	14.5	2054	No
020	146.451	−21.544	5	Bully Creek	504	9.6	2054	No
021	146.414	−21.814	7	Tomahawk Creek	94	0.0	–	No
022	146.701	−21.874	8	North Creek	1,178	12.5	2033	No
023	146.942	−21.957	6	Mistake Creek	7,744	0.0	–	No

Model node	Longitude	Latitude	Tributary number	River	Contributing area (km^2)	Maximum CRDP (percentage of contributing area)	Year of maximum extent	Interaction with groundwater model
024	146.836	−21.621	2	Belyando River	33,283	1.4	2040	Yes
025	146.904	−21.469	1	Suttor River	46,645	1.1	2040	Yes
026	147.042	−21.521	4	Suttor River	10,801	0.0	–	No
027	146.854	−20.821	1	Suttor River	51,967	1.0	2040	Yes
028	146.824	−20.809	3	Cape River	19,491	0.0	–	No
029	146.854	−20.811	1	Suttor River	71,532	0.7	2040	No
030	146.856	−21.069	1	Suttor River	51,177	1.0	2040	Yes
031	147.176	−21.601	4	Suttor River	10,464	0.0	–	No
032	146.876	−21.396	1	Suttor River	47,110	1.1	2040	Yes
033	146.741	−21.752	2	Belyando River	23,691	1.9	2040	No
034	146.541	−22.227	2	Belyando River	18,538	1.3	2040	Yes
035	146.550	−23.753	11	Alpha Creek	2,440	0.0	–	Yes
036	146.678	−23.576	11	Native Companion Creek	4,142	0.2	2043	Yes
037	146.629	−23.374	11	Native Companion Creek	4,703	0.1	2043	Yes
038	146.711	−23.296	11	Native Companion Creek	4,871	0.1	2043	Yes
039	146.661	−23.251	11	Native Companion Creek	5,058	0.1	2043	Yes
040	146.679	−23.156	11	Native Companion Creek	5,169	0.1	2043	Yes
041	146.576	−22.894	11	Native Companion Creek	5,515	0.1	2043	Yes
042	146.544	−22.944	10	Sandy Creek	2,844	8.2	2040	No
043	146.556	−22.870	2	Belyando River	14,502	1.7	2040	Yes
044	146.526	−22.648	2	Belyando River	15,863	1.5	2040	Yes
045	146.553	−21.932	8	North Creek	777	15.6	2033	No

Model node	Longitude	Latitude	Tributary number	River	Contributing area (km²)	Maximum CRDP (percentage of contributing area)	Year of maximum extent	Interaction with groundwater model
046	146.286	−21.769	7	Pigeonhole Creek	264	0.0	–	No
047	146.341	−21.749	7	Tomahawk Creek	55	0.0	–	No
048	146.844	−21.627	6	Mistake Creek	8,586	0.0	–	No
049	145.474	−20.477	3	Cape River	786	0.0	–	No
050	146.434	−20.996	3	Cape River	15,432	0.0	–	No
051	146.919	−21.229	1	Suttor River	50,322	1.0	2040	Yes
052	147.714	−21.450	4	Suttor River	1,917	0.0	–	No
053	146.860	−21.533	2	Belyando River	35,326	1.4	2040	Yes
054	146.906	−21.474	4	Suttor River	11,158	0.0	–	No
055	146.900	−21.473	2	Belyando River	35,486	1.4	2040	No
056	146.706	−21.691	5	Bully Creek	774	6.3	2054	No
057	146.709	−21.701	5	Bully Creek tributary	475	0.0	–	No
058	146.831	−21.624	5	Bully Creek	1,552	3.1	2054	No
059	146.731	−21.751	7	Tomahawk Creek	912	0.0	–	Yes
060	146.711	−21.878	2	Belyando River	22,092	1.4	2040	Yes
061	146.562	−22.101	2	Belyando River	18,968	1.5	2040	Yes

2.6.1.3.5 Estimation of hydrological changes due to additional coal resource development

The changes in daily streamflow at each model node due to additional coal resource development are estimated as the total of two impacts: changes in direct runoff as a result of reduction in surface area generating runoff due to the open-cut mine, and changes in baseflow. For more detailed descriptions of mine impacts on hydrology, readers are referred to companion product 2.3 on conceptual modelling of causal pathways (Evans et al., 2018) for the Galilee subregion, which outlines the potential modes of impact between mining operations and surface water and groundwater systems. 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 Resources Assessment landscape model (AWRA-L) daily streamflow multiplied by the ratio of the footprint area to each node's contribution area. This means that there will be no impact on streamflow if there is no additional coal resource development, and the reduction in streamflow will be 100% if the footprint area covers 100% of the node’s contribution area. Prediction model nodes are located in 11 tributary catchments (Figure 9) and 4 out of 7 proposed mines directly affect the flow regimes in catchment 10.

Underground mining can cause land subsidence contributing to a reduction in surface water flow. Therefore, a proportion of the underground mining area is included in the surface water disturbed area for assessing changes in flow regime. In the Galilee subregion it is assumed that 5% of the land surface area above a collapsed underground panel is potentially susceptible to retention of surface runoff through increased ponding. This value was selected as a conservative estimate based on consultation among the broader hydrological modelling team in the bioregional assessments, and was informed through discussions with proponents and experienced consultants. However, as the assumption is unlikely to have a major impact on predictions given the spatial and temporal scale of the regional modelling undertaken for the Galilee subregion, it was not incorporated in the quantitative uncertainty analysis.

The hydrological change to baseflow is estimated using the groundwater model, which is described in detail in Section 2.6.2.2.3 of companion product 2.6.2 for the Galilee subregion (Peeters et al., 2018). The groundwater model estimates monthly baseflow for each of the surface water model nodes 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.

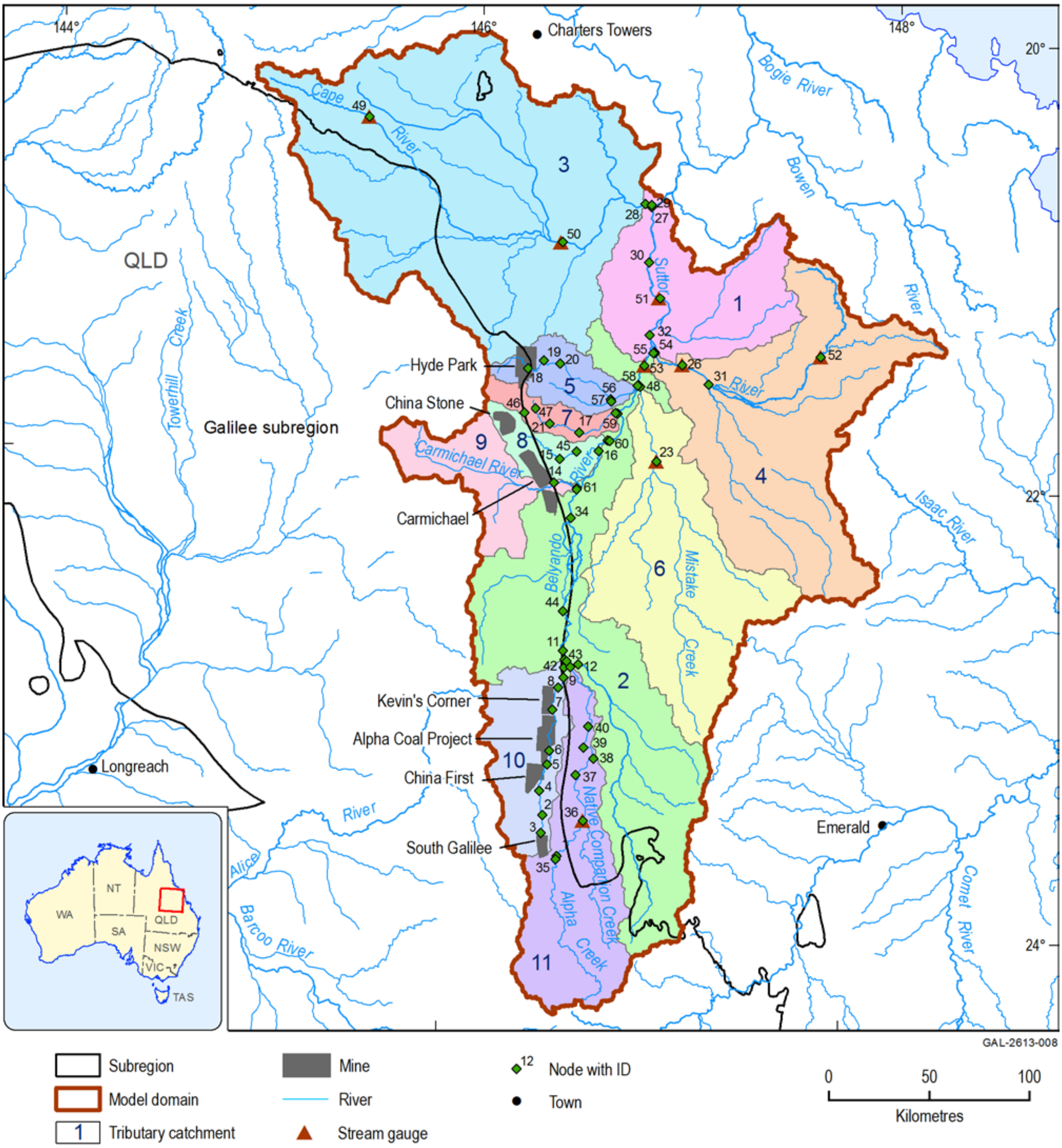

Figure 9 Spatial extents of the 11 tributary catchments and their associated model nodes that are defined within the surface water modelling domain

Data: Bioregional Assessment Programme (Dataset 4, Dataset 6, Dataset 7)

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2.6.1.4 Calibration

Summary

This section summarises surface water model calibration for the Galilee subregion. The Australian Water Resources Assessment landscape model (AWRA-L) was regionally calibrated at eight unregulated catchments using two calibration schemes: one biased towards high streamflow and the other biased towards low streamflow.

The high-streamflow calibration yields relatively better (i.e. less biased) predictions for annual flow while the low-streamflow calibration yields better predictions for low-flow spells and zero-flow days. The two calibration sets yield predictions with similar levels of bias for most of the remaining hydrological response variables. One variable, daily flow at the 1st percentile (P01), is unable to be predicted by either calibration parameter set because the flow in most catchments is ephemeral so P01 takes a value of zero in most years at most sites.

A consequence of the regionalisation scheme used in this Assessment is that prediction performance in ungauged parts of the subregion is likely to be similar to that in the calibration catchments. This, therefore, provides confidence for applying the AWRA-L model to each model node where there are no streamflow observations. The performance of the calibrated parameters for estimating the hydrological response variables suggests the 10,000 model parameter sets generated using the calibrated parameters can produce a reasonable estimate range for the majority of hydrological response variables. However, both calibrations substantially under-predict the number of low-flow days. This suggests that less confidence may be ascribed to the prediction of this variable in Section 2.6.1.6 than to the prediction of the other variables.

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

2.6.1.4.1 Data

Input climate data were daily time series of maximum temperature, minimum temperature, incoming solar radiation and precipitation from 1981 to 2012 at 0.05 x 0.05 degree (~5 x 5 km) grid cells from the gridded data originally generated by the Bureau of Meteorology (Dataset 1).

Daily streamflow data from eight gauging sites with unregulated catchments located in and around the Galilee subregion (Figure 10) were used to calibrate the surface water hydrological model.

Criteria for selecting the calibration catchments included that they:

- have long-term measurements (>20 years from 1980)
- are currently not impacted by coal mining or coal seam gas or other major extractive industries
- have no significant flow regulation (e.g. dams)
- are not nested
- are located within or close to the Galilee subregion and have similar catchment sizes and climate regimes.

The catchments of five of the eight gauges are located partly or fully within the Galilee subregion. These are Flinders River at Glendower (915013), Cape River at Pentland (120307), Mills Creek at Oondooroo (002105), Cornish Creek at Bowens Downs (003204) and Alice River at Barcaldine (003302). The catchments of the three remaining gauges (Porcupine Creek at Mount Emu Plain (915011), Darr River at Darr (003205) and Theresa Creek at Valeria (130210)) are located outside but close to the Galilee subregion boundary. Observed daily mean streamflow data for the above gauges were obtained from the Bureau of Meteorology (Dataset 2).

Boundaries for the eight catchments were delineated using the Geofabric (Bureau of Meteorology, Dataset 3).

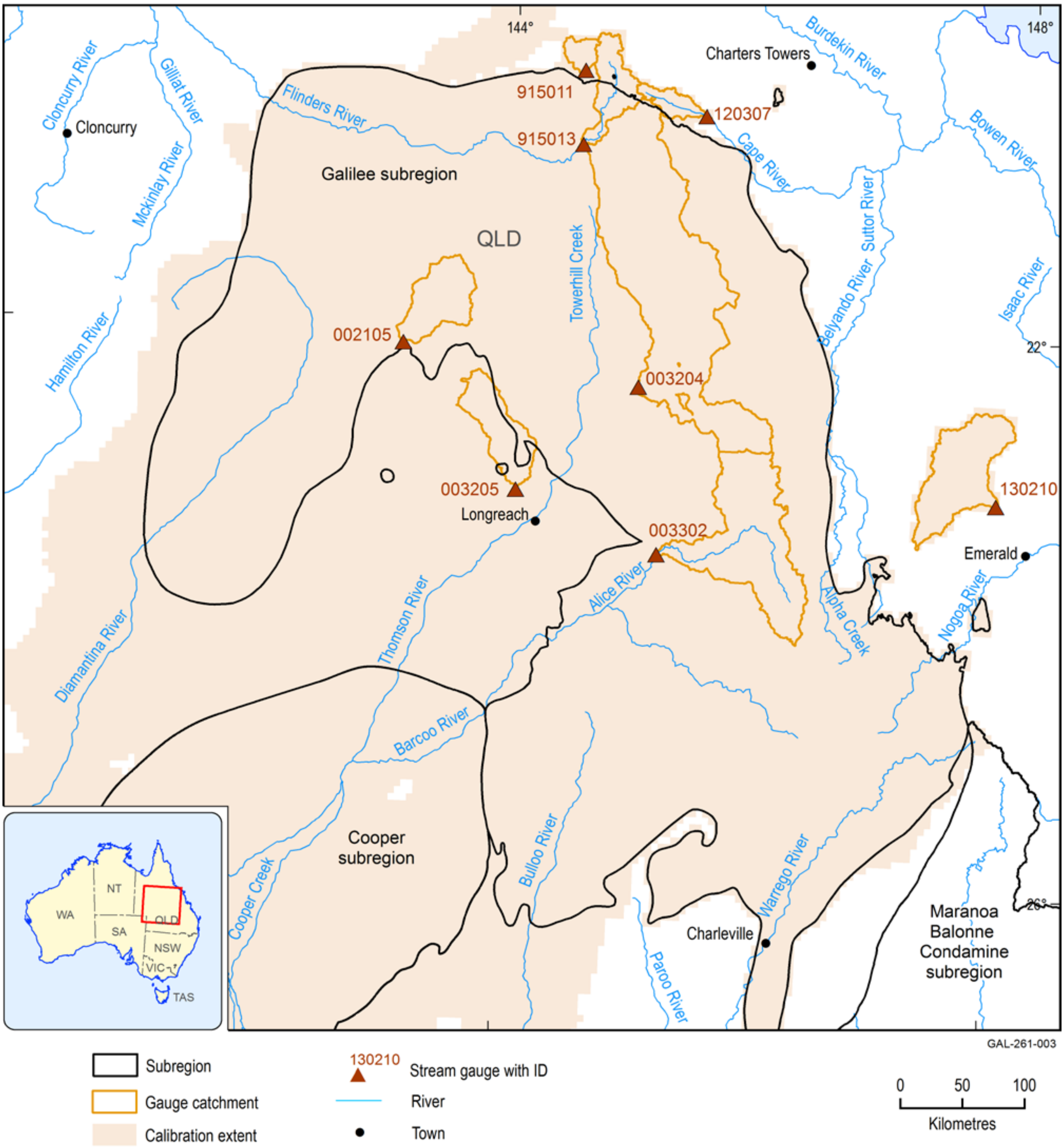

Figure 10 Location of the gauge catchments that were used for Australian Water Resources Assessment landscape model (AWRA-L) calibration for the Galilee subregion

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

2.6.1.4.2 Model calibration results

Figure 11 and Table 5 summarise regional model calibration performance for the eight calibration catchments. For both high-streamflow and low-streamflow calibrations, three metrics (F value, daily efficiency and model bias) are shown and their details are explained in the notes of Figure 11 and in Viney (2016).

The high-streamflow calibration yields slightly better results in terms of model bias, indicated by a mean bias of –2% and a median bias of 5%. Overall, the model under-predicts streamflow at three of the eight calibration sites and slightly over-predicts at the remaining five. In terms of Nash–Sutcliffe efficiency (denoted as E) of daily streamflow ($E_d(1.0)$), the high-streamflow calibration yields somewhat satisfactory results, indicated by mean and median E_d values of 0.38 and 0.36, respectively.

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 can ensure the model evaluation is putting more weight on low streamflow than on higher streamflow. The low-streamflow calibration has a stronger tendency towards over prediction with a median bias of 20%. In terms of efficiency, the low-streamflow calibration yields similar results to high-streamflow calibration, indicated by mean and median E_d values of 0.32 and 0.39, respectively. The low-streamflow calibration is poor at gauging site 002105, but is satisfactory elsewhere.

The eight calibration catchments cover a wide range of climate and topographic conditions, where mean annual streamflow varies from 7 mm/year at catchment 003302 to 78.6 mm/year at catchment 915013 (Table 5). This indicates that the Australian Water Resources Assessment landscape model (AWRA-L) is suitable to predict streamflow in the Galilee subregion where climate conditions vary widely. Furthermore, the performance of the high-streamflow calibration for the eight catchments is not significantly related to catchment wetness, as it does not perform better with a wetter climate.

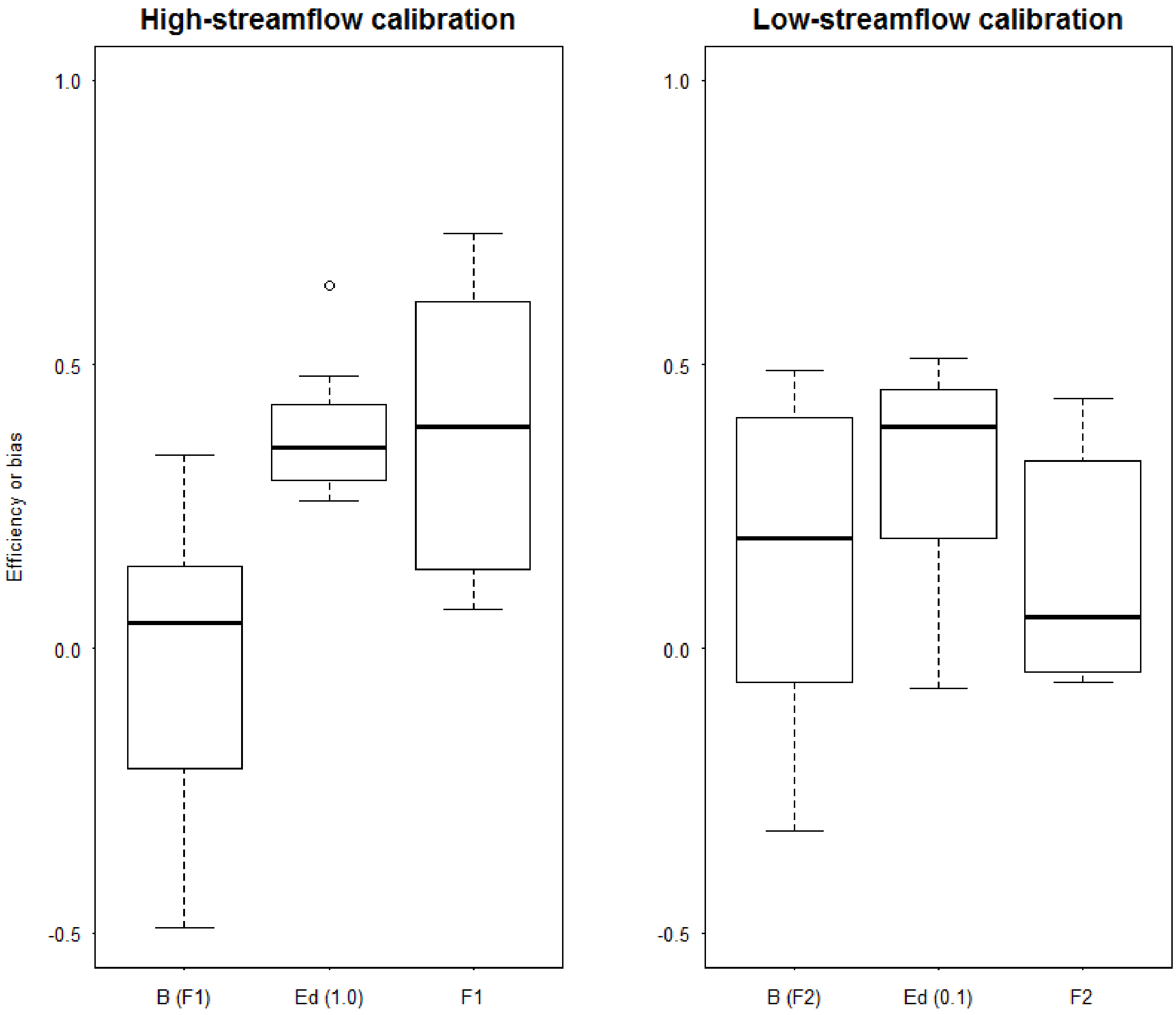

Figure 11 Summary of two AWRA-L model calibrations for the Galilee subregion

In each boxplot, the bottom, middle and top of the box are the 25th, 50th and 75th percentiles, respectively, and the bottom and top whiskers are the 10th and 90th percentiles, respectively. F1 is the F value for high-streamflow calibration; F2 is the F value for low-streamflow calibration; Ed(1.0) is the daily efficiency with a Box-Cox lambda value of 1.0; Ed(0.1) is the daily efficiency with a Box-Cox lambda value of 0.1; and B is model bias (Viney, 2016). AWRA-L = Australian Water Resources Assessment landscape model

Data: Bureau of Meteorology: forcing data (Dataset 1) and streamflow data (Dataset 2)

Table 5 Summary of model calibration for the eight gauged catchments in the Galilee 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]
002105	11.4	0.65	0.38	0.06	–9.12	–0.07	2.55
003204	19.3	0.07	0.28	–0.28	–0.02	0.46	–0.32
003205	18.7	–1.46	0.31	–0.49	0.12	0.19	0.20
003302	7.0	0.21	0.26	0.34	–0.01	0.20	0.32
120307	73.0	0.73	0.64	0.06	–0.06	0.43	0.49
130210	30.9	0.35	0.33	0.03	0.44	0.45	0.09
915011	61.6	0.43	0.38	0.23	0.28	0.35	0.19
915013	78.6	0.57	0.48	–0.14	0.38	0.51	–0.21
Mean	37.6	0.19	0.38	–0.02	–1.0	0.32	0.41

[a] *F1* is the F value for high-streamflow calibration (see Viney, 2016); [b] *F2* is the F value for low-streamflow calibration
E_d(1.0) is the daily efficiency with a Box-Cox lambda value of 1.0; E_d(0.1) is the daily efficiency with a Box-Cox lambda value of 0.1.
Data: Bureau of Meteorology: forcing data (Dataset 1) and streamflow data (Dataset 2)

Figure 12 shows the performance of the two calibration schemes (high-streamflow calibration and low-streamflow calibration) for predicting nine hydrological response variables (details for each hydrological response variable are shown in Table 6). The high-streamflow calibration yields relatively better (i.e. less biased) predictions for annual flow (AF) while the low-streamflow calibration yields better predictions for low-flow spells (LFS) and zero-flow days (ZFD). The two calibration sets yield predictions with similar levels of bias for interquartile range (IQR), flood (high-flow) days (FD) and low-flow days (LFD), though the latter is poorly predicted by both. Curiously, one of the high-flow metrics, daily flow at the 99th percentile (P99), appears to be predicted better by the low-flow calibration, while one of the low-flow metrics, longest low-flow spell (LLFS), appears to be predicted slightly better by the high-flow calibration. The remaining hydrological variable, daily flow at the 1st percentile (P01), is unable to be predicted by either calibration parameter set because most catchments are ephemeral so P01 takes a value of zero in most years at most sites.

Table 6 Summary of nine hydrological response variables for streamflow

Abbreviation	Hydrological response variable	Unit
P01	Daily flow 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)	ML/day
LFS	Low-flow spells	Times/year
LLFS	Longest low-flow spell	Days
P99	Daily flow at the 99th percentile	ML/day
FD	Flood (high-flow) days	Days
AF	Annual flow	GL/year
IQR	Interquartile range	ML/day

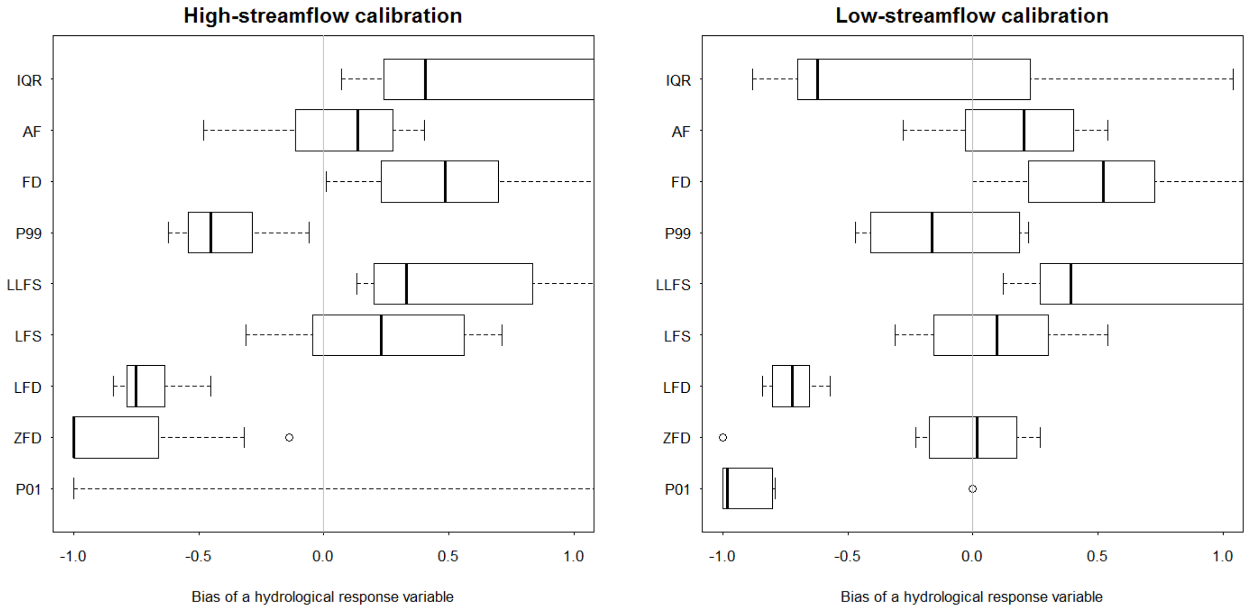

Figure 12 Summary of predicted bias of the nine hydrological response variables obtained using the two AWRA-L model calibrations

Boxplots are obtained from the statistics (Nash–Sutcliffe efficiency and bias) results at the eight calibration catchments. In each boxplot, the left, middle, and right of the box are the 25th, 50th and 75th percentiles, respectively, and the left and right whiskers are the 10th and 90th percentiles, respectively. AWRA-L = Australian Water Resources Assessment landscape model
Data: Bureau of Meteorology: forcing data (Dataset 1) and streamflow data (Dataset 2)

The calibration results summarised in Figure 11 and Figure 12 indicate that neither of the calibration methods are good at predicting all of the hydrological response variables analysed in this Assessment. The main limitation is the lack of a long period of continuously observed streamflow data for model calibration. Stream gauges in the Galilee subregion are sparse and the length of data records is relatively short (less than 25 years). As stated by Viney (2016), it is expected that for most model nodes, the variables P01 and ZFD will be mutually exclusive in that one or the other will produce useful information, but not both. In the Galilee subregion, P01 is unlikely to provide useful predictions in model nodes.

2.6.1.4.3 Implications for model predictions

The regional model calibration results (Table 5 and Figure 11) suggest that the AWRA-L model performs satisfactorily in estimating most hydrological response variables in the Galilee subregion and its surrounding area when it is calibrated against in situ high streamflow and low streamflow, respectively.

It is noted that when the regional model is calibrated against observations from eight streamflow gauges it does not generate a uniform model performance. Though the AWRA-L model performs well overall, it performs poorly in some catchments and does not estimate the suite of hydrological response variables equally effectively. For instance, the high-streamflow model calibration under-predicts streamflow at catchment 003205 and the low-streamflow model calibration over-predicts at catchment 002105 (Table 5). For other gauges in the Galilee subregion, the model performs well in terms of model efficiency and bias.

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 model nodes the $E_d(1.0)$ values will be of the order of 0.3 to 0.4 and the biases will be of the order of –0.3 to +0.3. This, therefore, provides confidence in the prediction quality of the AWRA-L model outputs in each model node where there are no streamflow observations.

Although not directly calibrated towards any of the hydrological response variables, an assessment of how well the two calibration sets predict the hydrological response variables serves as a further assessment of model performance. In general, one or other of the two calibration sets provides predictions of the hydrological response variables with little bias. An exception is for the variable describing the number of low-flow days, which both parameter sets severely under-predict. This suggests that less confidence may be ascribed to the prediction of this variable in Section 2.6.1.6 than to the prediction of the other variables.

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2.6.1.5 *Uncertainty*

Summary

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

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

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

A comprehensive sensitivity analysis is carried out to ensure that the parameters that can be constrained by the historical observations are the same as those 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 particular selection of CRDP developments chosen for assessment and for the corresponding mine footprints implemented in the model sequence.

2.6.1.5.1 Quantitative uncertainty analysis

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

Acceptable model behaviour is defined for each hydrological response variable based on the capability of the model to reproduce 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.

2.6.1.5.1.1 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, the range and distribution type sampled in the design of experiment and the transformation of the parameter. The Australian Water Resources Assessment landscape model (AWRA-L) parameters in Table 7 are explained in the AWRA-L v4.5 documentation (Viney et al., 2015).

Table 7 AWRA-L parameters included in the quantitative uncertainty analysis

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

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

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

Each of the 10,000 parameter sets is used to drive AWRA-L to generate streamflow time series at each 0.05 x 0.05 degrees grid cell.

2.6.1.5.1.2 Observations

For eight of the nodes in the model domain, observations of streamflow are available. For these catchments the historical observations of streamflow are summarised into the eight hydrological response variables (daily flow at the 1st percentile (P01) is not used) for all years with a full observational record. The equivalent historical simulated hydrological response variable values are computed from the 10,000 design of experiment runs.

Preliminary runs revealed that some parameter sets result in the effect of the 2010–2011 floods on the low-flow part of the hydrograph to persist for up to 25 years after the flooding. This in turn results in the counter-intuitive and unrealistic artefact that even under a drying climate the flow rates in dry periods increase. As the extreme 2010–2011 floods happen late in the observation record, the available observations are not able to constrain the AWRA-L parameters sufficiently to avoid this artefact. The parameter combinations were therefore filtered by removing any parameter combination that resulted in a significant negative trend in the annual minimal flow between 2019 and 2037. As a result, 6537 parameter sets were removed and the further analysis is based on the remaining 3463 parameter sets.

The goodness of fit between these observed and simulated historical hydrological response variable values is used to constrain the 3463 parameter combinations and select the best 10% of replicates that are used in Section 2.6.1.6.

2.6.1.5.1.3 Predictions

For each of the 61 model nodes the post-processing of design of experiment results in 3463 time series with a length of 90 years of hydrological response variable values for baseline, $HRV_b(t)$, and coal resource development conditions, $HRV_c(t)$.

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

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

One of the nine hydrological response variables defined in companion submethodology M06 for surface water modelling (Viney, 2016), P01, is not reported in this product. The observed values of P01 in the observation catchments are all zero, which is in accordance with the ephemeral nature of the river system. The changes simulated in this modelling exercise, a climate with less rainfall and coal mine operations that intercept rainfall and potentially increase the loss of surface water to groundwater, can only lead to a decrease in the low flow. As the P01 is already zero, it can decrease no more and it is therefore not necessary to explicitly compute the change in this hydrological response variable.

2.6.1.5.2 Qualitative uncertainty analysis

The major assumptions and model choices underpinning the Galilee subregion surface water model are listed in Table 8. 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 indicates 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. Again, a ‘low’ score indicates the same assumption would have been made with unlimited resources, while a ‘high’ score indicates the assumption is driven by resource constraints. The third attribute deals with the technical and computational issues. ‘High’ is assigned to assumptions and model choices that are dominantly driven by computational or technical limitations of the model code. These include issues related to spatial and temporal resolution of the models. The final and most important column is the effect of the assumption or model choice on the predictions. This is a qualitative assessment of the modelling team of the extent to which a model choice will affect the model predictions, with ‘low’ indicating a minimal effect and ‘high’ a large effect.

A detailed discussion of each of the assumptions, including the rationale for the scoring, follows 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 also seeks to assist in an open and transparent review of the modelling.

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

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

* Section of this product that contains more details on the assumption/model choice

2.6.1.5.2.1 Selection of calibration catchments

The parameters that control the transformation of rainfall into streamflow are adjusted based on a comparison of observed and simulated historical streamflow. Only a limited number of the model nodes have historical streamflow. The parameter combinations that achieve an acceptable agreement with observed flows are deemed acceptable for all model nodes 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 are scored low.

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 for the Galilee subregion and the effect on predictions is therefore deemed to be small.

While the regionalisation assumption is valid, the availability of additional calibration catchments may further constrain the predictions. However, the overall effect of the choice of calibration catchments on the predictions is still considered to be low.

2.6.1.5.2.2 High-flow and low-flow objective function

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

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

The high-streamflow objective function is a weighted sum of the Nash–Sutcliffe efficiency (E) and the bias. The former is most sensitive to differences in simulated and observed daily and monthly streamflow, while the latter is most affected by the discrepancy between long-term observed and simulated streamflow. The weighting of both components represents the trade-off between simulating short-term and long-term streamflow behaviour. It also reflects the fact that some parameters are more sensitive to daily behaviour and some are more sensitive to long-term hydrology.

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

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

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

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

The goodness-of-fit function for each hydrological response variable for uncertainty analysis has a very similar role to the objective function in calibration. Where the calibration focuses on identifying a single parameter set that provides an overall good fit between observed and simulated values, the uncertainty analysis aims to select an ensemble of parameter combinations that are best suited to make the chosen prediction.

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

The goodness-of-fit statistic is tailored to each hydrological response variable and averaged over the calibration catchments that contribute to flow to the modelling domain. This ensures parameter combinations are chosen that are able to simulate the specific part of the hydrograph relevant to the hydrological response variable, at a local scale. There are other ways to summarise the difference between observed and simulated values.

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 scores for these attributes.

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

2.6.1.5.2.4 Selection of acceptance threshold for uncertainty analysis

The acceptance threshold ideally is independently defined based on an analysis of the system (see companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016)). For the surface water hydrological response variables such an independent threshold definition can be based on the observation uncertainty, which depends on an analysis of the rating curves for each observation gauging station as well as at the model nodes. The resources required to carry out such an analysis are not justifiable within the BAs.

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.

2.6.1.5.2.5 Interaction with the groundwater model

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

Most of the streams in the model domain are ephemeral and considered to be disconnected from groundwater. Only the main channel of the Belyando River is considered to be connected with the alluvial groundwater system. The river system is mostly considered to be losing water to groundwater. In the weeks and months after major flood events, the groundwater sustains river flow. There are, however, very few joint observations of river flow and groundwater head in the alluvial groundwater systems to test these hypotheses. The data scarcity therefore warrants a medium score for the data column.

Even with more observations to infer the river – groundwater connection status, considerable resources would be required to generalise or establish a more detailed connection status, as most of the observations have only a very limited spatial support. This explains the medium score for resources.

The main assumption in the groundwater model is that the river is always connected and always able to provide water to groundwater. This is an overestimate of the available water and thus the estimated change in surface water – groundwater flux is also an overestimate.

In the tributaries of the stream network that are not included in the groundwater model (see Table 4 in Section 2.6.1.3), if the assumption of the disconnected status is not valid, the surface water – groundwater flux obviously is under estimated. A comparison of magnitude of the estimated fluxes compared to the magnitude of the direct impact of mines due to interception of runoff shows that the potential effect of underestimation of the surface water – groundwater flux is minor. The overall effect, therefore, is scored medium to reflect that while the perceived impact is minor, the large uncertainty in connection status warrants further research.

2.6.1.5.2.6 Implementation of the coal resource development pathway

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

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

2.6.1.5.2.7 No streamflow routing

Streamflow routing is not taken into account in the Galilee subregion as the system is unregulated. This also means that lags in streamflow as water moves down the river are not taken into account.

Inferring routing parameters from river channel characteristics is difficult due to the limited observation dataset so the data column is scored medium. With this information it would be possible, within the operational constraints and technical ability of the modelling team to simulate streamflow routing (hence low scoring in both columns).

Routing of flow, however, would only change the simulated daily flow. The effect on hydrological response variables, which are annual summaries, is insignificant. The effect on predictions is therefore scored low.

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2.6.1.6 Prediction

Summary

Section 2.6.1.6 summarises the predicted changes in eight hydrological response variables caused by the additional coal resource development in the Galilee subregion. The impacts on each model node 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 Galilee subregion can have substantial impact on the hydrological response variables. The comparison among the 61 model nodes shows that for the hydrological response variables that characterise high-streamflow conditions, the relative hydrological changes are largest for the model nodes where the maximum additional coal resource development percentage is largest. In general, the biggest impacts (flow reductions of up to 20%) occur immediately downstream of additional coal resource development and are particularly evident in model nodes where the footprint forms a large proportion of the node's catchment. For every high-streamflow hydrological response variable, the biggest impacts are predicted to occur at node 3 on Sandy Creek. This model node is located downstream of the South Galilee Coal Project.

The impacts due to the additional coal resource development on the low-streamflow hydrological response variables are more substantial than those on the high-streamflow hydrological response variables. However, they also appear to be associated with greater uncertainty in both the predicted change and the year of maximum change. For the low-streamflow variables the biggest impacts occur in the middle reaches of the Belyando River and reflect an accumulation of impacts from multiple developments.

These results also suggest that changes to low-streamflow characteristics are caused by a combination of the instantaneous impact of interception from the mine footprints and the cumulative impact on baseflow over time caused by drawdown of the watertable. The changes to high-streamflow characteristics are dominated by direct interception of runoff.

2.6.1.6.1 Introduction

Section 2.6.1.6 summarises the prediction results for eight hydrological response variables at 61 surface water model nodes. The eight hydrological response variables for streamflow are:

- AF – the annual flow volume (GL/year). This is the maximum value over the 90-year period (from 2013 to 2102)
- IQR – the interquartile range in daily flow (ML/day); that is, the difference between the daily streamflow rate at the 75th percentile and at the 25th percentile. This is the maximum value over the 90-year period (from 2013 to 2102)
- P99 – the daily flow rate at the 99th percentile (ML/day). This is the maximum value over the 90-year period (from 2013 to 2102)

- FD – the number of high-flow days per year. This is the maximum value over the 90-year period (from 2013 to 2102). The threshold for high-flow days is the 90th percentile from the simulated 90-year period (2013 to 2102). In some early products, this was referred to as 'flood days'
- ZFD – the number of zero-flow days per year. This is the maximum value over the 90-year period (from 2013 to 2102)
- LFD – the number of low-flow days per year. This is the maximum value over the 90-year period (from 2013 to 2102). The threshold for low-flow days is the 10th percentile from the simulated 90-year period
- LFS – the number of low-flow spells per year. This is the maximum value over the 90-year period (from 2013 to 2102). A spell is defined as a period of contiguous days of streamflow below the 10th percentile threshold
- LLFS – the length (days) of the longest low-flow spell each year. This is the maximum value over the 90-year period (from 2013 to 2102).

A ninth hydrological response variable defined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) – the daily streamflow rate at the 1st percentile (P01) – is excluded from the analysis. The P01 flow is not reported because all of the P01 observations are zero for the Galilee subregion.

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

For each model node, 10,000 sets of randomly selected parameter values were used to generate 10,000 replicates of development impact. A filter was applied to remove model runs in which future flow increases were due to overestimated streamflow persistence in the decades following the 2010–2011 floods. This reduced the number of replicates for result analyses to 3463. From these, the best 10% of total model replicates for each hydrological response variable, as assessed by their ability to predict that hydrological response variable at the observation sites, were chosen for further analysis.

Results are presented using a series of bar graphs for each hydrological response variable. Each bar graph was generated from the resulting 347 samples. The bar graphs show the distributions over the 347 replicates of the maximum raw change (*amax*) in each metric between the baseline and coal resource development pathway (CRDP) predictions, the corresponding maximum percentage change (*pmax*) and the year of maximum change (*tmax*). In general, the most meaningful diagnostic for the flux-based metrics (AF, IQR, P99 and FD) will be *pmax*, while the most meaningful diagnostic for the frequency-based metrics (ZFD, LFD, LFS and LLFS) will be *amax*. It is important to recognise that the *amax* and *pmax* values give the largest annual departure between the baseline and CRDP predictions for the respective hydrological response variables. As such, *amax* and *pmax* represent extreme responses. They do not represent the magnitudes of responses that would be expected to occur every year. The bar graphs show the distributions of these predictions of maximum impact from among the 347 replicates.

2.6.1.6.2 Results analysis

Annual flow

Figure 13 shows the hydrological changes to the annual flow (AF) at 61 model nodes. The biggest impact occurs at node 3 (the uppermost model node in Sandy Creek), where the median *pmax* is −21%. That is, of the reductions in streamflow between the baseline and CRDP from the 347 replicates, the median of the predicted maximum changes is 21%. There is a tightly constrained distribution of *pmax* values around this median value. At all other model nodes in Sandy Creek (tributary 10) the median reduction in *pmax* exceeds 9%.

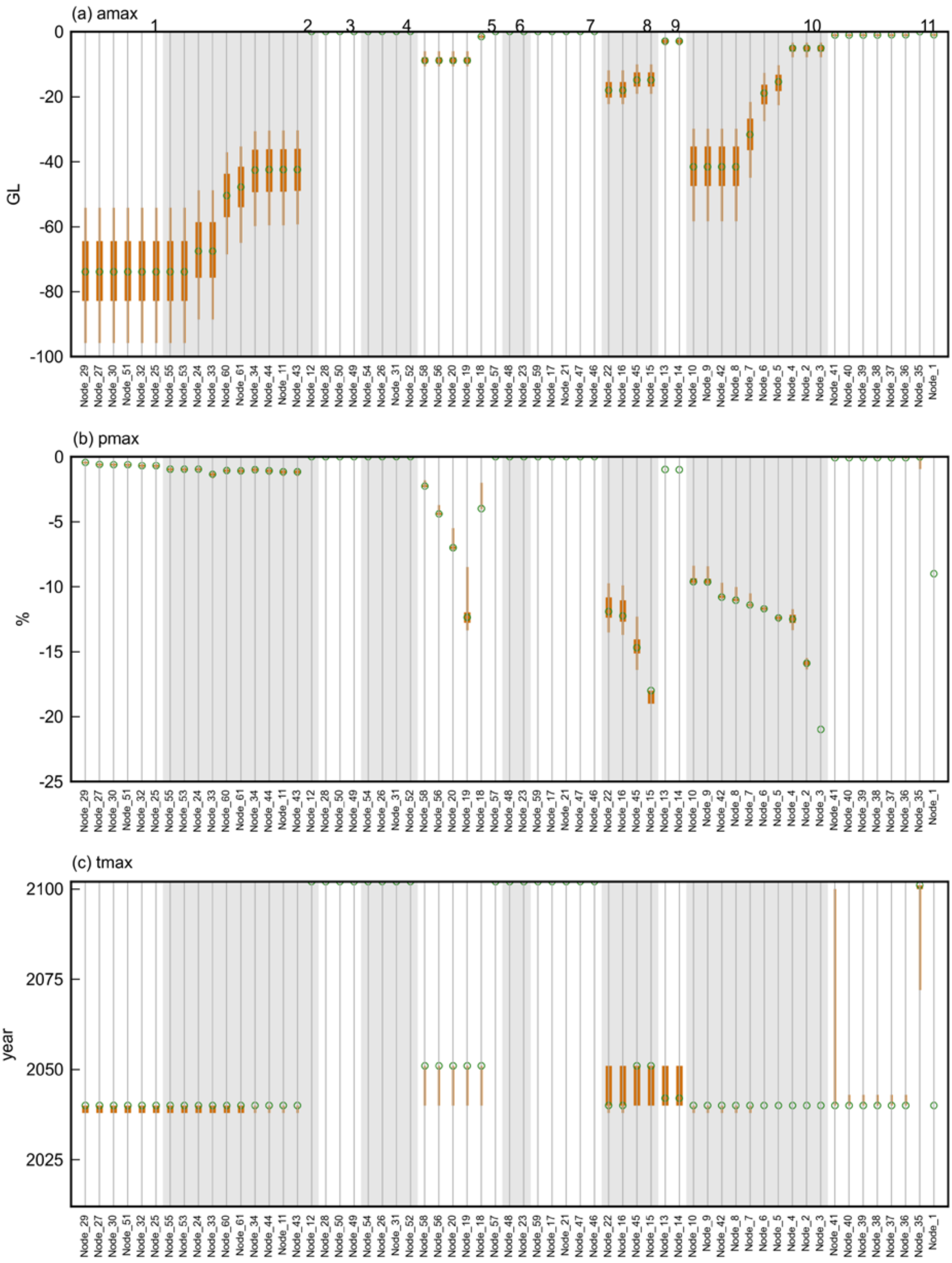

Figure 13 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percentage change (*pmax*) and (c) year of maximum change (*tmax*) for annual flow (AF) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
Data: Bioregional Assessment Programme (Dataset 1)

Elsewhere, there are median reductions of between 12% and 18% in North Creek (tributary 8), up to 12% in Bully Creek (tributary 5) and up to 9% at node 1 which is on a tributary of Native Companion Creek (tributary 11). In the Belyando River (tributary 2) the median impact on *pmax* is less than 2%, while further downstream in the Suttor River (tributary 1) the median impact is less than 1% and corresponds to a decrease in flow of about 75 ML/day (or 28 GL/year). The additional coal resource development has no impact at all on AF in tributaries 3, 4, 6 and 7.

The maximum changes in AF occur in 2040 at most of the model nodes in tributaries 11, 10, 2 and 1 and there is little uncertainty in these years of maximum change. There is greater uncertainty in *tmax* at the model nodes in tributaries 9, 8 and 5, where the median *tmax* values occur between 2040 and 2051.

Nodes 3 and 1 have relatively small catchment areas which both contain parts of the South Galilee Coal Project. The projected changes in *pmax* at these locations are similar in magnitude to the proportion of their catchment areas that are included in the mine footprint (24% and 10%, respectively, Table 4 in Section 2.6.1.3). The model nodes in tributary 8 are downstream of the proposed Carmichael Coal Mine Project and the China Stone Coal Project, while most of the model nodes in tributary 5 are downstream of the Hyde Park Coal Project.

Among the most heavily impacted model nodes, the largest uncertainties in *pmax* occur in tributaries 5 and 8 (Carmichael River and North Creek, respectively). The impact on *pmax* at node 35 (Native Companion Creek) is very small for most replicates, but the 5th percentile change is 4% and the year of maximum change (the median *tmax* is in 2093) is much later than at other model nodes. This model node is upstream of all coal mines, but does have interaction with the groundwater model, so the only source of flow perturbation is through reductions in baseflow associated with groundwater drawdown.

Interquartile range

Figure 14 shows the changes to the interquartile range (IQR) in AF. As for AF, the largest median *pmax* values occur in tributaries 10 and 8. The median reductions in IQR vary between 10% and 21% in tributary 10 (Sandy Creek) and between 17% and 19% in tributary 8 (North Creek). Although the median changes in tributaries 2 and 11 are smaller, there is greater uncertainty at some model nodes with some extreme replicates having predicted IQR reductions in excess of 60%.

The median *tmax* values for IQR are almost all in 2040, though some of the model nodes in tributary 11 (Native Companion Creek) have median *tmax* values of 2043 and are associated with considerable uncertainty.

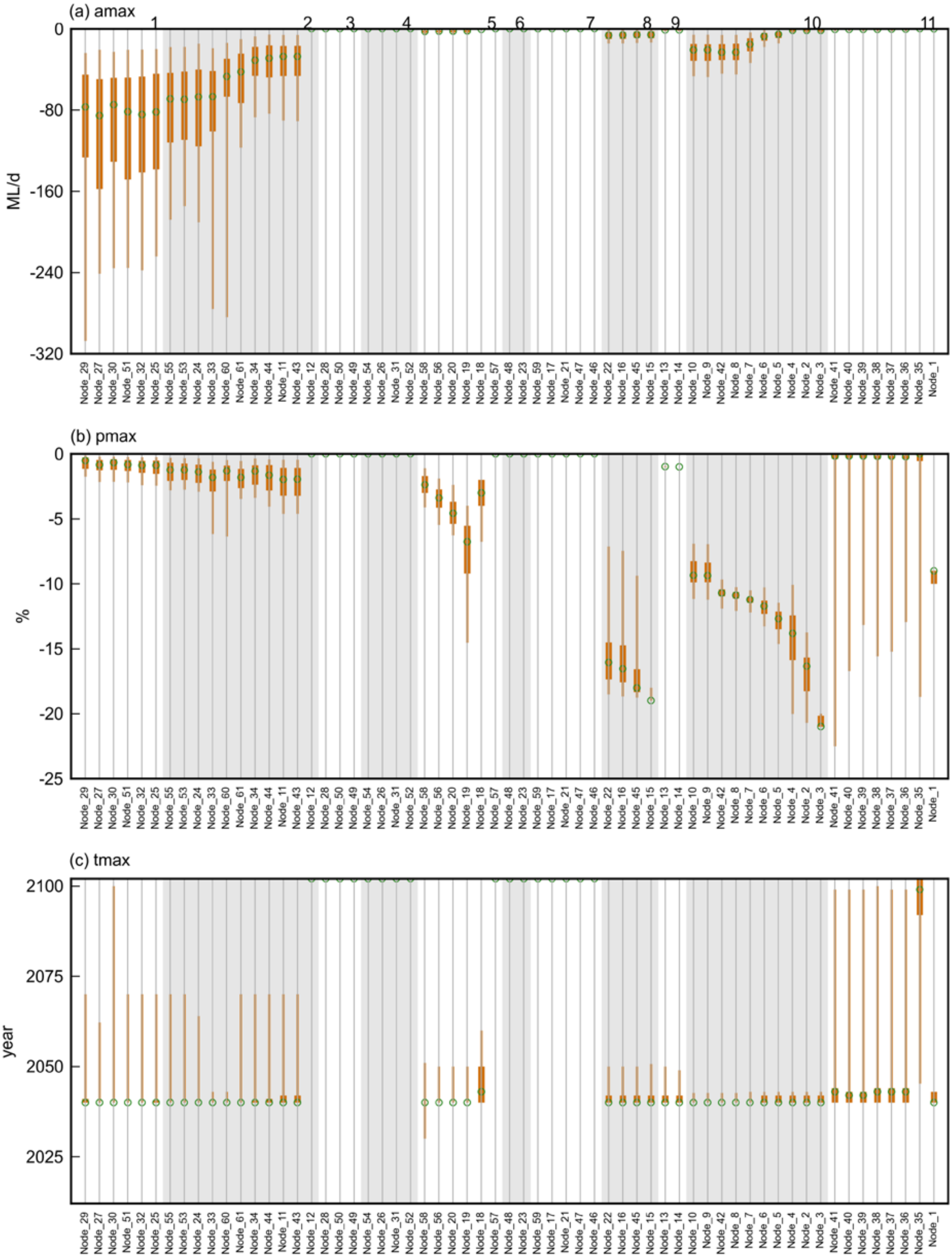

Figure 14 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for interquartile range (IQR) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
Data: Bioregional Assessment Programme (Dataset 1)

99th percentile

Figure 15 shows the decrease in daily streamflow rate at the 99th percentile (P99) in the 61 model nodes. Again, the biggest median reductions are in tributaries 10 (21% at node 3) and 8 (19% at node 15). However, there are also substantial impacts predicted for nodes 19 and 1 with reductions of 12% and 9%, respectively. The median year of maximum change in P99 remains 2040 in tributaries 10 and 11, but is slightly earlier (2038) in some model nodes in tributaries 1, 2 and 5, and slightly later in tributaries 8 (2042) and 9 (2051).

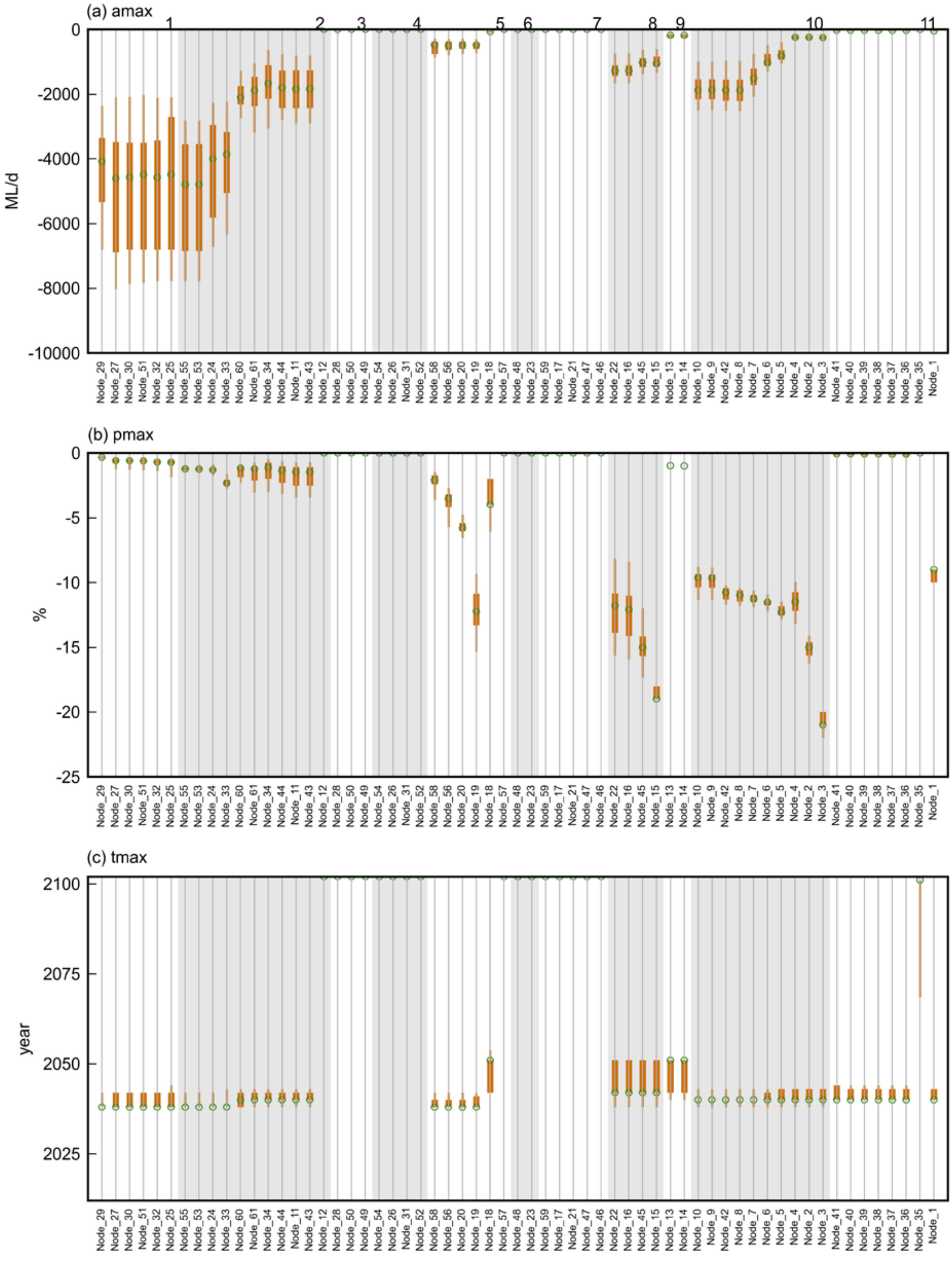

Figure 15 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the daily streamflow rate at the 99th percentile (P99) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
Data: Bioregional Assessment Programme (Dataset 1)

Flood (high-flow) days

Figure 16 shows the changes to the number of flood (high-flow) days (FD) at the 61 model nodes. There are reductions in median *amax* of up to 31 days in tributary 10, up to 24 days in tributary 8 and up to 15 days in tributary 11. However, there is much greater uncertainty around changes in the number of high-flow days (and in the timing of the maximum impacts) than there is for changes in annual flow.

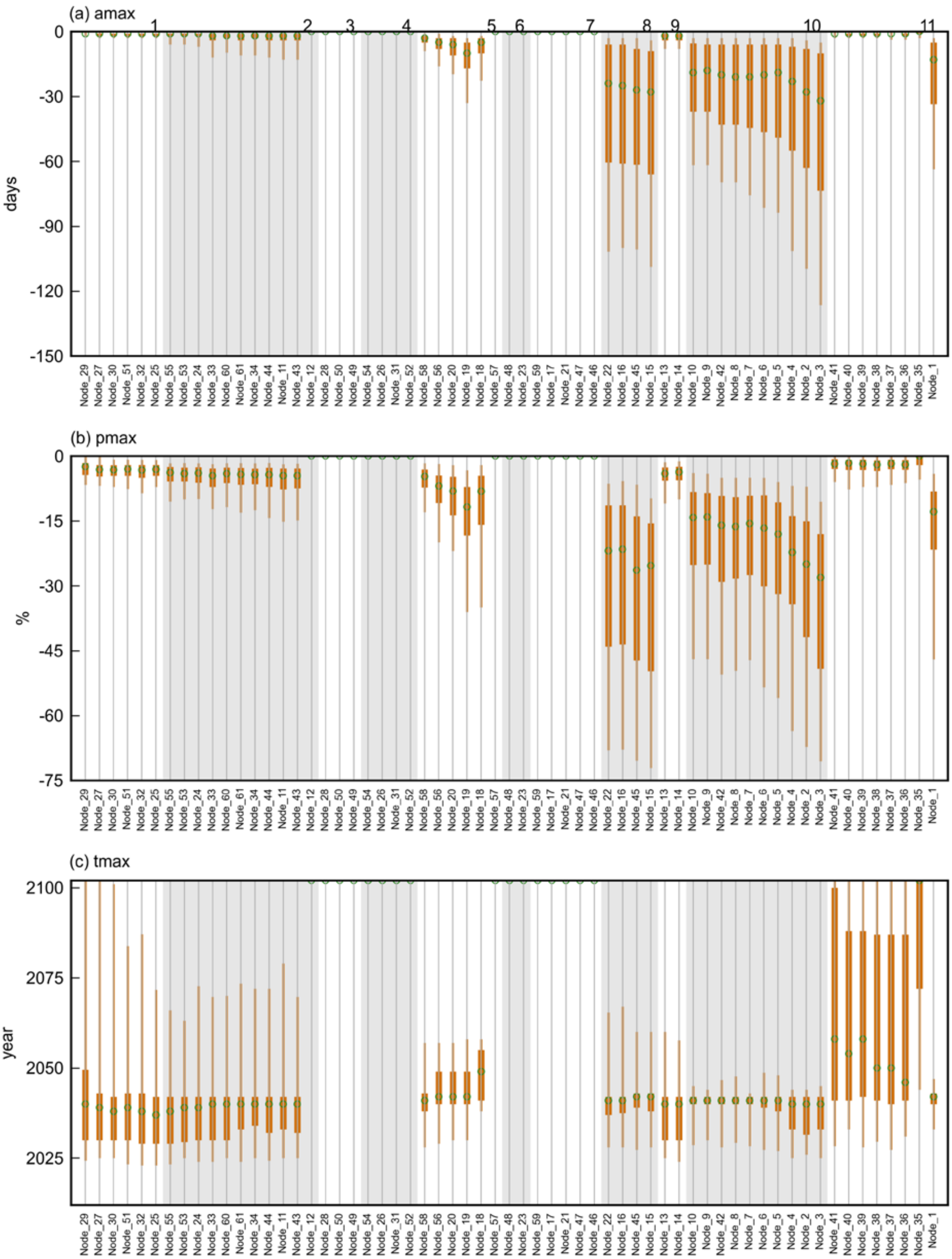

Figure 16 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of flood (high-flow) days (FD) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
Data: Bioregional Assessment Programme (Dataset 1)

Zero-flow days

The remaining results figures characterise the changes for the low-streamflow hydrological response variables. Figure 17 shows the changes to the number of zero-flow days (ZFD) at the 61 model nodes. The biggest changes are in the lower parts of the Belyando River (tributaries 1 and 2) where the median number of ZFD increase by more than 75 days per year in the reaches between nodes 34 and 32. The increases exceed 65 days further downstream in the Suttor River (tributary 1). Elsewhere, there are predicted median increases in ZFD of up to 16 days in Native Companion Creek (tributary 11) with the increases getting larger with distance downstream. In all model nodes with substantial increases in ZFD, there is considerable uncertainty in the *amax* values.

The increases in ZFD in tributaries 1, 2 and 11 tend to occur relatively late in the simulation period, with median predicted *tmax* values occurring later than 2080. In other model nodes with less substantial increases in ZFD, the median year of maximum change is earlier and occurs between 2030 and 2050.

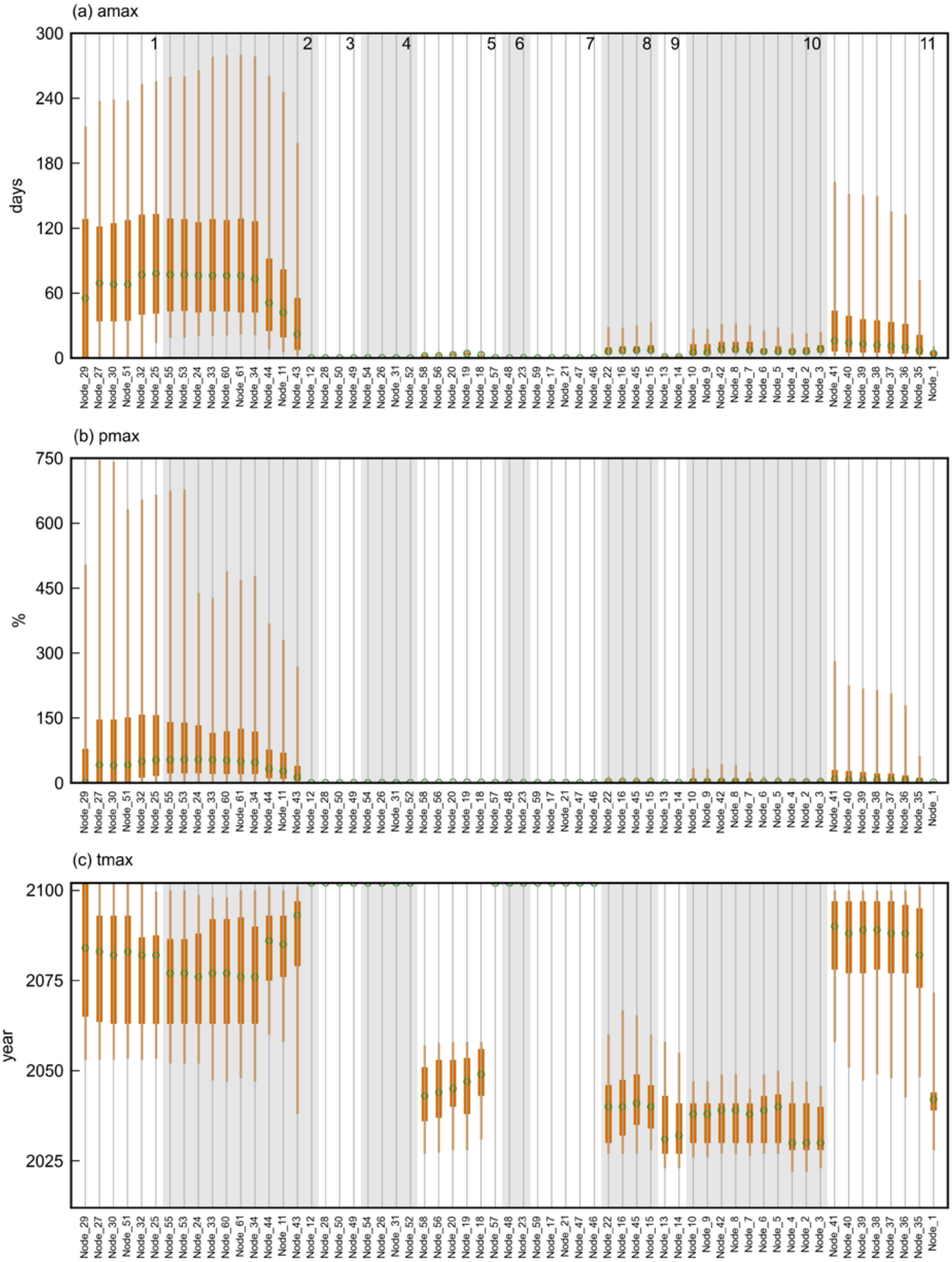

Figure 17 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of zero-flow days (ZFD) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
Data: Bioregional Assessment Programme (Dataset 1)

Low-flow days

Figure 18 shows the predicted changes to low-flow days (LFD), the number of days per year the flow is less than the long-term 10th percentile, at 61 model nodes. As for ZFD, the largest changes in the frequency of LFD occur in tributaries 1 and 2, where median increases in the predicted maximum annual difference between the two development pathways are between 100 and 200 days. Increases of LFD of more than 40 days per year are predicted for some model nodes in Sandy Creek and Native Companion Creek (tributaries 10 and 11, respectively).

Years of maximum change in LFD reflect those for ZFD, with later median *tmax* values being predicted for tributaries 1, 2 and 11 contrasting with earlier *tmax* values for model nodes in tributaries 8 and 10.

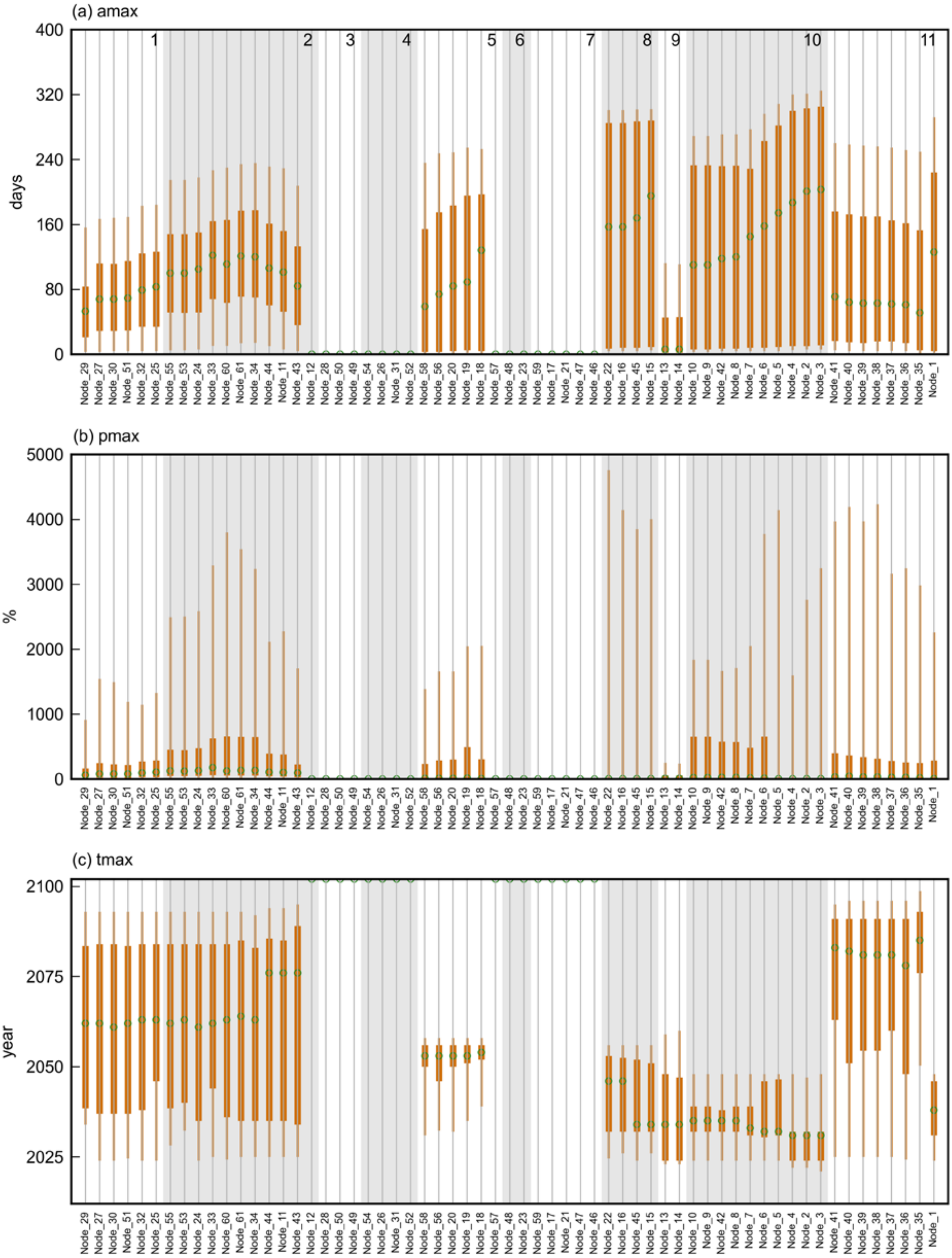

Figure 18 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of low-flow days (LFD) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
Data: Bioregional Assessment Programme (Dataset 1)

Low-flow spells

Figure 19 shows the changes to the number of low-flow spells (LFS) at the 61 model nodes. The maximum annual number of LFS across the modelling domain is simulated to increase by a median of up to 10 events. Median maximum increases of more than five events per year are predicted for some model nodes in tributaries 1, 2, 5 and 10, with smaller median increases in tributaries 8, 9 and 11. Maximum changes in LFS are likely to occur before 2050 in all parts of the subregion, except tributary 11, where median *tmax* values of between 2061 and 2075 are predicted.

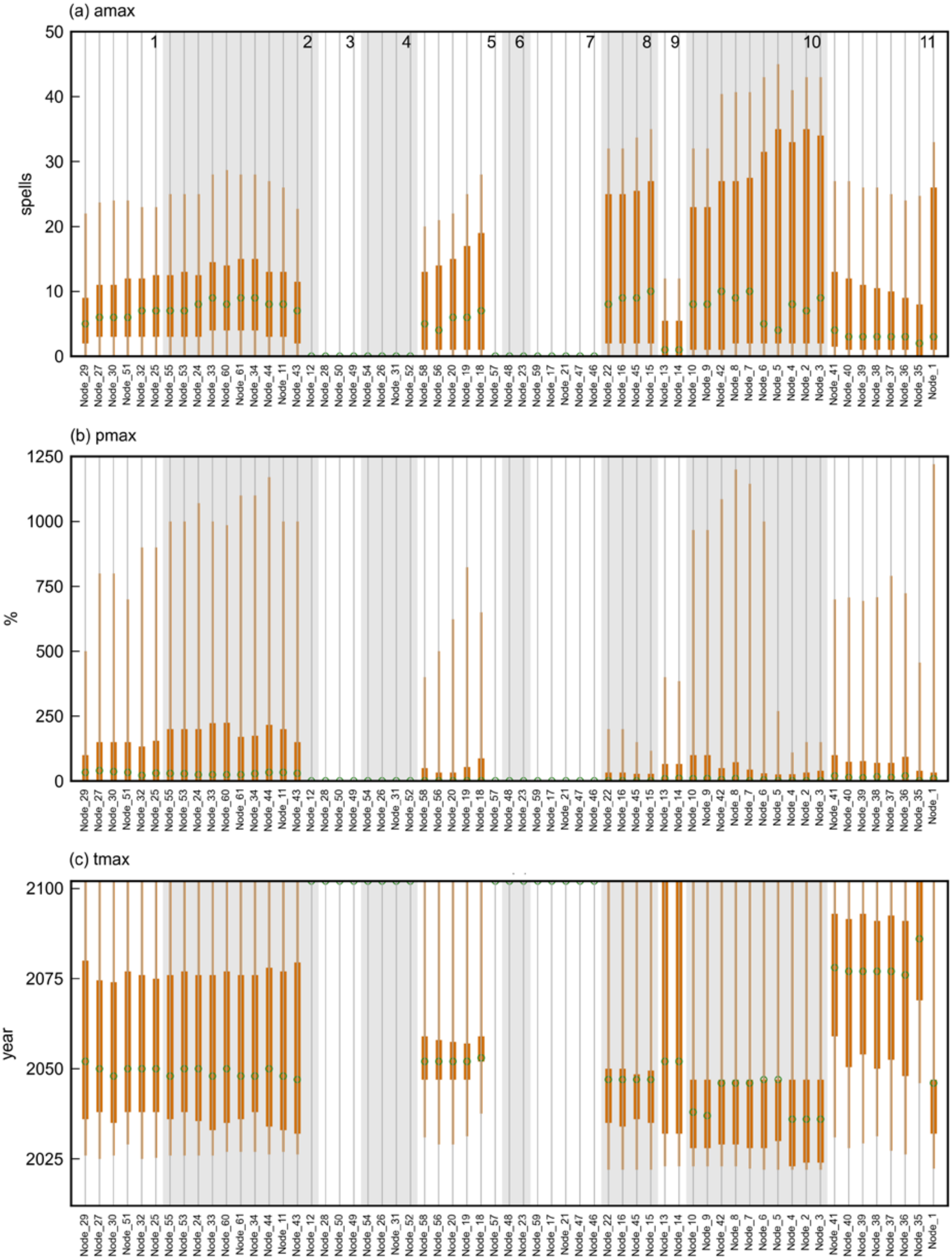

Figure 19 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the number of low-flow spells (LFS) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
Data: Bioregional Assessment Programme (Dataset 1)

Longest low-flow spell

Figure 20 shows the maximum changes to the length of the longest low-flow spell (LLFS) at the 61 model nodes. The longest low-flow spell is projected to increase in length by about 70 days between nodes 34 and 33 in the Belyando River (tributary 2). Other substantial increases in LLFS (by more than 20 days) are predicted for tributaries 1, 8, 10 and 11. The large changes in LLFS are likely to occur between 2065 and 2081 in tributaries 1, 2 and 11, but between 2032 and 2043 in tributaries 8 and 10.

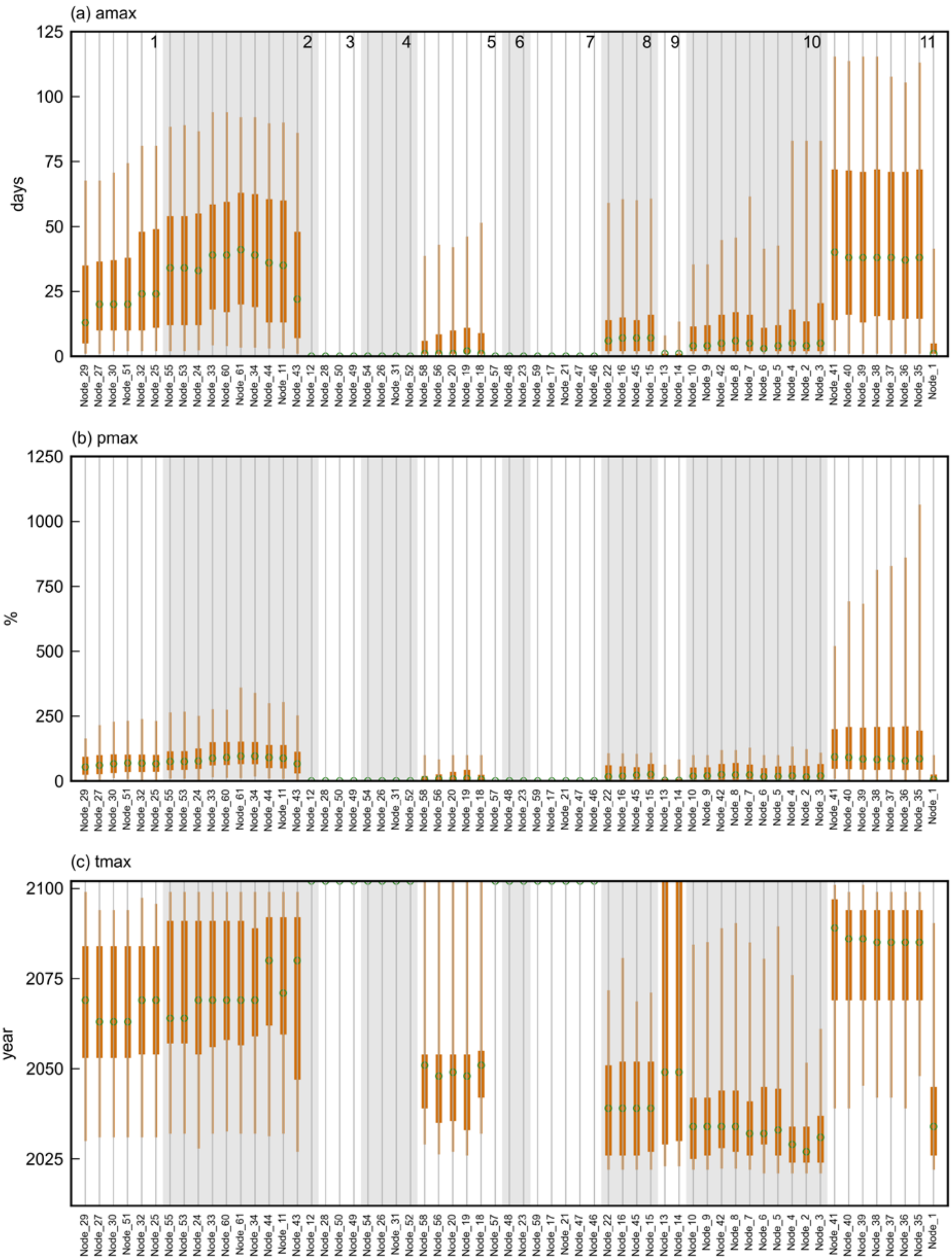

Figure 20 Predictive distribution of (a) maximum raw change (*amax*), (b) maximum percent change (*pmax*) and (c) year of maximum change (*tmax*) for the length of the longest low-flow spell (LLFS) at the 61 model nodes in the Galilee subregion

The alternating grey and white shaded zones indicate which surface water model nodes belong to each of the 11 tributaries that comprise the surface water modelling domain in the Galilee subregion. These are numbered at the top of the uppermost figure and are described in more detail in Table 4 and shown in the map on Figure 9. The circle indicates the median prediction, the thick orange vertical line spans the 25th and 75th percentiles and the thin orange vertical line spans the 5th and 95th percentiles.
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 Galilee subregion can have considerable impacts on all of the hydrological response variables. The comparison among the 61 model nodes shows that the relative hydrological changes are larger for the model nodes where the maximum additional coal resource development percentage is larger. For instance, the model nodes with the three largest additional coal resource development footprints are nodes 3, 15 and 2, where the maximum percentage increases in footprint are 24%, 19% and 17%, respectively. The resulting median *pmax* values for the three high-streamflow flux-based variables (AF, P99 and IQR) are around –21% for node 3, –19% for node 15, and –16% for node 2. In general, the median impact on these variables is highly correlated with and commensurate with the maximum proportion of the catchment that is included in the additional coal resource development footprint.

For each of the flux-based hydrological response variables, the biggest impacts (in terms of *pmax*) are predicted to occur at nodes 3 and 15. Node 3 is located downstream of the additional coal resource development expansions to the South Galilee Coal Project, while node 15 is downstream of the China Stone Coal Project and Carmichael Coal Mine Project. Both nodes 3 and 15 have relatively small catchment areas. While there are bigger predicted changes in *amax* at model nodes further downstream, the proportional impacts of these changes are diluted by relatively unaffected inflows.

In contrast, the biggest impacts (in terms of *amax*) on the low-streamflow hydrological response variables are predicted to occur further downstream at node 7 (in Sandy Creek) for LFS and at nodes 34 and 61 (in the Belyando River) for ZFD, LFD and LLFS. Node 7 is wholly or partly downstream of all four mine developments along Sandy Creek (Kevin's Corner, Alpha, China First and South Galilee coal projects). In addition to being downstream of these same developments, nodes 34 and 61 are either partly downstream of, or affected by groundwater drawdown associated with, the proposed Carmichael Coal Mine Project.

The prediction that the biggest impacts occur downstream of multiple mine developments highlights the cumulative nature of potential hydrological impacts, particularly on low-streamflow characteristics. These impacts, however, are not quite as large further down the Belyando River, despite the potential for further additional coal resource development impacts from the proposed Carmichael Coal Mine Project and the China Stone and Hyde Park coal projects. This suggests that, with augmentation from unaffected tributaries such as the upper Carmichael River, Tomahawk Creek and Mistake Creek, low flows are more stable in the reaches below node 61.

The additional coal resource development impacts on the low-streamflow hydrological response variables (ZFD, LFD, LFS and LLFS) appear to be less substantial than those on the high-streamflow hydrological response variables (AF, P99 and FD) for model nodes immediately downstream of mine developments, but more substantial for nodes further downstream of the developments and where impacts from multiple developments accrue. This is demonstrated by comparison of the two frequency-based variables that are most directly comparable – FD and LFD. In model nodes immediately downstream of the developments, the impact (in absolute terms) on FD is greater than on LFD. For example, at node 3, FD decreases by 24 days, while LFD increases by only 15 days. On the other hand, further downstream at node 61, where the impacts of several coal mines accumulate, FD decreases by 3 days, while LFD increases by 200 days.

The magnitude of some of the changes in ZFD and LFD are particularly noteworthy, especially as these variables are likely to be particularly important in an ecological context. Median maximum increases of 200 days per year in LFD in the middle reaches of the Belyando River represent more than half the year. While this change reports the median of the greatest predicted annual change among the 347 replicates, and is therefore not expected to occur every year, it nonetheless represents a substantial reduction in flow characteristics.

The change in hydrology predicted due to the additional coal resource development is largest in absolute terms at the downstream end of the Belyando River system, where a median maximum decrease of about 28 GL in AF is predicted, which corresponds to a change of less than 1%. The relative decrease is largest in the model nodes immediately downstream of mines, with median decreases of up to 20% downstream of the South Galilee Coal Project and the proposed Carmichael Coal Mine Project.

For high-streamflow hydrological response variables, the *tmax* at model nodes with noticeable changes occurs approximately when the maximum additional coal resource development occurs. For most such model nodes, this is 2040. This indicates that the instantaneous streamflow reduction caused by the additional mine footprint dominates *amax* and *pmax* in these hydrological response variables and suggests that the changes from the cumulative impact on baseflow over time caused by drawdown of the watertable are negligible.

For low-streamflow hydrological response variables, the *tmax* at model nodes with noticeable changes does not occur consistently with the time when the maximum additional coal resource development footprint occurs. At the most heavily impacted model nodes (those in tributary 2), the predicted median *tmax* values tend to be a little later for three of the low-streamflow hydrological response variables (ZFD, LFD and LLFS), with the greatest impacts typically being predicted to be after 2060. This is much later than the times of maximum additional coal resource development footprint (Table 4). This indicates that the causes of the impacts on the low-streamflow 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 drawdown of the watertable.

Further discussion on the implications of changes to surface water hydrological response variables and their potential for impact to surface water systems are outlined in Section 3.3 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018).

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Viney NR (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) GAL AWRA-L Model v01. Bioregional Assessment Derived Dataset. Viewed 31 October 2017, http://data.bioregionalassessments.gov.au/dataset/85fb8186-8455-4f58-8253-d065fa79f775.

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

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

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

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.

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

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

baseline drawdown: the maximum difference in drawdown (dmax) under the baseline relative to no coal resource development

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.

causal pathway: for the purposes of bioregional assessments, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets

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

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)

diversion: see extraction

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

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

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

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

Galilee subregion: The Galilee subregion is part of the Lake Eyre Basin bioregion and is entirely within Queensland. It extends westwards across the Great Dividing Range and into the Lake Eyre drainage basin. The subregion is sparsely populated, with most people living in towns and localities including Charleville, Barcaldine, Blackall and Hughenden. The subregion encompasses the headwaters of several major waterways including the Cooper Creek and the Diamantina, Belyando, Cape, Thomson, Barcoo, Flinders, Bulloo, and Warrego rivers. In addition to the river systems, the subregion has numerous wetlands, springs, waterholes and lakes, including the nationally important lakes Buchanan and Galilee. Some of these are home to diverse and unique plants and animals, many of which are listed as rare or threatened under Queensland and Commonwealth legislation. Native vegetation consists largely of grasslands in the west and open eucalyptus woodlands in the east. Cattle and sheep grazing on native pasture is the main land use and groundwater is of great importance.

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

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

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

groundwater system: see water system

hazard: an event, or chain of events, that might result in an effect (change in the quality and/or quantity of surface water or groundwater)

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

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

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

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

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

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

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

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

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

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

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

likelihood: probability that something might happen

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

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

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

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

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

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

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

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

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

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

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

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

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

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

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

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)

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

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

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

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