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

Australian Government

BIOREGIONAL ASSESSMENTS

Impact and risk analysis for the Hunter subregion

Product 3-4 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment

2018

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

The Bioregional Assessment Programme

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

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

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

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Authorship is listed in relative order of contribution.

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Cover photograph

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

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

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Executive summary

The impact and risk analysis for the Hunter subregion is a regional overview of potential impacts on, and risks to, water resources and water-dependent ecological, economic and sociocultural assets. Hydrological and ecosystem changes due to coal resource development are quantified and impacts that are *very unlikely* (less than 5% chance) are ruled out.

Results of regional-scale hydrological modelling indicate potential risks to Wyong River and Saddlers, Loders and Wollar creeks due to additional coal resource development. More detailed local-scale information is required to determine the level of risk and potential impacts.

The Hunter subregion is just over 17,000 km^2 and is located north of Sydney, NSW. The Hunter subregion straddles three of the five coalfields that make up the Sydney geological basin: mainly the Hunter and Newcastle coalfields and part of the Western Coalfield.

Coal resources

The impact and risk analysis considered two potential coal resource development futures:

- *baseline coal resource development (baseline)*: a future that includes all coal mines and coal seam gas (CSG) fields that were commercially producing as of December 2012. In the Hunter subregion, this includes 42 mining operations, comprising 22 open-cut mines and 20 underground mines
- *coal resource development pathway (CRDP)*: a future that includes all coal mines and CSG fields that are in the baseline as well as the additional coal resource development (those that were expected to begin commercial production after December 2012). In the Hunter subregion, the additional coal resource development includes 22 proposals, including 4 new open-cut coal mines, 2 new underground coal mines and 16 expansions to baseline mining operations. As of May 2015, there is no CSG production in the Hunter subregion, nor any proposals for CSG development in the future.

The difference in results between CRDP and baseline is the change that is primarily reported in a bioregional assessment (BA). This change is due to the *additional coal resource development*.

Zone of potential hydrological change

The zone of potential hydrological change covers an area of 3213 km^2 (19% of the assessment extent). The zone is the union of the groundwater zone of potential hydrological change and the surface water zone of potential hydrological change:

- The *groundwater zone of potential hydrological change* is defined as the area with at least a 5% chance of exceeding 0.2 m of drawdown in the regional watertable. In the Hunter subregion, it spans an area of 2441 km^2 and comprises five discrete drawdown areas.
- The *surface water zone of potential hydrological change* incorporates a total stream length of 1228 km where a change in any one of the nine surface water hydrological response

variables has at least a 5% chance of exceeding its specified threshold. The thresholds can be generally described as at least a 5% chance of a 1% (or 3 day) or greater change in a flow volume or frequency.

The zone was used to rule out potential impacts on ecosystems and water-dependent assets within the Hunter assessment extent. Water resources and water-dependent assets outside the zone are *very unlikely* to be impacted.

Potential hydrological changes

Groundwater

Results from regional groundwater modelling show cumulative drawdowns of greater than 0.2 m due to additional coal resource development is *very likely* (greater than 95% chance) at distances of up to 5 km from mine sites and *very unlikely* to occur at distances exceeding 20 km.

Results of the groundwater modelling of drawdown extent suggest it is:

- *very likely* that an area of at least 528 km^2 exceeds 0.2 m of drawdown and *very unlikely* that more than 2441 km^2 exceeds 0.2 m of drawdown (Figure 19 and Table 8)
- *very likely* that an area of at least 121 km^2 exceeds 2 m of drawdown and *very unlikely* that more than 927 km^2 exceeds 2 m of drawdown (Figure 19 and Table 8)
- *very likely* that an area of at least 35 km^2 exceeds 5 m of drawdown and *very unlikely* that more than 524 km^2 exceeds 5 m of drawdown (Figure 19 and Table 8).

When drawdown predictions are constrained using local information, the range of predicted drawdown extent can be reduced. For example, drawdown extents predicted around Wallarah 2 based on local hydrogeological information are predicted to be smaller than extents based on the regional parameter set (Section 3.3.2).

Surface water

Changes in streamflow regimes due to additional coal resource development were assessed using three hydrological response variables, which characterise the low-flow and high-flow parts of the flow regime, as well as total flow (Table 6).

The largest flow regime changes are modelled to occur downstream of multiple mine developments, reflecting the cumulative nature of potential hydrological changes. Results of regional-scale modelling suggest large changes in flow regime are *possible* as a result of additional coal resource development in Loders Creek, Dry Creek and two unnamed creeks near the Mount Pleasant and Mount Thorley–Warkworth coal mines. Dry Creek and the unnamed creeks are small and the hydrological changes are localised. The Hunter Regulated River, into which these creeks flow, is not very sensitive to changes from these creeks (Section 3.3.3).

Wollar Creek, Saddlers Creek and the Wyong River are modelled to have relatively large hydrological changes at the 50th percentile. Wollar Creek, Saddlers and Loders Creek do have a hydrological effect on the Goulburn and Hunter rivers into which they flow. However, changes in baseflow to the Goulburn and Hunter rivers due to groundwater drawdown could be more significant than changes in tributary inflows on Goulburn River and Hunter River flows (Section 3.3.3.).

Results for the Hunter Regulated River show that decreases in mean annual flow of between 1% and 2% are *very likely*. These changes need to be interpreted with caution, since the Australian Water Resources Assessment river model (AWRA-R) has not been constructed to specifically represent operational management of releases from Glenbawn and Glennies Creek storages.

The potentially large changes in hydrology predicted in the Wyong River reduce considerably when the regional results are constrained using local information. The small chance of at least 200 or more low-flow days per year based on the regional analysis becomes a small chance of at least 7 additional low-flow days when the baseflows from the groundwater model are based on local hydrogeological data.

Generally, the modelled changes are small relative to the interannual variability due to climate, especially for high-flow (Figure 27) and annual flow (Figure 28) days. There is a chance that changes in low-flow days could significantly impact the values associated with streams near all the mining areas, with smaller intermittent and perennial streams close to Central Hunter and Lower Hunter additional coal resource developments particularly at risk (Figure 24). Areas identified as at risk of large hydrological changes require further investigation using local-scale information.

Water quality

Any change in hydrology could result in changes in groundwater and/or stream water quality but this was not modelled. However, the implications for stream salinity in the Hunter subregion were considered in light of the modelled hydrological changes due to additional coal resource development, salinity hazard mapping and existing regulatory controls (Section 3.3.4). Some of the streams identified as at risk of potentially large hydrological changes, such as Loders Creek and Saddlers Creek, are naturally highly saline, and this would be expected to influence the management response to the predicted hydrological changes.

A range of regulatory requirements are in place in NSW that are intended to minimise potential water quality impacts from coal resource development. For example, in the Hunter Regulated River, a salinity trading scheme manages mine and industry discharges to the river to acceptable levels. Modelling results suggest there will be negligible impact on the number of high-flow days when discharge is permitted under the scheme.

Changes in stream salinity cannot be ruled out. Groundwater is typically more saline than surface runoff. This suggests that reductions in baseflow are more likely to lead to decreases in stream salinity, while reductions in catchment runoff could lead to increases in salinity. The actual effects depend very much on local conditions and relative changes in surface water and groundwater components of the streamflow.

Impacts on, and risks to, landscape classes

The impact and risk analysis investigates how hydrological changes due to additional coal resource development may affect ecosystems at a landscape scale. In the Hunter subregion these ecosystems are classified into landscape classes and aggregated into five landscape groups: ‘Riverine’, ‘Groundwater-dependent ecosystem (GDE)’, ‘Coastal lakes and estuaries’, ‘Non-GDE vegetation’ and ‘Economic land use’.

The vast majority (3012 km^2 or 94%) of the zone of potential hydrological change includes the ‘Non-GDE vegetation’ landscape group, which is not water dependent, and the ‘Economic land use’ landscape group.

Estimates of overall ecosystem risk integrate understanding from the conceptual model of causal pathways, hydrological modelling and expert opinion. The strength of this approach is that it provides a measure of relative risk and emphasises where attention should focus, and also where it should not. In the Hunter subregion estimates for overall ecosystem risk were informed by six receptor impact models in five landscape classes.

‘Riverine’ landscape group

Permanent or perennial streams – Potentially large hydrological changes are possible along reaches of the Wyong River, and possibly Dora Creek, in the Macquarie-Tuggerah lakes basin, with potential for adverse ecological impacts. Results from receptor impact modelling, which predicts changes in the probability of presence of riffle-breeding frogs and densities of riffle-dwelling caddisfly larvae (Hydropsychidae), suggest that instream habitats of these streams could be impacted. However, when local hydrogeological information is used to constrain the hydrological change predictions in this area, the likelihood of potentially significant changes in instream habitat is low. Elsewhere in the subregion, it is *very unlikely* that instream habitats of permanent or perennial streams are impacted (Section 3.4.3.3.1).

Lowly to highly intermittent streams – Potentially large hydrological changes are possible in Saddlers and Loders creeks in the Hunter Basin. Results from receptor impact modelling, which predicts changes in the probability of presence of riffle-breeding frogs and richness of invertebrate hyporheic taxa, indicate a risk of adverse impacts upon instream habitats in these intermittent systems. Instream habitats of other intermittent streams near all additional coal resource developments are also potentially impacted, but the hydrological changes in these streams were not modelled. Local information is needed to determine the actual risk, having regard to stream condition, habitat diversity, other catchment stressors and recovery potential. (Section 3.4.3.3.2).

‘Groundwater-dependent ecosystem (GDE)’ landscape group

Wet sclerophyll forests and dry sclerophyll forests – Overall, the modelled results suggest little detectable impact on the condition of wet sclerophyll forests and dry sclerophyll forests in the Hunter subregion due to additional coal resource development. Results from receptor impact modelling, which predicts changes in projected foliage cover, suggest there is a 5% chance that 10 to 15 km^2 of mainly dry sclerophyll forests in the Macquarie-Tuggerah lakes basin may be subjected to adverse ecological impacts, although risk is much reduced when the groundwater modelling result are constrained by local hydrogeological information (Section 3.4.4.3.1).

Forested wetlands – Nearly all the riverine forested wetlands in the Hunter and Goulburn basins are potentially subject to drawdown of less than 2 m, and about 2.6 km^2 of the coastal forested wetlands are potentially subject to drawdown of more than 2 m (Section 3.4.4.2.1.). Results from receptor impact modelling, which are based on predicted changes in projected foliage cover, suggest little likelihood of impacts on riverine forested wetlands along unregulated rivers in the Hunter river basin. The model is not considered appropriate for application to the regulated river. Riverine forested wetlands along the Goulburn River are identified as more at risk, but the significance of this risk can only be determined through more local information (Section 3.4.4.3.2). The ecological impact on the coastal forested wetlands in the Macquarie-Tuggerah lakes basin was not represented in the receptor impact model.

Rainforests – Most communities are unlikely to be impacted, because if they are dependent on groundwater at all, it is local groundwater sources. The exception are the riparian rainforests of the Wyong River catchment, which, given they occupy the same landscape position as the 'Forested wetland' landscape class (i.e. alluvium along perennial streams), are likely to have a dependency on streamflow and alluvial groundwater. They are potentially impacted by changes in groundwater levels and streamflow due to the proposed Wallarah 2 and Mandalong Southern Extension developments, but are not explicitly represented in any of the qualitative or quantitative models developed for the landscape classes.

Freshwater wetlands – Experts were uncertain about the groundwater dependencies of these systems and their sensitivity to potential hydrological changes from underground coal mining higher up in the catchment. It was thought that tidal fluctuations influence water levels in the lagoons and that any drawdown would be compensated by the inflow of seawater intrusion, leading to no change in water levels, but potential changes in salinity of the wetland water. Given the lack of certainty about the key driving processes, a quantitative model was not developed for this landscape class. The potential for ecological impacts on this landscape class is a knowledge gap.

Semi-arid woodlands, heathlands and grassy woodlands – These landscape classes are *very unlikely* to be impacted because they are located almost exclusively outside the zone of potential hydrological change.

Springs – This landscape class is represented by four assets within the water-dependent asset register for the Hunter subregion. None of these four assets intersects the zone of potential hydrological change. This landscape class is considered *very unlikely* to be impacted by additional coal resource development.

Impacts on, and risks to, water-dependent assets

Ecological assets

The Hunter subregion has 1652 ecological assets in the assessment extent. The 921 ecological assets outside the zone are considered to be *very unlikely* (less than 5% chance) to be impacted due to additional coal resource development in the Hunter subregion.

Out of the 731 assets in the zone of potential hydrological change 210 are identified as being 'more at risk of hydrological changes' because all or part of the area where the assets occur is within one or more of the potentially impacted landscape groups and there is a greater than 50% chance of the modelled hydrological change exceeding the defined threshold for the relevant landscape class (Section 3.5.2.1). These assets include:

- One endangered ecological community (EEC), the Hinterland Spotted Gum EEC, where 3.6 km^2 is in the zone and of this 1.3 km^2 is associated with wet and dry sclerophyll forests (Figure 70).
- Twenty-three potential habitats of species listed by the state or Commonwealth including the regent honeyeater (*Anthochaera phrygia*), swift parrot (*Lathamus discolor*) and koala (*Phascolarctos cinereus*). Some species, including migratory species such as the black-faced monarch (*Monarcha melanopsis*), cattle egret (*Ardea ibis*), fork-tailed swift (*Apus pacificus*), great egret (*Ardea alba*) and satin flycatcher (*Myiagra cyanoleuca*), have very large potential distributions that cover most, or all, of the zone and use a variety of landscape classes beyond the potentially impacted classes.
- Potential habitats of three state-listed species: green-thighed frog (*Litoria brevipalmata*), red-crowned toadlet (*Pseudophryne australis*) and wallum froglet (*Crinia tinnula*). These all have extensive potential distributions across 2150 to 3170 km^2 of the zone.
- Three Important Bird Areas within the zone that were associated with potentially impacted GDE landscape classes: 134 km^2 of the Greater Blue Mountains Important Bird Area, associated with 1.5 km^2 of forested wetlands; 112 km^2 of the Lake Macquarie Important Bird Area, associated with 5.0 km^2 of wet and dry sclerophyll forests and 3.8 km^2 of forested wetlands; and 395 km^2 of the Mudgee-Wollar Important Bird Area, associated with 1.0 km^2 of wet and dry sclerophyll forests and 10.1 km^2 of forested wetlands.
- Five protected areas listed in the Collaborative Australian Protected Areas Database (CAPAD) were associated with potentially impacted GDE landscape classes, and include 3.6 km^2 of the hinterland spotted gum endangered ecological community, which is associated with 1.3 km^2 of wet and dry sclerophyll forests and 1.5 km^2 of forested wetlands.

Economic assets

Impacts on economic assets were assessed in terms of changes in water availability, reliability of supply and potential for invoking 'make good' provisions under the *NSW Aquifer Interference Policy*.

There are 123 economic assets in the zone of potential hydrological change. Five groundwater and 19 unregulated and alluvial surface water sources were identified as being potentially impacted due to additional coal resource development.

There are 3831 water supply bores and surface water extraction points in the zone of potential hydrological change. Just over half are associated with the Hunter Regulated River water source, 32% with unregulated and alluvial water sources and 15% with non-alluvial groundwater (Section 3.5.3.1, Figure 73).

Decrease in mean annual water availability is *very likely* to exceed 5 GL/year in the Hunter Regulated River at Greta (less than 1% of mean annual flow), but *very unlikely* to exceed 12 GL/year (1.6% of mean annual flow). In unregulated and alluvial water sources, there is a 5% chance of reductions in water availability of 3 to 6 GL/year in the Singleton, Muswellbrook, Jerrys and Wyong River water sources.

Potentially significant changes in reliability of supply (as indicated by change in number of cease-to-pump days) are possible for some creeks in the Singleton, Jerrys and Muswellbrook water sources, and in the Wyong River. In the Wyong River, the median change over the three 30-year periods is modelled to be between 6 and 8 days, with a 5% chance of 145 days per year in 2043 to 2072). Modelling with local-scale information indicates that the changes are more likely to be towards the lower end of this range (Section 3.5.3.3).

Of the 1450 bores in the zone, 170 have at least a 5% chance of drawdowns exceeding 2 m. Of these, 159 are on mining and exploration leases. There is at least a 5% chance that the drawdown due to the additional coal resource developments will exceed 2 m at 11 of these bores that include non-mining water supply sources: Sydney Basin – North Coast groundwater source (7) and Jilliby Jilliby Creek (2), Tuggerah Lake (1) and South Macquarie Lake (1). Five of these bores have a 50% chance of drawdowns exceeding 2 m (Section 3.5.3.4, Figure 74).

Sociocultural assets

There are 67 water-dependent sociocultural assets within the zone of potential hydrological change; 45 of these are built infrastructure and were not assessed and 22 are reserves or national parks. The reserves and national parks overlap with 13 km^2 of potentially impacted GDEs.

There are three National Heritage-listed areas within the zone of potential hydrological change in the Hunter subregion as well as 137 km^2 of the Greater Blue Mountains World Heritage Area. Any impact on these assets is predicted to be minor (Section 3.5.4).

There are two Indigenous sites within the zone of potential hydrological change in the Hunter subregion:

- Register of National Estate-listed Swansea Heads Area – Lambton Parade, Swansea Heads – not predicted to be impacted by additional coal resource development
- Register of National Estate-listed Bobadeen Area (Hands on the Rock Shelter) – Cassilis Rd, Ulan – requires site-specific study for assessment of potential impact.

To demonstrate how BA data can be used to assess potential impacts on a particular asset, malleefowl (*Leipoa ocellata*), Section 3.5.5 provides an analysis. This analysis found that there is little chance of any impact of additional coal resource development on the ‘potential distribution of Malleefowl (*Leipoa ocellata*)’.

Future monitoring

Monitoring is important to evaluate the risk predictions of the assessment. Monitoring efforts should reflect the risk predictions, with the greatest effort directed to areas where changes are expected to be the largest and local-scale information supports the regional-scale assessment of risk. Monitoring in locations with lower risk predictions can help to confirm the range of potential impacts and identify unexpected outcomes.

Suggested priorities for groundwater monitoring based on potentially impacted bores are the Sydney Basin – North Coast, Jilliby Jilliby Creek, Tuggerah Lakes and South Lake Macquarie water sources. In addition, groundwater level monitoring for the area west of the proposed West Muswellbrook Project is recommended before its development.

Future surface water monitoring should focus on streams identified as potentially at risk from large changes in flow regime and include the Wyong River and nearby Dora Creek and possibly Loders Creek, Saddlers Creek and Wollar Creek. Streamflow and groundwater monitoring could be of value in Mannering, Morans, Stockton, Wallarah and Wyee creeks given potential changes in flow regime that may arise from the proposed Mandalong Southern Extension Project and Wallarah 2. Monitoring of the Goulburn and Hunter rivers should continue, given potential changes in baseflow. Additional streamflow monitoring in the Wybong river basin would help to assess potential impacts from the proposed West Muswellbrook Project.

Gaps and opportunities

There are opportunities to build on this assessment and address science gaps and include future coal resource developments. For example, seven mining proposals identified as additional coal resource developments as at September 2015 were not included in the surface water and/or groundwater modelling. Based on proposal details, the Austar underground, Chain Valley underground and Mount Arthur open-cut developments were considered unlikely to result in significant hydrological change (Section 3.6). The non-modelled Mandalong underground, West Muswellbrook open-cut, Wambo underground and Wilpinjong open-cut additional coal resource developments could increase the regional impact. The potential impacts are explored in Section 3.6 of this product.

The assessment is regional and cumulative, and provides an important frame for local-scale environmental impact assessments of new coal resource developments, and the local geological, hydrogeological and hydrological modelling that support them (Section 3.7.4). There are opportunities to tailor the BA modelling results for more local analyses, for example:

- combining detailed local geological information with the groundwater emulators developed through BA
- considering alternative coal resource development pathways.

There are specific opportunities for improvement:

- incorporating additional geophysical, well and bore data
- **improved characterisation of hydraulic properties of sedimentary rocks**
- **i**mproved mapping of depth to groundwater, and its spatial and temporal variation
- mapping groundwater depths outside of alluvial layers to build understanding of interactions between changes in groundwater availability and the health and persistence of groundwater-dependent vegetation
- incorporating feedback mechanisms in more closely coupled surface water and groundwater models to reduce predictive uncertainty
- more extensive sets of surface water model nodes to improve the interpolation of surface water hydrological response variables

- reviewing vegetation mapping in the subregion, and undertaking field-based studies to assess condition, determine degree of groundwater dependence and sensitivity to changes in groundwater levels
- identifying the spatial location of water-dependent assets valued by the local Indigenous communities.

The full suite of information, including information for individual assets, is provided at www.bioregionalassessments.gov.au. Users can explore detailed results for the Hunter subregion using a map-based interface in the BA Explorer, available at www.bioregionalassessments.gov.au/explorer/HUN.

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Introduction

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

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

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

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

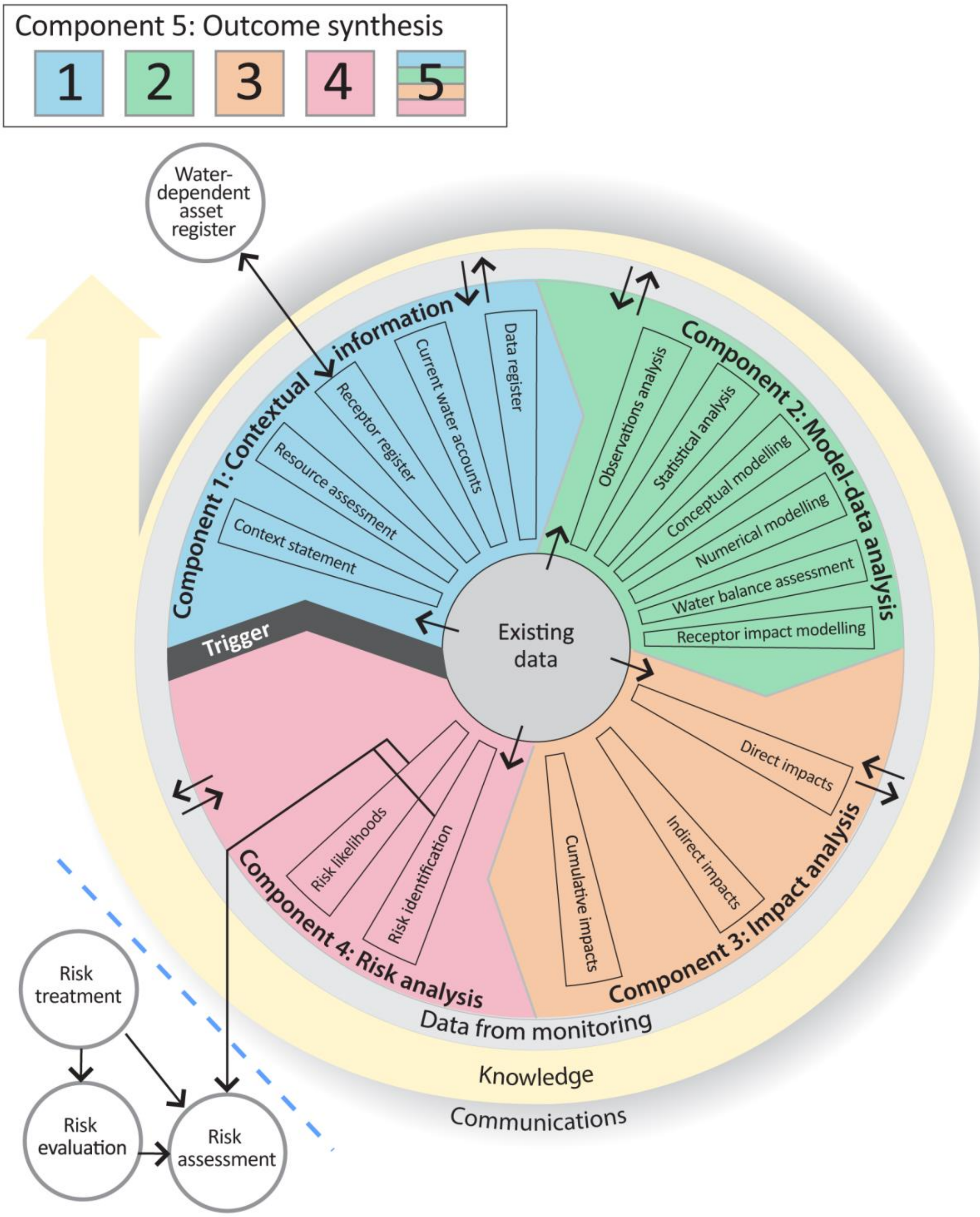

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

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

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

Table 1 Methodologies

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

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

Technical products

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

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

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

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

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

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

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

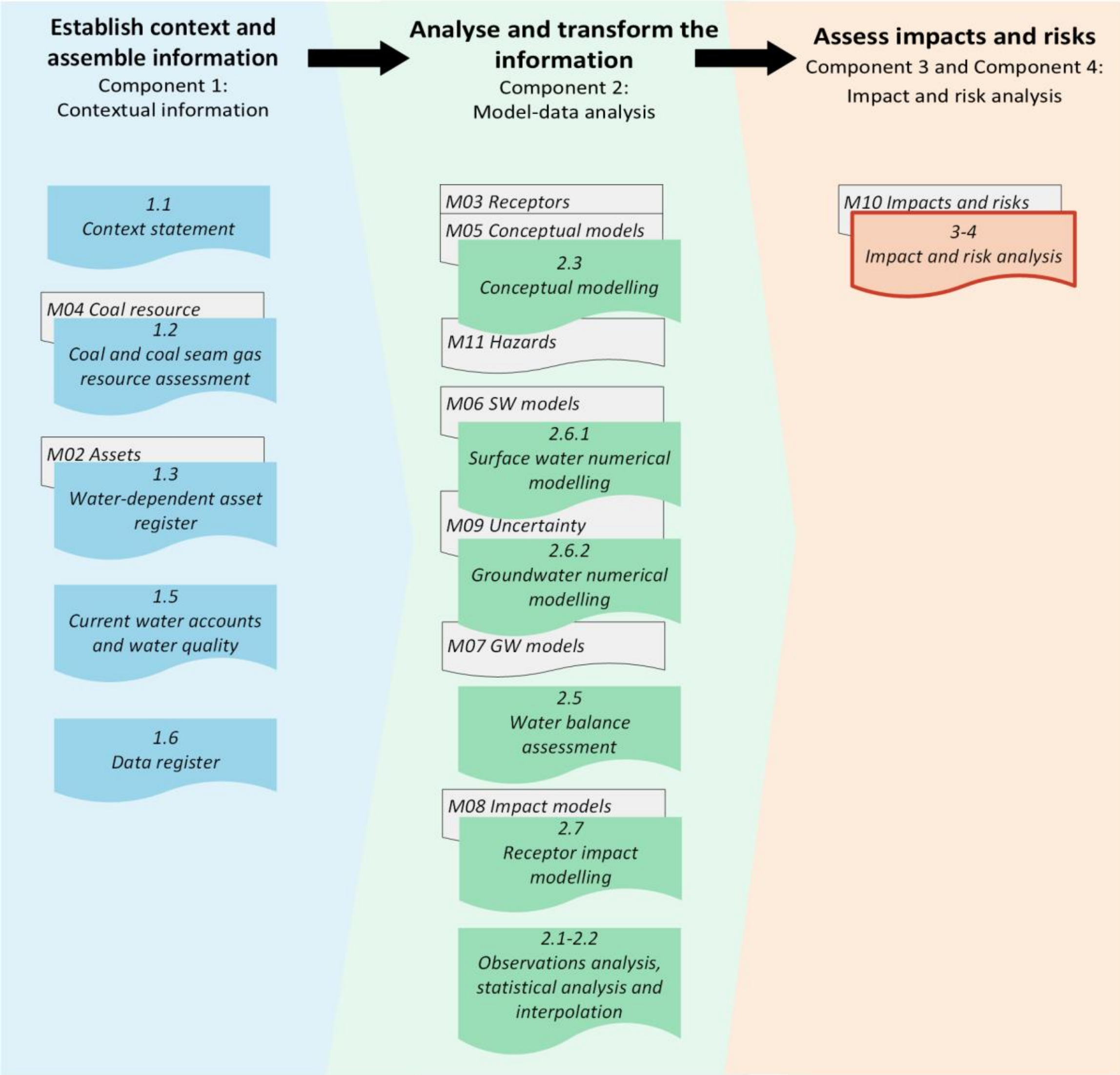

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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

Table 2 Technical products delivered for the Hunter subregion

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

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

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

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

About this technical product

The following notes are relevant only for this technical product.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Northern Sydney Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://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 20 May 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 20 May 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

3 Impact analysis for the Hunter subregion

The impact and risk analysis is the key output of a bioregional assessment (BA). This product presents potential impacts of coal resource development on water resources and water-dependent assets in the Hunter subregion. Risks are analysed by assessing the magnitude and likelihood of these potential impacts.

The impact and risk analysis (Component 3 and Component 4) builds on the contextual information (Component 1) and knowledge from the model-data analysis (Component 2).

In the impact and risk analysis:

- A zone of potential hydrological change is determined using both the surface water and groundwater numerical hydrological modelling results (from product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling)).
- The zone of potential hydrological change is overlain with the extent of the landscape classes (product 2.3 (conceptual modelling)) and water-dependent assets (product 1.3 (description of water-dependent asset register)) to identify those ecosystems and assets that might be subject to hydrological change.
- Potential impacts to ecological assets are considered via:
  - qualitative mathematical models, which predict (at a high level) how components of specific ecosystems (represented by landscape classes) might respond to changes in hydrology
  - quantitative receptor impact models (where applicable), which numerically translate the changes in hydrology into predicted changes in components of ecosystems.
- Potential impacts to economic and sociocultural assets are considered via changes to water availability and accessibility.

The product then describes potential impacts for those coal resource developments that cannot be modelled and concludes with key findings, knowledge gaps, how to use the assessment and how to build on this assessment.

3.1 Overview

Summary

The objective of the Bioregional Assessment Programme is to understand and predict regional-scale cumulative impacts on water resources and water-dependent assets caused by coal resource developments in Australia's major coal-bearing basins. Areas identified in a bioregional assessment (BA) as not being at risk of significant hydrological changes allow further local-scale investigation to be more focussed.

The Hunter subregion covers an area of 17,045 km^2, which includes a significant part of the Hunter river basin and all of the Macquarie-Tuggerah lakes basin in NSW. Along the coast, the dominant land use is urban, with grazing, production forestry and nature conservation areas prevalent in the hinterland areas of Gosford and Wyong. In the Hunter River valley, there is a greater mix of intensive land uses including urban, coal mining, energy production and irrigated agriculture.

The subregion is of great ecological significance because a natural topographic break links coastal and inland NSW, and there is overlap between tropical and temperate climate zones. The asset register for the Hunter subregion (companion product 1.3 (Macfarlane et al., 2016; Bioregional Assessment Programme, 2017; Bioregional Assessment Programme, Dataset 1)) identifies 1652 water-dependent ecological assets, including World Heritage Areas, Ramsar-listed wetlands, and other nationally important wetlands and bird areas.

The area has a long history of coal production. Potential impacts on and risks to water resources and water-dependent assets due to additional coal resource development were assessed by comparing results for two futures: baseline coal resource development (baseline) and the coal resource development pathway (CRDP). In the Hunter subregion, the baseline includes 42 coal mines across the Western, Hunter and Newcastle coalfields. The CRDP includes all baseline coal resource developments plus 22 additional coal resource developments, including 6 proposals for new mines and 16 expansions to existing operations. Not all additional coal resource developments were able to be represented in the modelling. The potential impacts of the non-modelled developments are considered in Section 3.6.

A number of design choices have steered the direction of the BAs. These relate to the choice of modelled futures; the focus on changes in water quantity, with water quality considerations largely limited to the effect on stream salinity; the focus on cumulative changes at a regional-scale, rather than duplicating the local-scale modelling undertaken by mining proponents as part of the development approvals process; the adoption of a probabilistic approach to account for predictive uncertainty; the assessment of impacts by landscape classes to manage the inherent spatial variability; and the 'rule-out' approach by which the impact and risk analysis is directed to those landscape classes and assets where the changes in hydrology indicate a possibility of potentially adverse impacts.

3.1.1 Hunter subregion

The Hunter subregion covers an area of 17,045 km^2, which includes a significant part of the Hunter river basin and all of the Macquarie-Tuggerah lakes basin in NSW. The subregion is defined by the geological Sydney and Werrie basins to the north-east, coastline to the east, and topographic divides with the Hawkesbury-Nepean, Macquarie and Namoi river basins to the south-west and north-west, respectively. Major Hunter River tributaries include the Goulburn, Paterson and Williams rivers, Wollombi Brook and Fal Brook (Glennies Creek). The Hunter River is a regulated river downstream of Glenbawn Dam with regulated flows also coming in from Glennies Creek Dam (Figure 3). Major population centres include Newcastle and Gosford-Wyong along the coast, with smaller urban areas inland, including Maitland, Cessnock, Singleton, Muswellbrook and Scone.

The subsurface geology of the Hunter subregion is characterised by near-horizontal sandstone, shale and coal beds, which have undergone mild deformation. Permian-age coal seams are contained within the Western, Hunter and Newcastle coalfields of the geological Sydney Basin. The area has a long history of coal production; mining commenced in the Newcastle Coalfield near Lake Macquarie shortly before 1800, and expanded into the Hunter Coalfield around Muswellbrook and Singleton in the 1890s, and more recently into the Western Coalfield around Ulan.

Along the subregion coast, the dominant land use is urban, with grazing, production forestry and nature conservation areas prevalent in the hinterland areas of Gosford and Wyong. Underground coal mining continues around and under Lake Macquarie and in the coastal hinterland. Much of the southern part of the subregion is used for nature conservation; dryland grazing and cropping are significant in the northern Goulburn River catchment and along the valleys of its southern tributaries (Figure 4). Along the Hunter River valley, there is a greater mix of intensive land uses including urban, coal mining, energy production and irrigated agriculture. Viticulture and horse studs are very important rural industries in parts of the Hunter river basin.

There is significant competition for water due to high demands from urban, mining, power generation and coal mining sectors as well as the needs of the environment. Environmental water and access to water for consumptive use are managed through a number of water sharing plans that specify extraction limits and water access rights to the region's surface water and groundwater sources. Along the regulated river reaches, the water storages are the major water sources, while stream and alluvial water sources are important along unregulated reaches. The Stockton and Tomago coastal sand aquifers are important for urban water supply; away from the stream network, fractured and porous rock aquifers can be important water sources, particularly for stock and domestic use. Water source areas, major storages and water access rights are included as economic assets in the asset register for the Hunter subregion (companion product 1.3 (Macfarlane et al., 2016; Bioregional Assessment Programme, 2017; Bioregional Assessment Programme, Dataset 1)).

Concerns about increasing stream salinity levels from industry in the 1990s led to the establishment of the Hunter River Salinity Trading Scheme. This scheme manages the discharge of water by mines and power generators through a system of salinity credits that determine how much salt a participant can discharge and specify the flow rate thresholds above which discharges are permitted. The number of salinity credits is capped and credits can be traded.

Figure 3 The Hunter subregion

Data: Bioregional Assessment Programme (Dataset 2), Bureau of Meteorology (Dataset 3), NSW DECCW (Dataset 4)

Figure 4 Pastoral lands in the Bylong River valley, where the Bylong coal mine is proposed

Source: Martin Krogh (2017)

The subregion is of great ecological significance because it corresponds to a break in the Great Dividing Range, which provides a link between coastal and inland NSW, and includes an overlap between tropical and temperate climate zones. The asset register for the Hunter subregion (companion product 1.3 (Macfarlane et al., 2016; Bioregional Assessment Programme, 2017; Bioregional Assessment Programme, Dataset 1)) identifies 1652 water-dependent ecological assets including the Ramsar-listed Kooragang Nature Reserve and Shortland Wetlands; 17 wetlands in *A directory of important wetlands in Australia* (DIWA; e.g. Lake Macquarie, Tuggerah Lake and Colongra Swamp); 6 threatened ecological communities; 7 Important Bird Areas that generally correspond to DIWA wetlands; and 105 flora and fauna species listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

An introduction to the geography (physical, human and climate), geology, groundwater, surface water, surface water – groundwater interactions and ecology is provided in companion product 1.1 for the Hunter subregion (McVicar et al., 2015). The conceptual modelling that underpins the impact and risk analysis for the Hunter subregion is described in companion product 2.3 (Dawes et al., 2018).

3.1.2 Scope and context

The objective of the Bioregional Assessment Programme is to understand and predict regional-scale cumulative impacts on water resources and water-dependent assets caused by coal resource developments in Australia's major coal-bearing basins. The BAs distinguish areas where water resources and water-dependent assets are *very unlikely* to be impacted (with a less than 5% chance) from those where water resources and water-dependent assets are potentially impacted. Given the regional-scale focus, the modelling does not account for local-scale details (e.g. the presence of local aquitards; stream condition). Areas identified in a BA as at risk of potentially significant changes serve as 'red flags' for directing further local investigation. Governments, industry and the community can then focus on areas that are potentially impacted when making regulatory, water management and planning decisions. In some cases, the risk of adverse impacts may be substantially diminished or negligible when local-scale factors are brought to bear. An example of using local geological and hydrogeological information to constrain results from the regional-scale assessment is presented as part of the BA for the Hunter subregion (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018); Sections 3.3 and 3.4).

The impact and risk analysis considers only biophysical consequences, such as changes in hydrology or ecology; fully evaluating consequences requires value judgments and non-scientific information that is beyond the scope of BAs. A full risk assessment (with risk evaluation and risk treatment) is not conducted as part of BAs.

The purpose of this section is to highlight design choices that have steered the direction of this BA and culminated in the impact and risk analysis. Further details about the design choices are provided in companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018).

3.1.2.1 Choice of modelled futures

A BA is a regional analysis that compares two futures of coal resource development. In BAs, the term 'coal resource development' specifically includes coal mining (both open-cut and underground) as well as CSG extraction. Other forms of coal-related development activity, such as underground coal gasification and microbial enhancement of gas resources, were not within the scope of the assessment.

The two futures considered in a BA are:

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

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

In December 2012, there were 42 mining operations in the Hunter subregion, comprising 22 open-cut mines and 20 underground mines. As of September 2015, 22 proposals for coal resource developments were identified for the Hunter subregion (companion product 2.3 (Dawes et al., 2018)). Thus, the Hunter CRDP includes 64 mining operations (Table 3; Figure 5). Of these, 41 baseline mines and 17 additional coal mines were represented in the groundwater modelling (companion product 2.6.2 for the Hunter subregion (Herron et al., 2018)); and 28 baseline mines and 17 additional coal mines in the surface water modelling (companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)). The potential impacts due to the non-modelled coal mines are considered further in Section 3.6.

Table 3 Coal mines in the coal resource development pathway for the Hunter subregion

Baseline		Additional coal resource development	
Open-cut	**Underground**	**Open-cut**	**Underground**
Ashton	Abel	Ashton	Austar
Bengalla	Ashton	Bengalla	Bylong (new)
Bloomfield	Austar	Bulga	Chain Valley
Bulga	Awaba	Bylong (new)	Mandalong
Donaldson	Bulga	Drayton South (new)	Moolarben
Drayton	Chain Valley	Liddell	Mount Arthur
Glendell	Cumnock	Moolarben	Ulan
Hunter Valley Operations	Dartbrook	Mount Arthur	Wallarah 2 (new)
Integra	Integra	Mount Owen	Wambo
Liddell	Mandalong	Mount Pleasant (new)	
Mangoola	Mannering	Mount Thorley–Warkworth	
Moolarben	Moolarben	West Muswellbrook (new)	
Mount Arthur	Muswellbrook	Wilpinjong	
Mount Owen	Myuna		
Mount Thorley–Warkworth	Newstan		
Muswellbrook	Ravensworth		
Ravensworth	Tasman		
Ravensworth East	Ulan		
Rix's Creek	Wambo		
Ulan	West Wallsend		
Wambo			
Wilpinjong			

Figure 5 Location of baseline and additional coal resource development mines

The mines in the coal resource development pathway are the sum of those in the baseline and the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 2, Dataset 5)

The CRDP is the most likely future, based on the analysis and expert judgment of the Assessment team in consultation with coal and gas industry representatives, state agencies and the Australian Government. The CRDP was finalised for the Hunter subregion based on information available in September 2015 (see companion product 2.3 (Dawes et al., 2018)) to allow the hydrological numerical modelling to commence. It is acknowledged that developments in the CRDP may ultimately be implemented in different ways (e.g. changes to timing), or circumstances may change (e.g. a proposal may be rejected, as was the case for the Drayton South Project, which was rejected by the NSW Planning Assessment Commission in February 2017 for the fourth time). This reflects the dynamic nature of resource investment decision making, related to diverse economic, environmental, political and social factors. Consequently, the CRDP needs to be viewed as an indicative future that highlights potential changes for water resources and water-dependent assets that may need to be considered further in local analyses or via approval conditions required by regulators. Equally as important, the CRDP plays a role in identifying where changes will not occur, flagging where potential impacts to water resources and water-dependent assets are *very unlikely*.

BAs primarily focus on the potential impacts to water resources and water-dependent assets that are attributable to additional coal resource development. Potentially important impacts under the baseline, which might occur in parts of the Hunter subregion that are not further affected by additional coal resource development, are afforded less attention in the assessment. However, they could be important in interpreting impacts due to additional coal resource development. For instance, the implications for a groundwater-dependent ecosystem of an additional 2 m of drawdown in the regional watertable may depend on whether the drawdown under the baseline is 0.1, 1.0 or even 10 m.

Factors such as climate change and land use (e.g. agriculture) were held constant between the two futures. Although the future climate and/or land use may differ from those assumed in BAs, the effect of this choice is likely to be small because the focus of BAs is on reporting the difference in results between the CRDP and baseline.

3.1.2.2 Focus on water quantity and availability

BAs focus solely on water-related impacts, and specifically those related to water quantity and availability. Potential water quality hazards are identified, but the analysis, as determined by the BA scope, is limited to salinity and is only addressed qualitatively. BAs are also concerned with those surface water and groundwater effects that may accumulate, either over extended time frames or as a result of multiple coal resource developments. These typically correspond to changes in surface water and groundwater that are sustained over long periods of time, sometimes decades, and which may create the potential for flow-on effects through the wider hydrological system.

Many activities related to coal resource development may cause local or on-site changes to surface water or groundwater. These are not considered in the BA because they are assumed to be adequately managed by site-based risk management and mitigation procedures, and are unlikely to create potential cumulative impacts. Impacts and risks associated with water quality attributes other than salinity that are potentially affected by coal resource development are identified, but not analysed further, in this BA.

3.1.2.3 Assessment of regional-scale cumulative developments

BAs are designed to analyse the cumulative impacts of coal resource developments at a regional scale, and not focus specifically on individual mines or CSG operations. The baseline and CRDP for the Hunter subregion each comprise a suite of developments, which are distributed across the assessment extent at variable distances from each other and have variable, but often overlapping, periods of operation. Thus, there is potential for the impacts to accumulate to varying degrees in both space and time.

Regional-scale models are used to predict the cumulative hydrological changes and potential impacts of those developments on landscape classes and water-dependent assets from multiple developments over time. The area of potential impact is expected to be more extensive and extend greater distances downstream of developments than what is predicted from site-scale, single mine models. In some cases the spatial or temporal alignment of certain coal resource developments can allow for attribution of potential effects to individual developments, but that occurs because of that alignment rather than by design.

Results of the impact and risk analysis reported in this product do not replace the need for the detailed site- or project-specific investigations that are currently required under existing state and Commonwealth legislation. The hydrological and ecological systems modelling undertaken for a BA are appropriate for assessing the potential impacts on and risks to water resources and water-dependent assets at the ‘whole-of-basin’ scale, whereas the modelling undertaken by a mining proponent for an individual development, as part of an environmental assessment, occurs at a much finer scale and makes use of local information to more accurately represent the local situation. Therefore, results from these detailed mine-specific studies are expected to differ from those from a BA. However, as a range of potential parameter values are considered in a BA, it is expected that the range of possible outcomes predicted by a BA will encompass the results from individual site-specific studies. This is illustrated in this product using local hydrogeological data from the Wyong river basin to constrain the set of results based on the regional parameter set.

3.1.2.4 Focus on predictive uncertainty

In BAs, parameter uncertainty is considered as fully as possible when predicting hydrological outcomes (i.e. changes to surface water or groundwater) and ecological outcomes (i.e. changes to ecologically relevant receptor impact variables). For example, groundwater models are run many thousands of times using a wide range of plausible input parameters for the critical hydraulic properties, such as the hydraulic conductivity and storage coefficients of all modelled hydrogeological layers. This differs from the traditional deterministic approach used more routinely for groundwater and surface water modelling.

While models are constrained to data, the density of reliable observation data is sparse, so results may not represent local conditions well. However, they do consistently represent the risk and uncertainty at all sites through probability distributions of possible hydrological changes, where the area, depth, timing and assumed pumping rates of each development largely determine the spatial variation, and lack of detail about the physical environment at any given point in the assessment extent define the uncertainty.

Given the wide range of plausible input parameters used in the regional modelling, the hydrological changes due to additional coal resource development at any given location within the assessment extent can be assumed to lie within the distribution of modelled changes. This assumption may not be valid near open-cut mines where potentially steep hydraulic gradients at the mine pit interface are poorly resolved in the regional groundwater models. These areas are excluded from the ecological analysis for this reason. Where the BA regional-scale analysis identifies an area as 'at risk' of large hydrological changes and potentially significant impacts on ecological, economic and/or sociocultural values, local scale information may be necessary to constrain the predictive uncertainty to something more representative of local conditions, and more appropriate for informing the management response.

The quantitative representation of the predictive uncertainty through probability distributions allows BAs to consider the likelihood of impacts with a specified magnitude and underpins the impact and risk analysis. Sources of uncertainty that cannot be quantified are considered qualitatively.

3.1.2.5 A landscape classification

Subregions are complex landscapes with a wide range of human and ecological systems. The systems can be discrete, overlapping or integrated. Because of this complexity, a direct analysis of each and every point, or water-dependent asset, in the landscape across the subregion is not currently possible, nor warranted in a regional-scale assessment. Abstraction and a systems-level classification can simplify the challenges of the dimensionality of the task and direct the focus to those landscape classes that are water dependent.

A landscape class represents an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. A set of landscape classes was defined for the Hunter subregion that builds on existing well-accepted classifications and is described in detail in companion product 2.3 for the Hunter subregion (Dawes et al., 2018). While it is generally assumed that there will be less heterogeneity in the response within a landscape class than between landscape classes, the grouping of some landscape classes into one receptor impact model (companion product 2.7 for the Hunter subregion (Hosack et al., 2018)) suggests that at least some responses can be the same between landscape classes.

The assessment of impacts on and risks to water-dependent ecological assets relies heavily on the landscape classification. Potential impacts to individual assets are assessed via their constituent landscape classes. For each of those landscape classes, the assessment is based on the qualitative mathematical models for those landscape classes and the indicators of hydrological change or ecosystem change identified as important for that landscape class.

3.1.2.6 Ruling out potential impacts

An important outcome of the multiple components of this BA is to identify areas of the Hunter subregion that are *very unlikely* to be impacted by additional coal resource development. Potential impacts are ruled out where possible, both spatially and in terms of specific groundwater or surface water effects, in order to focus the analysis on where potential impacts have a higher probability of occurring. This process starts with defining a preliminary assessment extent (PAE) for a subregion or bioregion that is a conservative spatial boundary, encompassing areas of potential impact based on the most likely coal resource developments within the subregion. The PAE is where assessment effort was preferentially focused when collating water-dependent assets, defining landscape classes to summarise key surface ecosystems, and constructing numerical surface water and groundwater models.

Results of the hydrological modelling are used to finalise the 'assessment extent' used in the impact and risk analysis. No changes to the Hunter PAE were deemed necessary, and the 'assessment extent' for the Hunter subregion is the same as the PAE identified in companion product 1.3 for the Hunter subregion (Macfarlane et al., 2016).

Results of the hydrological modelling are also used to define the zone of potential hydrological change (Section 3.3.1). Potential impacts on water-dependent landscape classes and assets are ruled out if they are wholly outside the zone of potential hydrological change. Thus, the zone is used to identify landscape classes that should be investigated further through qualitative mathematical modelling and receptor impact modelling, and, as required, through use of local information to better define the risk and appropriate management response. Equally important, this logical and consistently applied process rules out landscape classes or water-dependent assets where potential impacts due to additional coal resource development are *very unlikely* (less than 5% chance) to occur.

3.1.3 Structure of this product

This product presents the impact and risk analysis for the Hunter subregion. The structure is as follows:

- Section 3.1 describes the scope of the BA conducted for the Hunter subregion and summarises the critical philosophical and operational choices.
- Section 3.2 describes the methods for assessing impacts and risks in the Hunter subregion. It includes details of the databases, tools and geoprocessing that support the impact and risk analysis, and the approach to aggregating potential impacts to landscape classes and assets. The approach is consistent with that outlined in companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018), and is in addition to the methods for receptor impact modelling reported in companion product 2.7 for the Hunter subregion (Hosack et al., 2018).
- Section 3.3 provides a closer look at the spatial extent of hydrological changes within the zone of potential hydrological change, using a subset of the hydrological response variables defined in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). The reported surface water hydrological response variables represent changes in low flows, high flows and annual flow due to additional coal resource development. While not explicitly modelled, the potential for additional coal resource development to impact water quality is reported in this section.
- Section 3.4 considers the impacts on and risks to landscape classes within the zone of potential hydrological change due to additional coal resource development. An aggregated, system-level analysis of potential impacts is possible at the scale of the landscape class. A

'rule-out' process identifies landscape classes that are *very unlikely* to be impacted due to hydrological changes. The impacts on and risks to landscape classes are assessed either quantitatively using the receptor impact models described in companion product 2.7 for the Hunter subregion (Hosack et al., 2018), or more qualitatively using the qualitative mathematical models developed through expert elicitation (Hosack et al., 2018).

- Section 3.5 considers the impacts on and risks to water-dependent assets in the zone of potential hydrological change due to additional coal resource development at the asset level. The analysis focuses predominantly on asset groups, not on each individual asset. It includes ecological, economic and sociocultural assets.
- Section 3.6 assesses the potential hydrological changes and impacts due to the additional coal resource developments that were not modelled. These include Mandalong Southern Extension underground, Wambo underground, West Muswellbrook open-cut and Wilpinjong open-cut.
- Section 3.7 concludes with key findings and knowledge gaps. Commentary is provided on how to validate and build on this assessment in the future.

The companion product 2.7 for the Hunter subregion (Hosack et al., 2018) summarises the overarching methodology and development of the Hunter subregion qualitative mathematical models and receptor impact models used to make predictions about the potential impacts on ecosystems reported in Section 3.4. As such, it serves as an appendix to this product.

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3.2 Methods

Summary

The impact and risk analysis for the Hunter subregion follows the overarching methodology described in companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018). The impact analysis quantifies the magnitude and extent of the potential hydrological or ecosystem changes due to additional coal resource development. The risk analysis considers not only the magnitude of the potential impact, but also the likelihood of the impact.

Impacts to water-dependent landscapes and assets can be caused by changes in streamflow regime and drawdown of the regional watertable. The impact and risk analysis uses the conceptual model of causal pathways and probabilistic estimates of hydrological changes to identify where impacts to landscapes and assets might occur. Receptor impact models are used to translate potential hydrological changes to potential ecosystem changes for the key landscape classes.

For bioregional assessment (BA) purposes, the regional watertable is the upper groundwater level within the unconfined aquifer, where pore water pressure is equal to atmospheric pressure. Within the Hunter subregion, the regional watertable exists in the alluvium of the Hunter river basin and Macquarie-Tuggerah lakes basin, and in the weathered and fractured rock units beyond the alluvium. Changes in drawdown of the regional watertable due to additional coal resource development were modelled using the finite element modelling package, MOOSE.

Surface water modelling was undertaken using the Australian Water Resources Assessment landscape model (AWRA-L) and river model (AWRA-R). Results for nine hydrological response variables were reported for 65 model nodes across the subregion and extrapolated to stream links to better represent changes in surface water across the assessment extent.

Results from the groundwater and surface water modelling are used to define the zone of potential hydrological change due to additional coal resource development. Potential impacts on landscape classes and assets are assessed by overlaying their locations on the zone of potential hydrological change. The potential for impacts upon landscape classes and assets outside this zone is deemed *very unlikely* (less than 5% chance) and they are ruled out of further analysis. Within this zone, the potential for impacts on landscape classes and assets is assessed using indicators of hydrological change (hydrological response variables) and ecosystem change (receptor impact variables).

The databases, tools and geoprocessing that support the impact and risk analysis are summarised in this section.

3.2.1 Impact and risk analysis

The *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) states:

> The central purpose of BAs is to analyse the impacts and risks associated with changes to water-dependent assets that arise in response to current and future pathways of CSG and coal mining development.

The impact and risk analysis for the Hunter subregion (Component 3 and Component 4) follows the overarching logic described in companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018), and is summarised diagrammatically in Figure 6. It builds on, and is only possible because of, the contextual information (Component 1) and knowledge from the conceptual models of causal pathways, numerical groundwater and surface water modelling, and data analysis (Component 2). These components are described in detail in preceding products for the Hunter subregion. The impact and risk analysis represents the culmination of effort to improve the knowledge base around coal resource development, and to understand how water resources and water-dependent assets may be affected by hydrological changes due to additional coal resource development in the Hunter subregion.

The impact analysis quantifies the magnitude and extent of the potential hydrological and ecosystem changes due to additional coal resource development. It includes:

- *direct impacts*: changes in water resources and water-dependent assets resulting from coal seam gas (CSG) and coal mining developments without intervening agents or pathways
- *indirect impacts*: changes in water resources and water-dependent assets resulting from CSG and coal mining developments with one or more intervening agents or pathways
- *cumulative impacts*: the total change in water resources and water-dependent assets resulting from CSG and coal mining developments when all past, present and reasonably foreseeable actions that are likely to impact on water resources are considered.

The risk analysis is related, but considers not only the magnitude and extent of a potential impact but also the likelihood of that impact. This is often framed as ‘consequence multiplied by the likelihood’. The quantification of the likelihood is underpinned by an uncertainty analysis that allows probabilistic statements about events or impacts occurring. Within BAs, the uncertainty analysis stochastically propagates uncertainties in underlying hydrological parameters through hydrological models to produce distributions of potential surface water and groundwater changes. These in turn can be used as input to receptor impact models to produce distributions of receptor impact variables, which are chosen as indicators of potential changes in ecosystems.

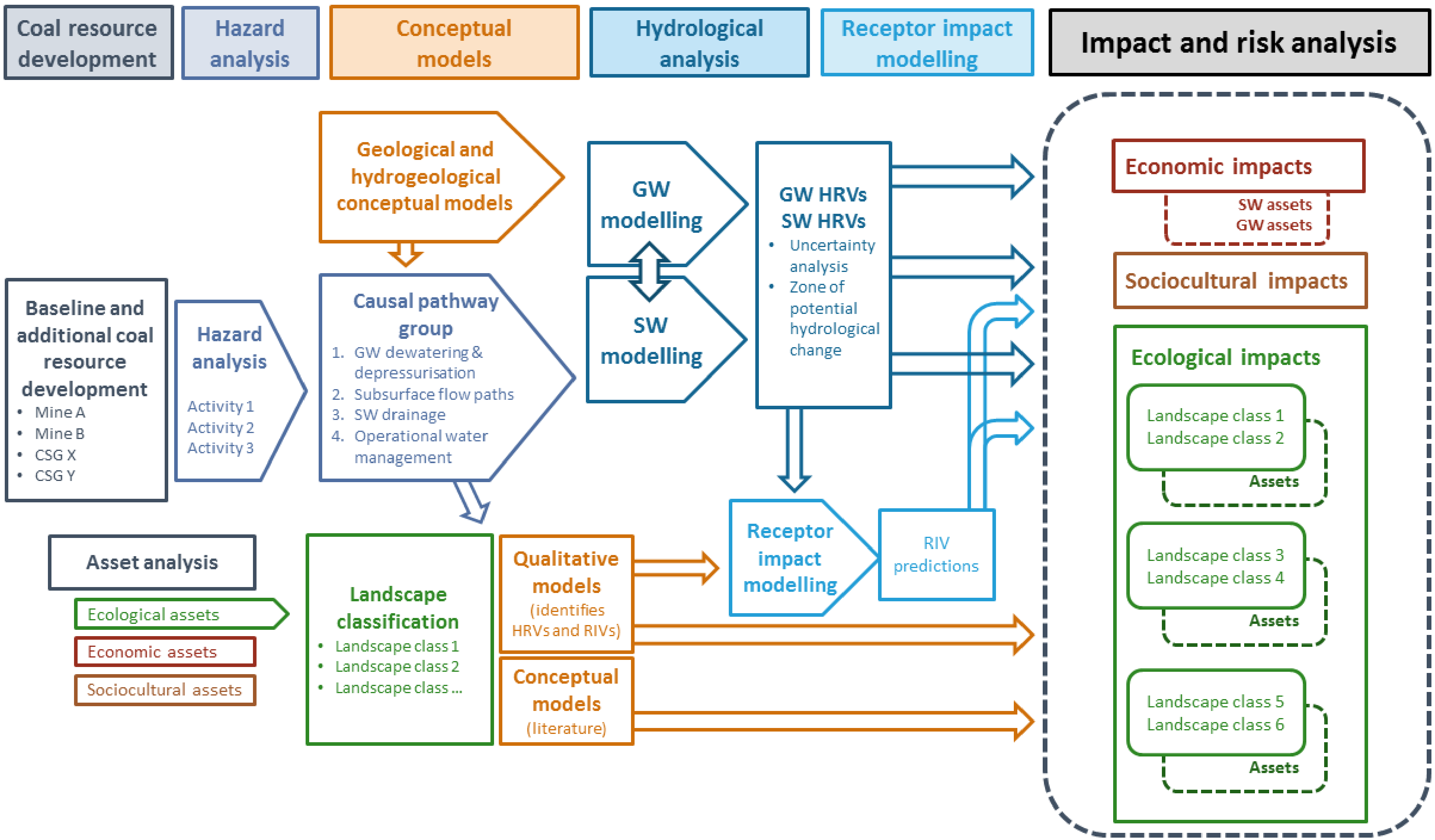

Figure 6 Overarching methodology for impact and risk analysis in bioregional assessments

CSG = coal seam gas, GW = groundwater, HRV = hydrological response variable, RIV = receptor impact variable, SW = surface water

BAs identify risks through a hazard analysis and analyse those risks by estimating the magnitude and likelihood of specific impacts. The risk assessment, risk evaluation and risk treatment that occur as part of the broader risk management (see, for example, ISO 31000:2009 Risk Management Standards) are beyond the scope of BAs because they require careful consideration of a number of non-scientific matters and value judgements; these are roles of proponents and government regulators in the first instance, often in response to specific community values.

This product describes the hydrological changes, and then the potential impacts of those changes on landscape classes and water-dependent assets, which contain ecological, economic and sociocultural values. These regional-scale results do not replace the need for detailed site- or project-specific studies, nor should they be used to pre-empt the results of detailed studies that may be required under NSW legislation. Where potentially significant impacts are identified from the regional-scale analysis, local-scale information can be used to better define the risk. This is illustrated for an area within the Hunter subregion where the regional-scale analysis indicated large changes in hydrology, with potentially significant impacts on landscape classes and water-dependent assets.

BAs present the likelihood of certain impacts occurring, for example, the percent chance of exceeding 0.2 m of drawdown in a particular aquifer and location (see Section 3.2.3). The underpinning data and information are available at www.bioregionalassessments.gov.au for others to access and use in their own targeted risk assessments. Users can choose thresholds of impact that may threaten the specific values they are trying to protect and calculate the corresponding likelihood of occurrence. More details about hydrological changes and potential impacts in the Hunter subregion are available at www.bioregionalassessments.gov.au/explorer/HUN.

3.2.2 Causal pathways

The conceptual model of causal pathways describes the logical chain of events – either planned or unplanned – that link coal resource development to potential impacts on water and water-dependent assets. The causal pathways provide the logical and transparent foundation for the impact and risk analysis.

A systematic hazard analysis, using the Impact Modes and Effects Analysis method (described in companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016)), was undertaken for the Hunter subregion to identify the activities that occur as part of coal resource development that might result in a change in the quality or quantity of surface water or groundwater. Hazards were prioritised according to the likelihood, severity and detectability of potential impacts (Bioregional Assessment Programme, Dataset 1). All hazards need to be addressed in some way for the impact and risk analysis, but this does not mean they all need to be assessed in the same way.

Individual 'hazards' are not represented in the hydrological models. Instead they were grouped into four causal pathway groups, which reflect the main hydrological pathways via which the effects of a hazard can propagate from its origin. These simplified pathways are broadly represented in the BA hydrological models. The causal pathway groups are:

- ‘Subsurface depressurisation and dewatering’
- ‘Subsurface physical flow paths’
- ‘Surface water drainage’
- ‘Operational water management’.

Figure 7 illustrates these causal pathway groups.

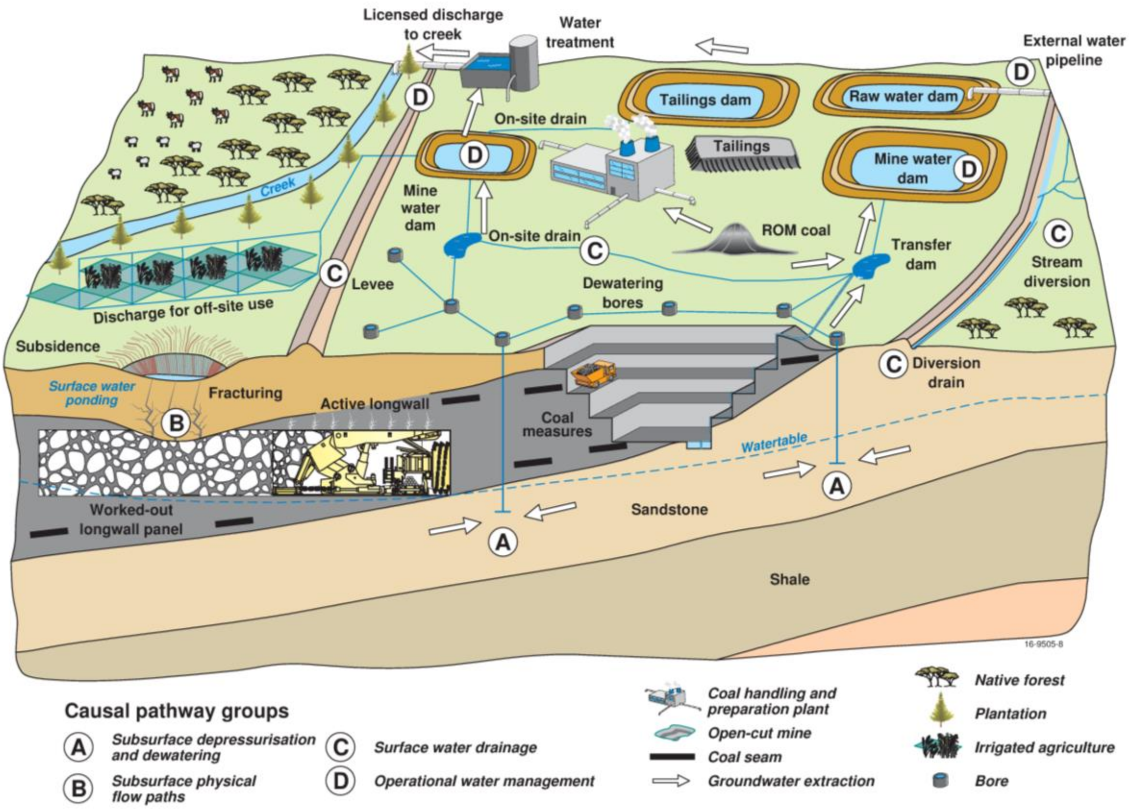

Figure 7 Conceptual diagram of the causal pathway groups associated with open-cut and underground coal mining

This schematic diagram is not drawn to scale.
ROM = run-of-mine

The effects of some hazards were not modelled. Changes in water quality due to coal resource development activities were generally deemed out of scope of the BA, except the potential effects on stream salinity. Changes in stream salinity were not modelled, but are considered qualitatively in Section 3.3.4. The physical process of subsidence is not simulated by the hydrological models, although some of the effects on hydrology from longwall panel collapse (i.e. hydraulic conductivity enhancement within the goaf) and subsidence at the land surface (i.e. interception of catchment runoff) are represented. Some identified hazards were deemed to be local in scale and addressed by existing site-based management; others were considered of such low likelihood and/or consequence (such as litter left by site contractors) that they were not included.

While the causal pathway groups are generic, the physical characteristics of a subregion, such as its geological, geophysical and topographic architecture, and related surface water and groundwater networks, will influence the hydrological connectivity across the subregion. The Assessment team’s conceptual understanding of the dominant geological and topographic influences on surface water and groundwater connectivity in the Hunter subregion is described in companion product 2.3 (Dawes et al., 2018).

Table 4 lists potential hazards arising from coal resource development in the Hunter subregion for each causal pathway group. Further details about hazards, their identified effects and their link to causal pathway groups are in companion product 2.3 for the Hunter subregion (Dawes et al., 2018).

The hydrological models represent causal pathways through their conceptualisation and parameterisation of changes in surface water drainage, dewatering of the mines, changes in hydraulic properties above longwall mines and discharges of mine water off site. The models integrate the hydrological changes from the different causal pathways into the predicted hydrological response across the model domain over time.

Table 4 Causal pathway groups and the associated hazards for the Hunter subregion

Causal pathway group	Hazards from Impact Modes and Effects Analysis (IMEA)
Surface water drainage	• water management structures (dams, levee bunds and diversions) • rainwater and runoff diversion • waste rock blasting, excavation and storage administration, workshop, service facilities (construction phase) • topsoil excavation and storage • mine access construction • longwall coal extraction • bord-and-pillar coal extraction • construct own quarry for road base, etc. • off-lease and on-lease roadways • rail easement construction • recontoured landforms (slopes, gradients, etc.) • topsoil and waste rock dump site preparation • ventilation shaft construction.
Operational water management	• discharge of treated mine water into the river (regulated) • discharge of treated mine water into the river (unregulated).
Subsurface depressurisation and dewatering	• longwall coal extraction • bord-and-pillar coal extraction • pit wall (stabilisation) dewatering, treatment, reuse and disposal • development of mine panels (construction of roadways) • mine access (shaft / incline) construction • mine access (adit / incline) construction • gas post-drainage, surface to goaf: drilling • ventilation shaft construction • drilling and coring • gas post-drainage, surface to goaf: drilling • gas pre-drainage, surface to inseam: drilling • gas pre-drainage, underground: drilling • inseam gas pre-drainage, underground: drilling • mine dewatering drilling: drilling.
Subsurface physical flow paths	• longwall coal extraction • bord-and-pillar coal extraction • post-closure water filling the pit • groundwater supply bore • mine access (adit / incline) construction • mine access (shaft / incline) construction • ventilation shaft construction • mine expansion too close to river/lake.

Data: Bioregional Assessment Programme (Dataset 1)

3.2.3 Hydrological analysis

The hydrological analysis encompasses the surface water and groundwater modelling reported in companion product 2.6.1 (Zhang et al., 2018) and companion product 2.6.2 (Herron et al., 2018b), respectively, for the Hunter subregion. The Hunter surface water and groundwater models were designed to quantify potential changes in hydrology from multiple coal resource developments and enable an assessment of the cumulative impacts of coal resource development at a regional scale. The assessment focuses on the hydrological changes in the zone of potential hydrological change. Outside this zone, potential impacts due to additional coal resource development are considered *very unlikely* (less than 5% chance). See Section 3.3.1 for more details.

3.2.3.1 Groundwater

Regional-scale groundwater modelling for the BA for the Hunter subregion was undertaken using a custom-built finite element groundwater model, built in the MOOSE modelling package (MOOSE, 2017).

Coal resource developments affect groundwater hydrology as a result of aquifer depressurisation from mine dewatering and changes to the subsurface physical flow paths, such as hydraulic enhancement above longwall mines. In the Hunter groundwater model, a single regional-scale watertable was subjected to groundwater pumping at locations, depths, rates and periods of time as specified in mine groundwater assessments for baseline and additional coal resource developments. Above longwall panels, the hydraulic properties of the overburden were enhanced stochastically to represent the range of potential physical changes associated with mine subsidence (see Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a)).

For BA purposes, the regional watertable is the upper groundwater level within the unconfined aquifer (not perched), where pore water pressure is equal to atmospheric pressure. In the Hunter subregion, it spans the modelling domain (Figure 8), which includes the alluvium of the Hunter and Macquarie-Tuggerah lakes river basins and the outcropping weathered and fractured layers beyond the alluvium.

The model simulates the changes in the regional watertable and surface water – groundwater fluxes from coal resource development between 1983 and 2102 and outputs results at model nodes across the modelling domain (Figure 8). Details of the groundwater modelling are reported in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b). To produce drawdown surfaces, the results generated at model nodes were spatially interpolated using Delaunay triangulation. The changes in surface water – groundwater fluxes were input into the Hunter AWRA-R model to represent the changes in baseflow along the modelled river network.

Forty-one baseline mines and 17 additional coal resource developments were included in the groundwater modelling under the coal resource development pathway (CRDP) (Table 3). Additional coal resource developments at Mount Arthur (open-cut), West Muswellbrook (open-cut), Wambo (underground) and Wilpinjong (underground) were not modelled (see Table 10 in companion product 2.3 for the Hunter subregion (Dawes et al., 2018)). The potential impacts from these mines are considered further in Section 3.6.

Section 3.3.1.1 describes how the groundwater modelling results are used to define the groundwater zone of potential hydrological change.

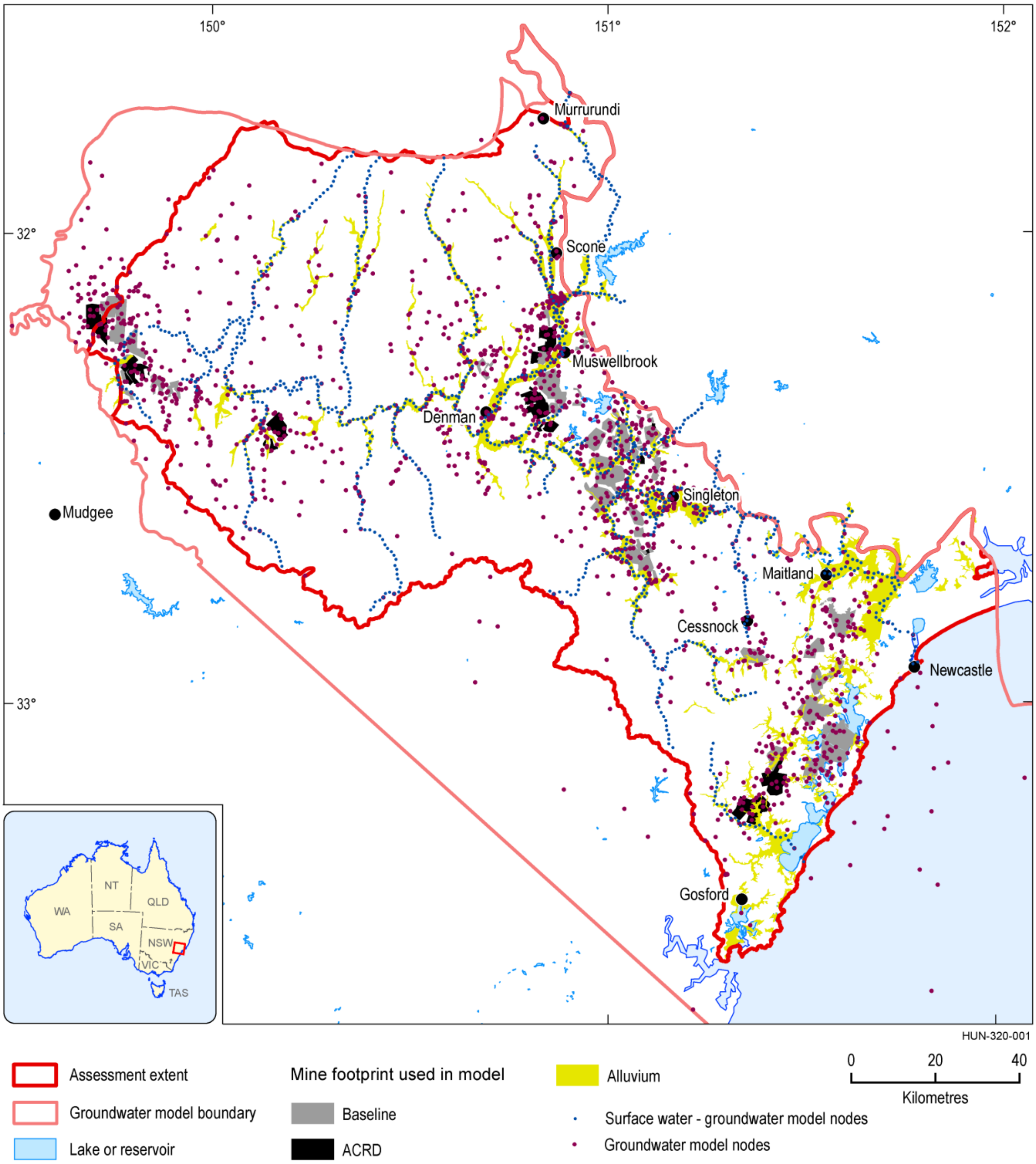

Figure 8 Groundwater modelling domain and model nodes for the Hunter subregion

The modelling domain extends about 100 km offshore. The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 2, Dataset 3, Dataset 4, Dataset 5), CSIRO (Dataset 6)

In areas identified from the regional-scale assessment as 'at risk' of potentially significant changes in hydrology, local information is needed to determine whether the assessment can be constrained to reduce the predictive uncertainty. Groundwater model emulators trained with local hydrogeological data or subsampling of the groundwater model simulations based on local data are two ways in which the predictions from the regional analysis can be constrained to produce more locally relevant results. In the Wyong river basin, where results from the regional-scale groundwater and surface water modelling indicate a risk of potentially significant changes in streamflow in what is an important urban water supply catchment, local-scale hydrogeological information has been used to refine the regional-scale predictions to get a better understanding of the risk in this area (see Section 2.6.2.8 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)).

3.2.3.2 Surface water

Surface water modelling for the Hunter subregion was undertaken using the AWRA-L and AWRA-R models. The AWRA-R model was used to model the Hunter river basin, but not for the smaller, unregulated coastal rivers in the Macquarie-Tuggerah lakes basin. Details of the application of these models to the Hunter subregion are reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

Coal resource developments affect surface water hydrology directly through disruption of surface drainage and some aspects of operational water management, and indirectly through changes in surface water – groundwater fluxes in response to aquifer depressurisation from mine dewatering and enhancement of subsurface physical flow paths. Changes in surface water – groundwater fluxes are generated in the Hunter groundwater model at points along the river network for input into AWRA-R (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)).

Twenty-eight baseline mines and 17 additional coal resource developments were included in the surface water modelling of the CRDP (see Table 9 in companion product 2.3 for the Hunter subregion (Dawes et al., 2018)). Additional coal resource developments at Mandalong (underground), West Muswellbrook (open-cut), Wambo (underground) and Chain Valley (underground) were not modelled (see Table 10 in Dawes et al. (2018)). The potential for impacts from these mines are considered further in Section 3.6.

Results for nine hydrological response variables (described in Table 6) were reported for 65 model nodes across the Hunter subregion. The locations of these model nodes are shown in Figure 9. Additional hydrological response variables have been defined for receptor impact modelling (see companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) and for assessing economic impacts, and are considered further in the impacts on landscape classes and assets sections (Section 3.4 and Section 3.5).

In order to carry out the impact and risk analysis, results from these model nodes needed to be extrapolated to stream links. Extrapolating these changes results in a more comprehensive assessment of the changes in surface water across the assessment extent. The process for extrapolating hydrological response variable values from model nodes to stream links is shown schematically in Figure 10. The schematic includes a number of stream links with no model nodes (dashed lines) for which model results were not generated, but which were important for doing the extrapolations. The junctions of these non-modelled streams with the modelled network correspond to large changes in streamflow and hence represent limits to extrapolation from the nearest upstream or downstream model node.

Extrapolations were also not undertaken for stream links that contain inflows from open-cut coal mines (e.g. Loders Creek between node 9 and its junction with Doctors Creek; Bylong River between nodes 43 and 44). Because the impact of a mine on streamflow diminishes with increasing distance downstream of the mine, it is difficult to know how far along the reach it is reasonable to extrapolate from the nearest model node before the hydrological changes at that node are no longer representative of the hydrological changes at that point in the reach. Thus, they were classified as potentially impacted and included in the zone of potential hydrological change. Modelled results from nodes 8, 9, 13, 15, 22, 26, 27, 28, 29, 30, 43, 44, 51 and 52 have not been used to characterise the hydrology of the reaches immediately upstream and downstream of them because they are not considered to be representative of those reaches, although they contain useful at-a-point information.

Section 3.3.1.2 describes how the surface water modelling results are used to define the surface water zone of potential hydrological change. In the subsequent analysis of hydrological changes within the zone of potential hydrological change (Section 3.3.3), the effect on Wyong River streamflow predictions of constraining the regional result set based on local hydrogeological information from the proposed Wallarah 2 mine area is presented. This involved calculating the hydrological response variables using only those surface water model simulations from the regional set, which included baseflow changes from the groundwater model constrained by local hydrogeological information (see Section 2.6.2.8 in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)).

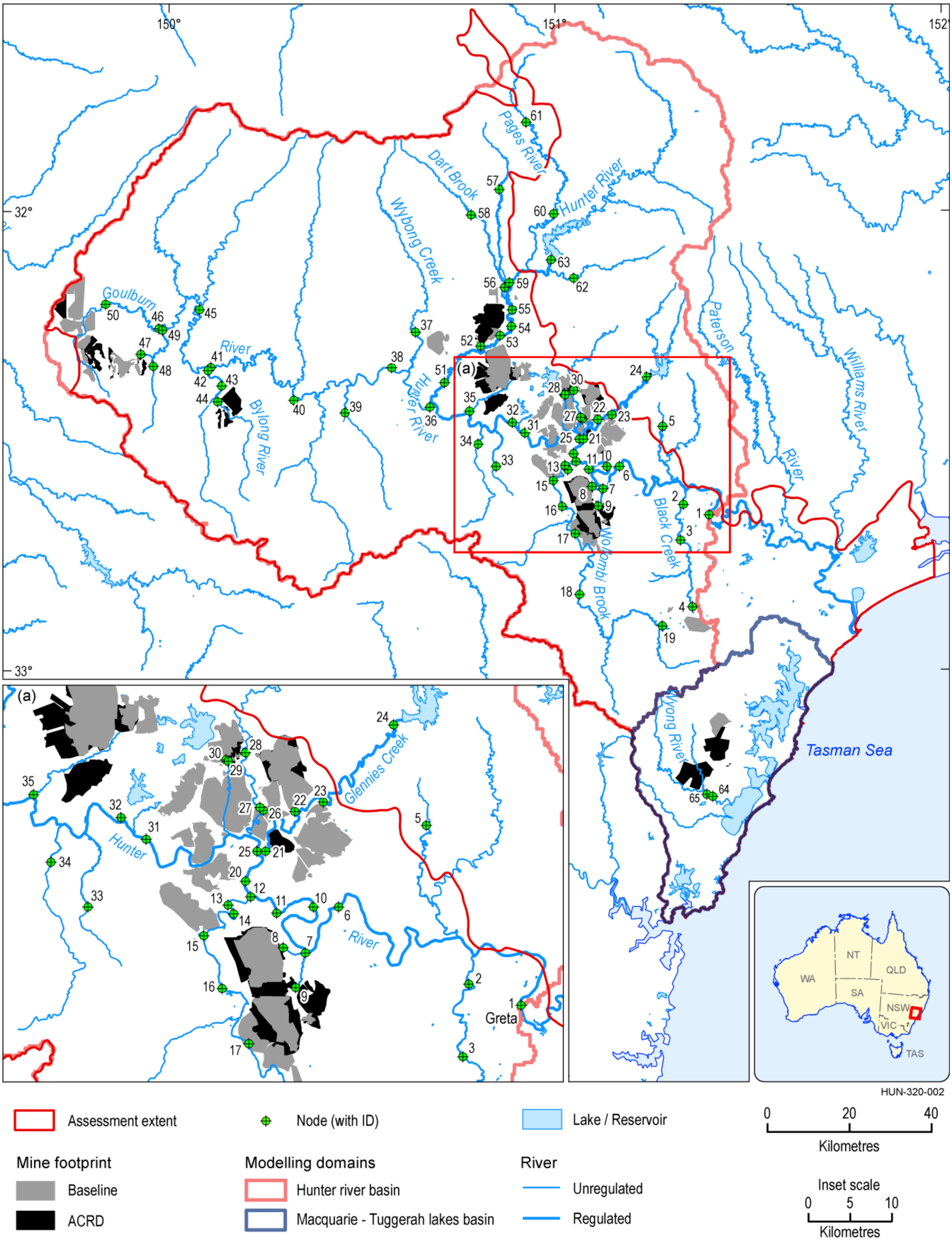

Figure 9 Surface water modelling domain, location of model nodes and maximum extents of mine footprints

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bureau of Meteorology (Dataset 7), Bioregional Assessment Programme (Dataset 8, Dataset 9, Dataset 10, Dataset 11, Dataset 12)

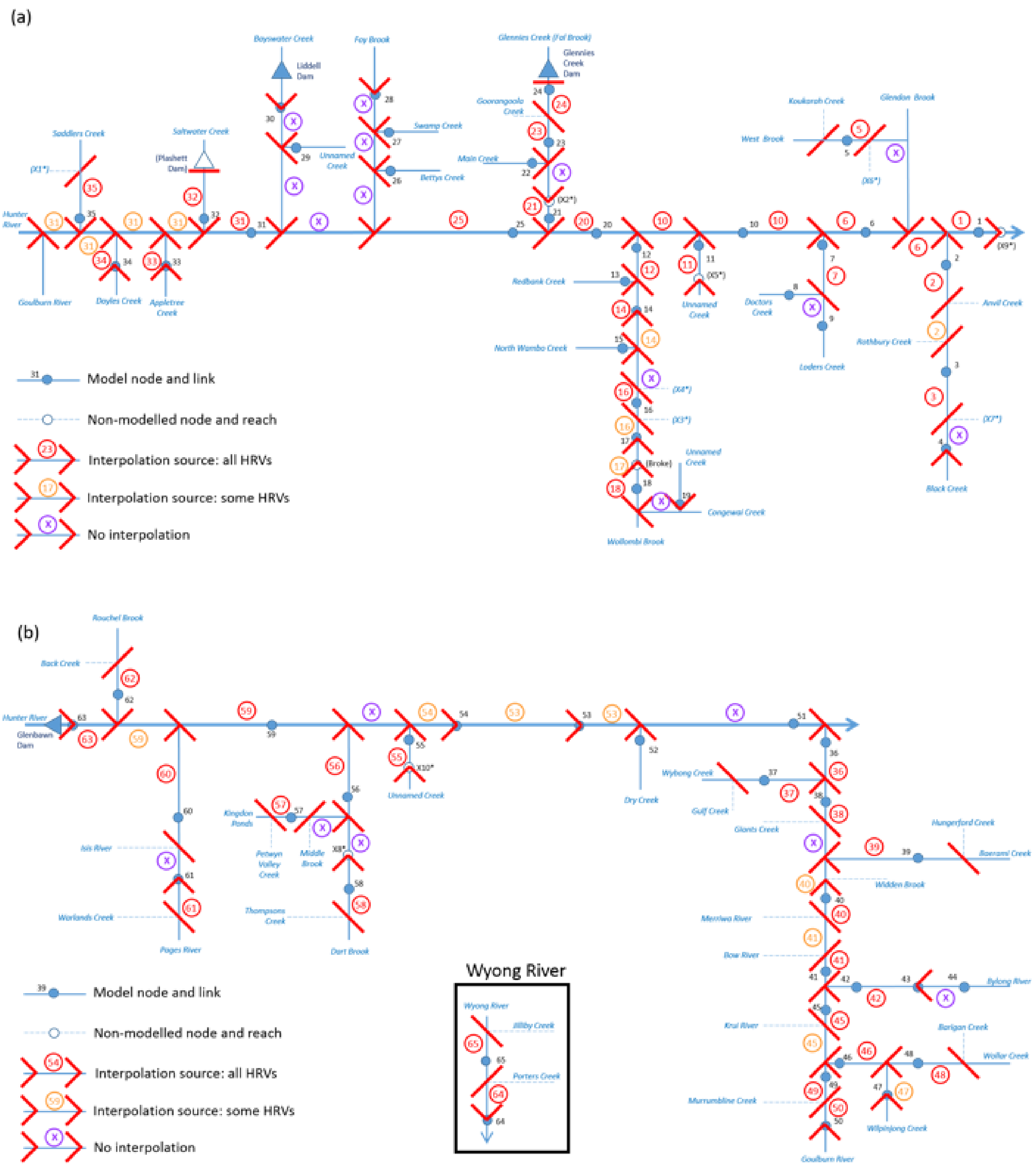

Figure 10 Scheme for extrapolating hydrological response variables from model nodes to stream links for (a) the Lower Hunter River and (b) modelled river networks for the Upper Hunter, Goulburn and Wyong rivers

HRV = hydrological response variable

3.2.3.3 Representing predictive uncertainty

The models used in the assessment produce a large number of predictions of groundwater drawdown and streamflow characteristics rather than a single number. This results in a range or distribution of predictions, which are typically reported as probabilities – the percent chance of something occurring (Figure 11). This approach allows an assessment of the likelihood of exceeding a given magnitude of change, and underpins the assessment of risk.

Groundwater models require information about physical properties such as the thickness of geological layers, how porous aquifers are, and whether faults are present. As the exact values of these properties are not always known, the modellers used a credible range of values, which are based on various sources of data (commonly point-scale) combined with expert knowledge. The groundwater model was run 1500 times using a different set of plausible values for those physical properties each time. Historical observations, such as groundwater level and changes in water movement and volume from across the subregion, were used to constrain and validate the model runs.

The resultant set of model runs produces a range or distribution of predictions (Figure 11) that are consistent with the available regional observations and the understanding of the modelled system. The range conveys the confidence in model results, with a wide range indicating that the expected outcome is less certain, while a narrow range provides a stronger evidence base for decision making. The distributions created from these model runs are expressed as probabilities that drawdown or a change in streamflow will exceed relevant thresholds, as there is no single ‘best’ estimate of change.

In this assessment, the estimates of drawdown or streamflow change are shown as 5th, 50th or 95th percentile results, corresponding to a 95%, 50% or 5% chance of exceeding thresholds. Figure 12 illustrates this predictive uncertainty spatially.

Throughout this product, the term ‘*very likely*’ is used to describe where there is a greater than 95% chance of something occurring, and ‘*very unlikely*’ is used where there is a less than 5% chance.

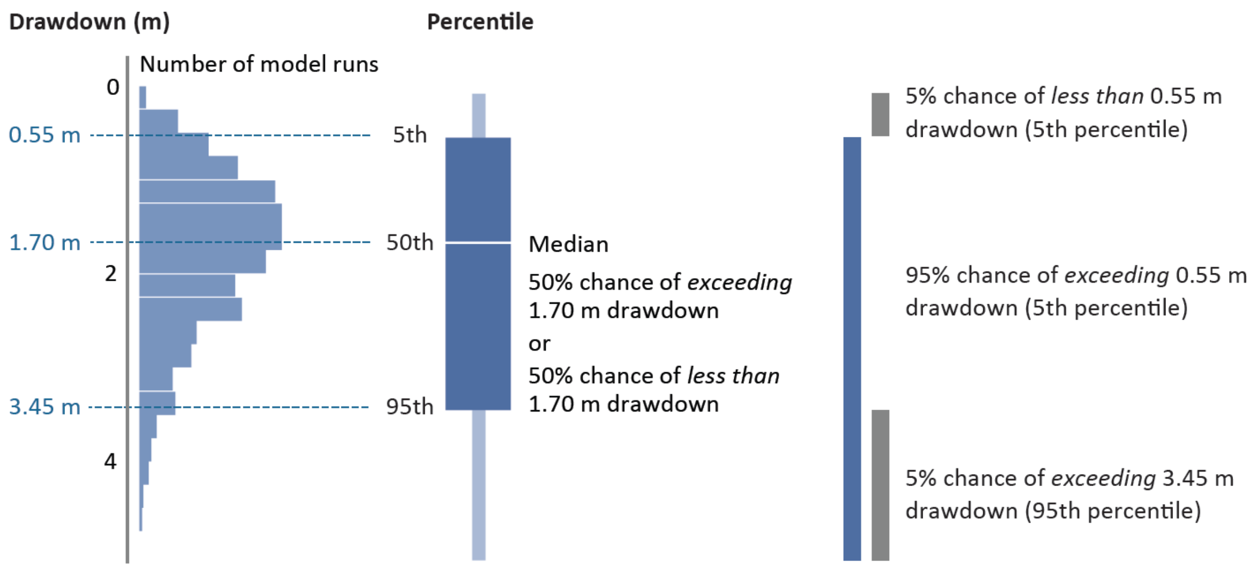

Figure 11 Illustrative example of probabilistic drawdown results using percentiles and percent chance

The chart on the left shows the distribution of results for drawdown, obtained from an ensemble of thousands of model runs that use many sets of parameters. These generic results are for illustrative purposes only.

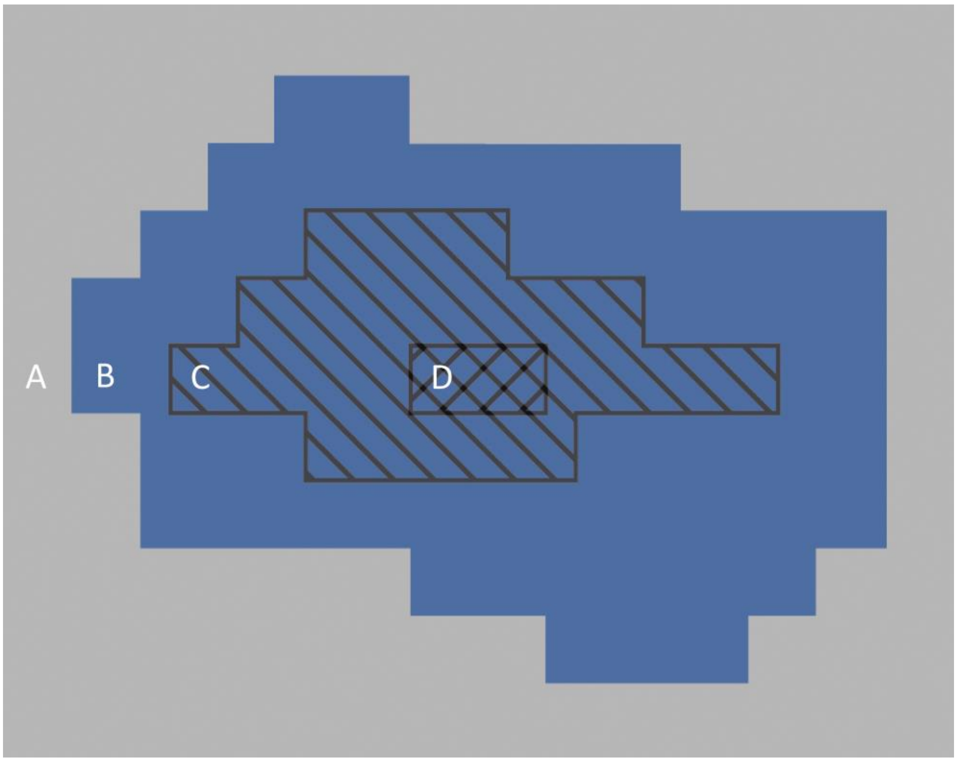

Figure 12 Illustrative example of key areas in the landscape defined by probabilistic results

The assessment extent was divided into smaller square assessment units (see Section 3.2.4.1) and the probability distribution (Figure 11) was calculated for each. In this product results are reported with respect to the following key areas:
A. outside the zone of potential hydrological change, where hydrological changes (and hence impacts) are *very unlikely* (defined by maps showing the 95th percentile)
B. inside the zone of potential hydrological change, comprising the assessment units with at least a 5% chance of exceeding the threshold (defined by maps showing the 95th percentile). Further work is required to determine whether the hydrological changes in the zone translate into impacts for water-dependent assets and landscape classes
C. with at least a 50% chance of exceeding the threshold (i.e. the assessment units where the median is greater than the threshold; defined by maps showing the 50th percentile)
D. with at least a 95% chance of exceeding the threshold (i.e. the assessment units where hydrological changes are *very likely*; defined by maps showing the 5th percentile).

3.2.4 Assessing potential impacts for landscape classes and assets

The approach for assessing potential impacts on landscape classes and water-dependent assets is discussed in M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018). The principal focus of BAs is water-dependent assets that are nominated by the community. These assets may have a variety of values, including ecological, sociocultural and economic values.

The water-dependent asset register (see companion product 1.3 for the Hunter subregion (Macfarlane et al., 2016) and Bioregional Assessment Programme, 2017, Dataset 13) provides a simple and authoritative listing of the assets within the assessment extent. The register is a compilation of assets identified in Local Land Services (formerly Catchment Management Authorities) databases and Commonwealth and state databases, and through the Hunter assets workshop. The identified assets were assessed by the Assessment team for fitness for BA purpose, location within the assessment extent and water-dependency. Assets that satisfy the requirements are considered in the impact and risk analysis reported in this product.

Landscape classification discretises the heterogeneous landscape into a manageable number of landscape classes for impact and risk analysis. Landscape classes represent key surface ecosystems, having broadly similar physical, biological and hydrological characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. They are used to reduce some of the complexity inherent in assessing impacts on a large number of water-dependent assets by focusing on the hydrological drivers and interactions relevant to a regional-scale assessment. The landscape classes provide a meaningful scale for understanding potential ecosystem impacts and communicating them through their more aggregated system-level view. The landscape classification for the Hunter subregion is described in companion product 2.3 (Dawes et al., 2018) and the methodology that underpins it is described in companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016).

Potential hydrological changes are assessed by overlaying the extent of a landscape class or asset on the zone of potential hydrological change. For the landscape classes or assets that lie outside the zone, the magnitude of the hydrological changes are considered *very unlikely* to result in adverse impacts, and thus they can be ruled out in terms of further assessment. Section 3.4.2 identifies landscape classes in the Hunter subregion that can be ruled out on this basis.

Where an asset or landscape class wholly or partially intersects the zone of potential hydrological change, there is the potential for impact. This does not mean there will be an impact, but rather based on the magnitude of the hydrological change, the possibility of an impact cannot be ruled out and further investigation is required. The nature of the water dependency of the landscape class can be important for informing the assessment. For example, if the water dependence of a landscape class relates to overbank flows to support seedling establishment, but the predicted hydrological changes in the nearby stream relate only to low-flow variables (i.e. flows within the bank), then it may be possible to rule out the landscape class from further consideration because it is *very unlikely* to be impacted.

Six receptor impact models were built, representing five landscape classes in the Hunter subregion (Table 5), and are used to quantify the impact of the predicted hydrological changes on one or more receptor impact variables within the receptor impact model (see companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)). Meaningful hydrological response variables and receptor impact variables (Table 5) were elicited from experts (listed in Table 3 in companion product 2.7 (Hosack et al., 2018a)) during qualitative and receptor impact model building workshops and subsequent follow-up by email. The receptor impact variables serve as indicators of ecosystem response for the landscape class or ecosystem represented in the model. Within a landscape class at a specific location, local information, such as condition of the associated habitat, species diversity and abundance, presence of other stressors (e.g. agricultural or urban land uses) and recovery potential will influence the perception of risk and whether risk management measures are required to minimise potential impacts. The assumptions and limitations of the receptor impact modelling are described in Table 4 in companion product 2.7 (Hosack et al., 2018a).

A full description of the receptor impact modelling is provided in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018b).

Table 5 Receptor impact models and their variables

Receptor impact model	Landscape class	Hydrological response variable	Receptor impact variable
Perennial streams – riffle-breeding frog	Permanent or perennial streams	Number of zero-flow days per year, averaged over a 30-year period (ZQD) Maximum length of spells (in days per year) with zero flow over a 30-year period (ZMA)	Probability of presence of riffle-breeding frog (over 100 m transect)
Perennial streams – Hydropsychidae larvae	Permanent or perennial streams		Mean number of Hydropsychidae larvae (per m^2 of riffle habitat)
Intermittent streams – riffle-breeding frog	Lowly to highly intermittent streams[a]	Number of zero-flow days per year, averaged over a 30-year period (ZQD) Maximum length of spells (in days per year) with zero flow over a 30-year period (ZMA)	Probability of presence of riffle-breeding frog (over 100 m transect)
Intermittent streams – hyporheic invertebrate taxa	Lowly to highly intermittent streams[a]		Mean hyporheic taxa richness (in 6 L of water pumped from 40 cm below the streambed)
Wet and dry sclerophyll forests	Wet sclerophyll forest	Maximum drawdown (*dmax*) Year of maximum change (*tmax*)	Projected foliage cover (m^2/m^2)
	Dry sclerophyll forest		
Forested wetland – riverine forest	Forested wetland	Overbank events (EventsR3.0) Overbench events (EventsR0.3) Maximum drawdown (*dmax*) Year of maximum change (*tmax*)	Projected foliage cover (m^2/m^2)

[a]The 'Lowly to moderately intermittent' and 'Moderately to highly intermittent' landscape classes are treated as one landscape class.

Potential impacts are reported in Section 3.4 for landscape classes and in Section 3.5 for assets. Given the large number of assets, the focus of Section 3.5 is on identifying the assets that are 'more at risk of hydrological changes' within the zone of potential hydrological change. These are the assets that overlap with areas in the zone that have at least a 50% chance of a hydrological change larger than the threshold hydrological response variable values used to define the zone. Local information is necessary to improve upon the regional-scale risk predictions at any given site.

In addition, impact profiles for landscape classes and assets are available at www.bioregionalassessments.gov.au. Each profile summarises the hydrological changes and potential impacts that pertain to that landscape class or asset (e.g. increase in the number of low-flow days for the 'Permanent or perennial streams' landscape class in the zone of potential hydrological change). Users can aggregate and consider potential impacts for their own scale of interest.

Users can also explore the results for landscape classes and assets using a map-based interface at www.bioregionalassessments.gov.au/explorer/HUN/landscapes and www.bioregionalassessments.gov.au/explorer/HUN/assets.

3.2.4.1 Information management and processing

A very large number of multi-dimensional and multi-scaled datasets is used in the impact and risk analysis for each BA, including model outputs, and ecological, economic and sociocultural data from a wide range of sources. To manage these datasets and produce meaningful results, a consistent spatial framework is needed that permits rapid spatial and temporal analyses of impacts without compromising the resolution of the results.

The datasets for this BA are organised into an *impact and risk analysis database* (Bioregional Assessment Programme, Dataset 14) to enable efficient management. The purpose of this database is to produce result datasets that integrate the available modelling and other evidence across the assessment extent of the BA. These datasets are required to support three types of BA analyses: analysis of hydrological changes, impact profiles for landscape classes, and impact profiles for assets. The results of these analyses are summarised in this product, with more detailed information available at www.bioregionalassessments.gov.au. The impact analysis database is also available at data.gov.au.

The datasets used in the impact and risk analysis database (Bioregional Assessment Programme, Dataset 14) include the assets, landscape classes, modelling results (groundwater, surface water and receptor impact modelling), coal resource development 'footprints' and other relevant geographic datasets, such as the boundaries of the subregion, assessment extent and zone of potential hydrological change. All data in the impact and risk analysis database (and the results derived from it) meet the Programme requirements for transparency.

The impact and risk analysis requires the geoprocessing of complex queries on very large spatial datasets. To overcome the computational overload associated with this task a relational approach, rather than a geospatial approach, was utilised. All dataset geometries are split against a universal grid of assessment units that exhaustively cover the assessment extent (Figure 13). An assessment unit is a geographic area represented by a square (1 km^2) polygon with a unique identifier. Assessment units were used to partition asset and landscape class spatial data for impact analysis. The gridded data can be combined and recombined into any aggregation supported by the conceptual modelling, causal pathways and model data.

The gridded data were normalised and loaded into the impact and risk analysis database (Bioregional Assessment Programme, Dataset 14).

Impact area, length and counts are calculated for individual features (e.g. stream reaches, individual assets, groups of assets or landscape classes) at the assessment unit level. An individual analysis result is executed by selecting the assessment units of interest and summing the pre-calculated values of area, length or count for the required dataset. This approach of front-loading the geospatial analysis through grid-base attribution is fundamental to enabling the volume of calculations required to complete the assessment. The approach uses the source geometries in calculation and hence does not impact on the analysis calculations. In a few cases, source geometries were found to create geospatial errors and were removed from the analysis. The removing of invalid geometries did not, in any case, affect the analysis results more than a combined total area of one assessment unit per geospatial item.

The interpolated modelled groundwater drawdowns are at the same resolution as the assessment unit and contain a single value per assessment unit. However, the surface water modelling generates results at points that are extrapolated to links (see Section 3.2.3.2), which must then be mapped to assessment units. For assessment units with only a single stream reach, the assessment unit stores the information associated with this stream segment. However, where the assessment unit contains multiple stream reaches (e.g. at the confluence of two streams), it is necessary to prioritise which stream reach is used to inform the value of the assessment unit for representing the surface water modelling results. The general rules for prioritising a stream reach take into account:

- whether the modelled reaches show a hydrological change (i.e. a reach with a potential hydrological change takes priority over a reach predicted to have no significant change)
- whether the stream reach is represented in the model (i.e. modelled reaches take priority)
- reach length (i.e. where two streams in an assessment unit are of equally high stream order, priority is given to the longer of the two).

Figure 13 Assessment units across the assessment extent

Data: Bioregional Assessment Programme (Dataset 15)

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3.3 Potential hydrological changes

Summary

Potential hydrological changes were derived for the two futures considered in bioregional assessments (BAs): the baseline and the coal resource development pathway (CRDP).

The groundwater zone of potential hydrological change is defined as the area with at least a 5% chance of drawdown exceeding 0.2 m in the regional watertable due to additional coal resource development (as predicted by numerical groundwater modelling). In the Hunter subregion, it spans an area of 2441 km^2 and comprises five discrete drawdown areas in the Upper Goulburn, Lower Goulburn, Central Hunter, Lower Hunter and Macquarie-Tuggerah lakes basins.

The surface water zone of potential hydrological change corresponds to the area along the modelled stream network where the change in at least one of nine surface water hydrological response variables exceeds its threshold due to the additional coal resource development. The thresholds can be generally described as at least a 5% chance of a 1% (or 3 day) or greater change in a flow volume or frequency. It also includes non-modelled perennial and intermittent streams in the groundwater zone of potential hydrological change and ephemeral streams that are directly affected by open-cut mining and site facilities. A total stream length of 1228 km was used to select the assessment units that define the surface water zone.

The combined groundwater and surface water zone of potential hydrological change in the Hunter assessment extent covers an area of 3213 km^2.

It is *very likely* (greater than 95% chance) that an area of at least 528 km^2 could experience 0.2 m of drawdown due to additional coal resource development (additional drawdown); it is *very unlikely* (less than 5% chance) that more than 2441 km^2 exceeds 0.2 m of additional drawdown. It is *very unlikely* that more than 927 km^2 exceeds 2 m of additional drawdown, and *very unlikely* that more than 524 km^2 exceeds 5 m of additional drawdown. When drawdown predictions are constrained using local information, the range of predicted drawdown extent can be reduced. For example, drawdown extents predicted around Wallarah 2 based on local hydrogeological information are predicted to be smaller than extents based on the regional parameter set.

The potential impacts due to additional coal resource development on surface water are assessed using hydrological response variables: low-flow days, high-flow days and annual flow. Results of regional-scale modelling suggest large changes in flow regime are *very likely* in Loders Creek, Dry Creek and two unnamed creeks near the Mount Pleasant and Mount Thorley–Warkworth coal mines. Dry Creek and the unnamed creeks are small and the

hydrological changes are localised. The Hunter Regulated River, into which these creeks flow, is not very sensitive to changes in inflows from them. Wollar Creek, Saddlers Creek and the Wyong River are modelled to have relatively large hydrological changes at the 50th percentile. Wollar Creek, Saddlers and Loders Creek have a hydrological effect on the Goulburn and Hunter rivers into which they flow. However, changes in baseflow to the Goulburn and Hunter rivers due to groundwater drawdown could be more significant than changes in tributary inflows on Goulburn River and Hunter River flows.

Results for the Hunter Regulated River show that decreases in mean annual flow of between 1% and 2% are *very likely*. These changes need to be interpreted with caution, since the Australian Water Resources Assessment river model (AWRA-R) has not been constructed to specifically represent operational management of releases from Glenbawn and Glennies Creek storages.

The potentially large changes in hydrology predicted in the Wyong River reduce considerably when the regional results are constrained using local information. The small chance of at least 200 more low-flow days per year based on the regional analysis becomes a small chance of at least 7 additional low-flow days when the baseflows from the groundwater model are based on local hydrogeological data.

Generally, the modelled changes are small relative to the interannual variability due to climate, especially for annual flow and high-flow days. There is a chance that changes in low-flow days could significantly impact the values associated with streams near all the mining areas, with smaller intermittent and perennial streams close to Central Hunter and Lower Hunter additional coal resource developments particularly at risk. Areas identified as at risk of large hydrological changes require further investigation using local-scale information.

Any change in hydrology could result in changes in stream water quality; however, this was not modelled. A range of regulatory requirements are in place in NSW, which are intended to minimise potential salinity impacts from coal resource development. In the Hunter Regulated River, a salinity trading scheme is managing mine and industry discharges to the river in order to keep salinity to acceptable levels. Discharges to unregulated streams are managed through licences, with conditions attached governing the volume, quality and timing of discharges. Groundwater is typically more saline than surface runoff, which suggests that the predicted reductions in baseflow are more likely to lead to decreases in stream salinity. However, the actual effects depend very much on local conditions, and increases in stream salinity cannot be ruled out.

Users can visualise more detailed results for hydrological changes using a map-based interface on the BA Explorer, available at www.bioregionalassessments.gov.au/explorer/HUN/hydrologicalchanges.

Potential hydrological changes due to additional coal resource development are summarised using hydrological response variables based on results from regional-scale surface water and groundwater modelling, reported in companion product 2.6.1 (Zhang et al., 2018) and companion product 2.6.2 (Herron et al., 2018b) for the Hunter subregion. These hydrological response variables have been defined to represent the maximum difference between the CRDP and baseline for groundwater drawdown and a range of streamflow characteristics. They have also been used to define the zone of potential hydrological change – the focal extent for the impact and risk analysis (Section 3.3.1).

Potential changes in groundwater and surface water within the zone of potential hydrological change are presented in Section 3.3.2 and Section 3.3.3, respectively. Areas are identified that are more at risk of hydrological changes, and hence potentially adverse impacts, due to additional coal resource development. Local scale information is needed to refine the assessment of risk and determine the appropriate management response in these areas. While changes in water quality were not part of the hydrological modelling, the potential for changes in water quality due to additional coal resource development in the Hunter subregion is considered in Section 3.3.4.

Additional hydrological response variables have been defined for input into the landscape class qualitative models and receptor impact models (companion product 2.7 for the Hunter subregion (Hosack et al., 2018)), and for quantifying potential impacts on economic assets. They represent key water dependencies in these systems and are based on average differences over 30-year and 90-year periods. Changes in these variables are presented as part of the impact and risk analysis in Section 3.4 and Section 3.5.

3.3.1 Defining the zone of potential hydrological change

The zone of potential hydrological change is the area within the subregion where changes in hydrology due to additional coal resource development exceed defined thresholds for groundwater and surface water. The impact and risk analysis presented in Section 3.4 and Section 3.5 focuses on landscape classes and assets that intersect this zone. Any landscape class or asset wholly outside of the zone of potential hydrological change is considered *very unlikely* (less than 5% chance) to be impacted due to additional coal resource development.

The zone of potential hydrological change is defined as the union of the groundwater zone of potential hydrological change (Section 3.3.1.1) and the surface water zone of potential hydrological change (Section 3.3.1.2). It is presented in Section 3.3.1.3.

3.3.1.1 Groundwater

The groundwater zone of potential hydrological change is defined as the area with a greater than 5% chance of exceeding 0.2 m of drawdown in the regional watertable due to additional coal resource development. Groundwater impacts of coal mines and coal seam gas (CSG) projects are regulated under state legislation and state regulatory and management frameworks. This 5% chance is determined based on the uncertainty analysis, described in Section 2.6.2.8 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b). It means that, for each individual assessment unit in the groundwater zone, 95% of groundwater model runs exceeded this level of drawdown. The 0.2 m drawdown threshold adopted in bioregional assessments (BAs) is consistent with the most conservative minimal impact threshold in the NSW *Aquifer Interference Policy* (DPI Water, 2012) and Queensland's *Water Act 2000*.

Figure 14 shows the areas with at least a 5% chance of drawdown exceeding 0.2 m under the baseline and the CRDP. The extent of drawdown under the baseline is 4307 km^2 (25% of the assessment extent). This increases to 5129 km^2 (30% of assessment extent) under the CRDP, which represents the combined extent of drawdown under baseline and due to additional coal resource development. It is the area where the drawdown due to the additional coal resource development has at least a 5% chance of exceeding 0.2 m that forms the basis of the groundwater zone of potential hydrological change.

The groundwater zone of potential hydrological change (Figure 15) covers an area of 2441 km^2, or 14% of the assessment extent. It represents the area with at least a 5% chance of exceeding 0.2 m of drawdown due to additional coal resource development. The locations of the additional coal resource developments that were not modelled are shown to identify where, had they been included in the modelling, the groundwater zone may be expected to differ from what is shown.

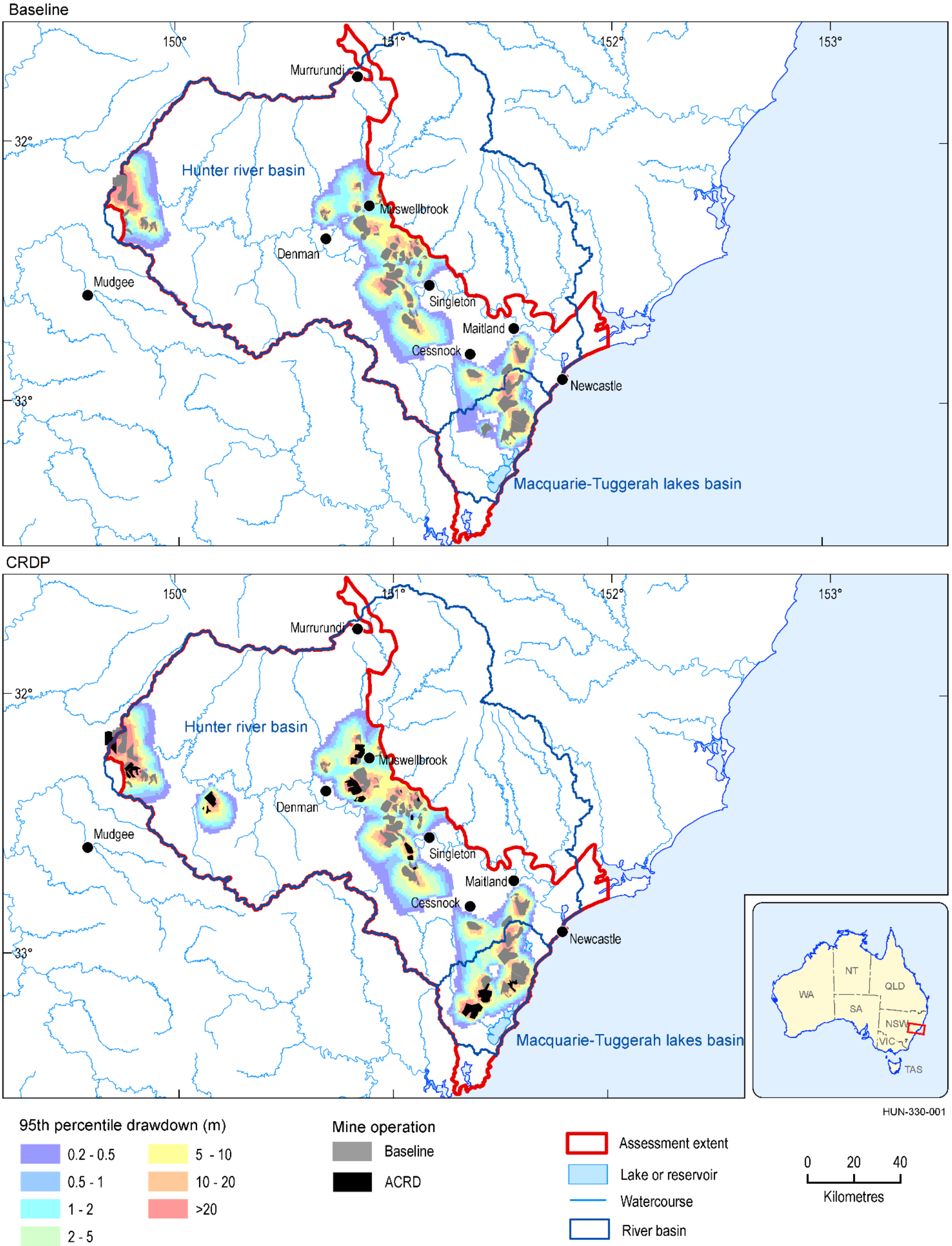

Figure 14 95th percentile of drawdown exceeding 0.2 m under the (a) baseline and (b) coal resource development pathway

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

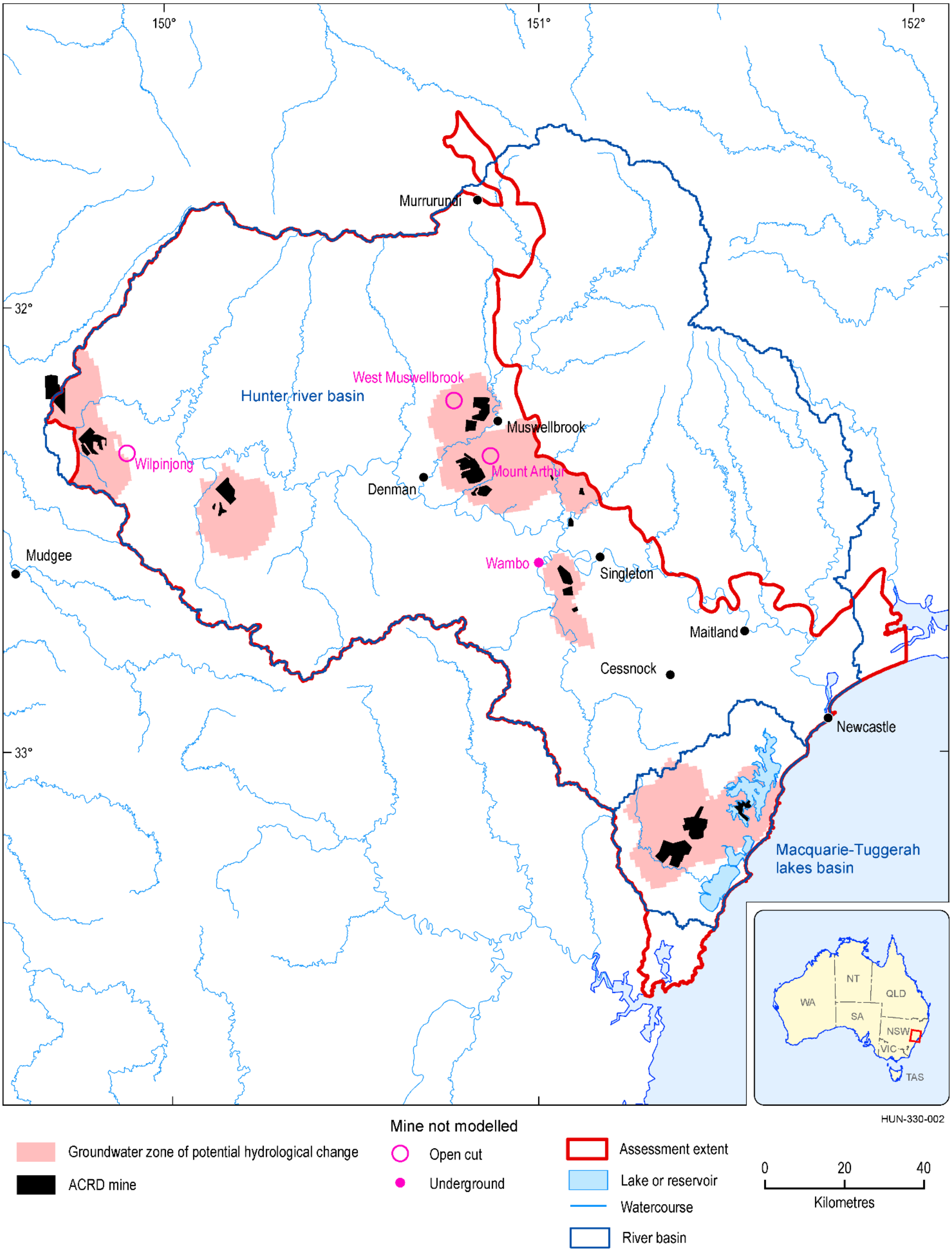

Figure 15 Groundwater zone of potential hydrological change for the Hunter subregion

Additional coal resource developments (ACRDs) that were not modelled in the groundwater model are shown to identify where, had they been included, the groundwater zone might differ.
Data: Bioregional Assessment Programme (Dataset 2, Dataset 3, Dataset 4, Dataset 5)

3.3.1.2 Surface water

The threshold hydrological change adopted for each hydrological response variable for defining the zone of potential hydrological change is given in Table 6. Together the hydrological response variables represent potential changes across the full flow regime, from low flows (P01, ZFD, LFD, LFS, LLFS) to high flows (P99 and FD), including two to represent changes in flow volume (AF) and variability (IQR) (see companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

Table 6 Surface water hydrological response variables and the thresholds used in defining the zone of potential hydrological change

Hydrological response variable	Units	Description	Threshold
AF	GL/year	The volume of water that discharges past a specific point in a stream in a year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	≥5% chance of ≥1% change in AF
P99	ML/day	Daily flow rate at the 99th percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	≥5% chance of ≥1% change in P99
IQR	ML/day	Interquartile range in daily flow; 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).	≥5% chance of ≥1% change in IQR
FD	days/year	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'.	≥5% chance of a change in FD ≥3 days in any year
P01	ML/day	Daily flow rate at the 1st percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	≥5% chance of ≥1% change in P01 and change in runoff depth >0.0002 mm
ZFD	days/year	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).	≥5% chance of a change in ZFD ≥3 days in any year
LFD	days/year	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.	≥5% chance of a change in LFD ≥3 days in any year
LFS	number/year	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 streamflow below the 10th percentile threshold.	≥5% chance of a change in LFS ≥2 spells in any year
LLFS	days/year	Length 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).	≥5% chance of a change in LLFS ≥3 days in any year

A location on the river is deemed to be in the zone if the change in at least one of the nine variables exceeds its threshold. Probability estimates are derived from the predictions of 300 model replicates, each of which uses a unique set of model parameter values. A 5% threshold implies that at least 15 of the 300 replicates have modelled changes that exceed the relevant change threshold. If fewer than 15 replicates have modelled changes that exceed the threshold at a particular location, then the change in that hydrological response variable at that location is considered *very unlikely* to impact water-dependent landscape classes and assets. Table 11 and Figure 28 in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018) identify the model nodes and links in the river-modelling network where the modelled hydrological change exceeds at least one of the hydrological response variable thresholds.

The surface water zone of potential hydrological change includes reaches that make up the AWRA-R link-node network (see Figure 34 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a)), but also needs to include reaches that were not modelled, but which could potentially be impacted due to additional coal resource development. They include:

- *Perennial and intermittent streams within the groundwater zone of potential hydrological change*. It is assumed that within the groundwater zone of potential hydrological change, streams connected to regional groundwater could potentially be affected by additional coal resource development. Streams tagged as 'perennial', 'lowly to moderately intermittent' or 'moderately to highly intermittent' in the modelled flow regime spatial layer for the Hunter subregion (Bioregional Assessment Programme, Dataset 6) are assumed to be connected to groundwater.
- *Ephemeral streams within areas of disruption to surface water drainage.* By definition, ephemeral streams flow only in response to precipitation and have no baseflow component. In other words, they are not connected to regional groundwater, and are unlikely to be affected by groundwater drawdown due to additional coal resource development. However, they can potentially be affected by disruption to surface water drainage on coal mining sites. The 'highly intermittent to ephemeral' stream reaches in the modelled flow regime spatial layer for the Hunter subregion (Bioregional Assessment Programme, Dataset 6) that intersect the surface water maximum footprint areas for open-cut mines for additional coal resource development (Bioregional Assessment Programme, Dataset 2) are potentially impacted.

Of the perennial, intermittent and ephemeral streams identified above, some have been or will be materially altered by mine site excavations under baseline developments, and are unlikely to be affected further due to additional coal resource development. A visual inspection was undertaken of the selected streams, comparing remotely sensed imagery and the surface water maximum footprint areas for open-cut mines under the baseline (Bioregional Assessment Programme, Dataset 2); these reaches were manually removed. The remaining reaches were clipped upstream of the groundwater zone of potential hydrological change (since there can by definition be no changes in this area). They were also extended downstream of the groundwater zone of potential hydrological change to where they join a reach already in the surface water zone of potential hydrological change or a lake, and added to the network of potentially impacted streams. In all, about 1228 km of streams were identified as potentially impacted. These 1228 km of potentially impacted streams were used to select the 1 km x 1 km assessment units (Bioregional Assessment

Programme, Dataset 7) that intersect the stream network (Bureau of Meteorology, Dataset 8) or contain riparian groundwater-dependent ecosystems (GDEs) (Bioregional Assessment Programme, Dataset 6), to define the surface water zone of potential hydrological change. GDEs within 200 m of the stream network were selected automatically, and this selection was inspected and manually adjusted to ensure that riparian vegetation that could potentially be impacted by changes in surface water hydrology is included in the zone. The surface water zone of potential hydrological change is shown in Figure 16. It shows the mine footprints that were included in the surface water modelling.

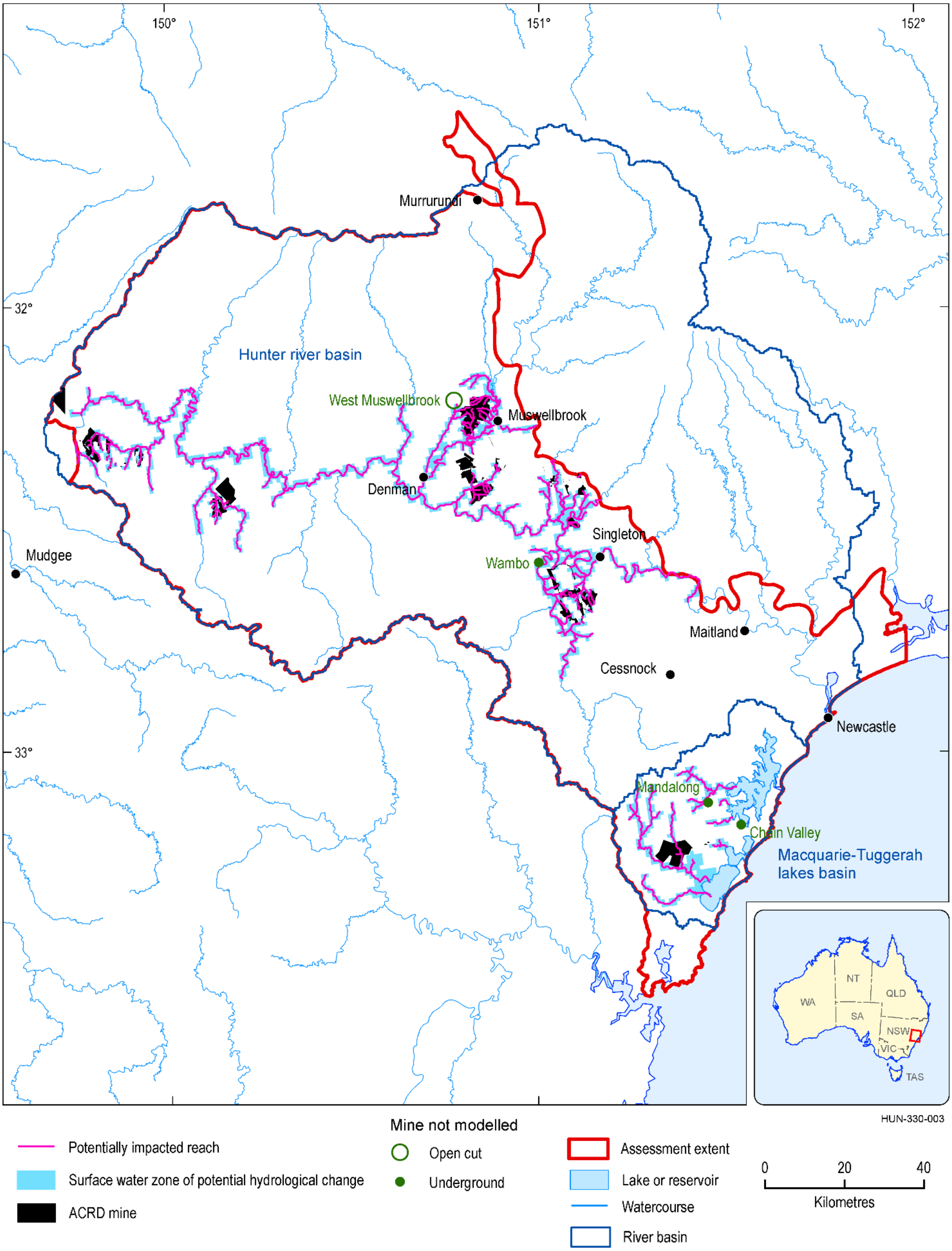

Figure 16 Surface water zone of potential hydrological change for the Hunter subregion

Additional coal resource developments (ACRDs) that were not included in the surface water modelling are shown to identify where, had they been included, the surface water zone might differ.
Data: Bioregional Assessment Programme (Dataset 2, Dataset 3, Dataset 4, Dataset 5), Bureau of Meteorology (Dataset 8)

The surface water zone of potential hydrological change covers an area of 1426 km^2 (about 8% of assessment extent). Given the wide distribution of mines across the subregion, it includes most of the Goulburn River, most of the Hunter Regulated River, Wollombi Brook, and many smaller tributaries of the Goulburn and Hunter rivers. The Wyong River, Jilliby Jilliby Creek, parts of Ourimbah Creek that flow into the Tuggerah Lakes, and a number of smaller streams that drain to Lake Macquarie are part of the surface water zone of potential hydrological change – predominantly due to changes in groundwater.

3.3.1.3 Zone of potential hydrological change

Hydrological changes assessed as part of a BA are summarised for the zone of potential hydrological change. This is derived from the union of the groundwater zone of potential hydrological change (Figure 15) and the surface water zone of potential hydrological change (Figure 16) clipped to the assessment extent, and is shown in Figure 17. The Hunter zone of potential hydrological change covers an area of 3213 km^2 (19% of assessment extent). A graphical summary of the areas (km^2) of the zone and its surface and groundwater components is provided in Figure 18. The zone contains approximately 3136 km of stream (based on the Geofabric stream network (Bureau of Meteorology, Dataset 8)), of which 1228 km are potentially impacted (Section 3.3.1.2) and 1908 km are predominantly low-order, ephemeral streams that can be ruled out as unlikely to be affected by hydrological change. Five reporting areas (Table 7) are defined for reporting purposes to provide greater detail around key coal resource development areas within the subregion.

The zone of potential hydrological change is the first filter applied to landscape classes and water-dependent assets in the Hunter subregion as part of a ‘rule-out’ process for the impact and risk analysis. Landscape classes and assets that are completely outside the zone are *very unlikely* (less than 5% chance) to be impacted due to additional coal resource development and do not have qualitative landscape models or receptor impact models. Landscape classes that intersect the zone have qualitative models and/or receptor impact models, which are used to assess the potential impact of the modelled hydrological changes on the ecosystems represented by the qualitative model or receptor impact models. Details of the qualitative models and receptor impact models are provided in companion product 2.7 for the Hunter subregion (Hosack et al., 2018). Results from the receptor impact modelling are presented in Section 3.4.

3.3.1.3.1 Mine pit exclusion zone

Figure 17 also shows the mine pit exclusion zone defined for the Hunter subregion. It is based on open-cut mine footprints under the CRDP within the zone of potential hydrological change. The mine pit exclusion zone identifies areas within the zone of potential hydrological change that are within, or in close proximity to, open-cut mine pits, and where:

- modelled drawdowns are highly uncertain due to the very steep hydraulic gradients at the mine pit interface
- changes in the drawdown are inevitable where the mine pit intersects the regional watertable and will be at least to the depth of the mine pit

- other factors, such as physical removal of a wetland or creek, may have a larger impact on a landscape class than the predicted decrease in groundwater level
- impacts are predominantly site-scale, and assumed to be adequately addressed through existing development approval processes, and hence not the primary focus of BAs.

The modelled estimates of drawdown, while large, are considered unreliable for use in the receptor impact modelling. Local-scale groundwater models are expected to give better estimates of drawdown around mine pits than is possible using a regional-scale model. The mine pit exclusion zone within the zone of potential hydrological change covers an area of 435 km^2 (Figure 18).

In the impacts on landscape classes and assets sections (Section 3.4 and Section 3.5, respectively), the initial rule-out assessment determines what is in the zone of potential hydrological change and, within that, what is in the mine pit exclusion zone. Features that have a groundwater dependency and occur in the mine pit exclusion zone do not have receptor impact modelling results generated for them; they are assumed to be 'potentially impacted but not quantified'.

Changes in surface water were analysed on an individual stream link basis. Stream links, where it was determined that the change in hydrology for that stream link could not be interpolated from a nearby model node are labelled as 'potential hydrological change' in the maps presented in this section, and are reported in results tables under the header 'potentially impacted but not quantified'.

3.3.1.3.2 Reporting areas

The zone of potential hydrological change has five discrete drawdown areas that correspond to the main areas potentially impacted due to additional coal resource development. Five reporting areas, which encompass the drawdown and potentially impacted surface water network associated with each mining area, have been defined to summarise results (Figure 17). Table 7 identifies the additional coal resource developments within each reporting area. In the Hunter river basin, four drawdown areas are connected by the surface water zone of potential hydrological change, which means that results reported for the Lower Hunter include changes from the Central Hunter, which include changes from the Lower Goulburn and the Upper Goulburn. The Macquarie-Tuggerah reporting area is almost entirely contained within the Macquarie-Tuggerah lakes basin and not hydrologically connected to the Hunter river basin reporting areas.

Table 7 Reporting areas and modelled additional coal resource developments

Reporting area	Additional coal resource developments modelled
Upper Goulburn	Moolarben, Ulan, Wilpinjong
Lower Goulburn	Bylong
Central Hunter	Ashton, Bengalla, Drayton South, Liddell, Mount Arthur, Mount Owen, Mount Pleasant
Lower Hunter	Bulga, Mount Thorley–Warkworth
Macquarie-Tuggerah	Chain Valley, Mandalong, Wallarah 2

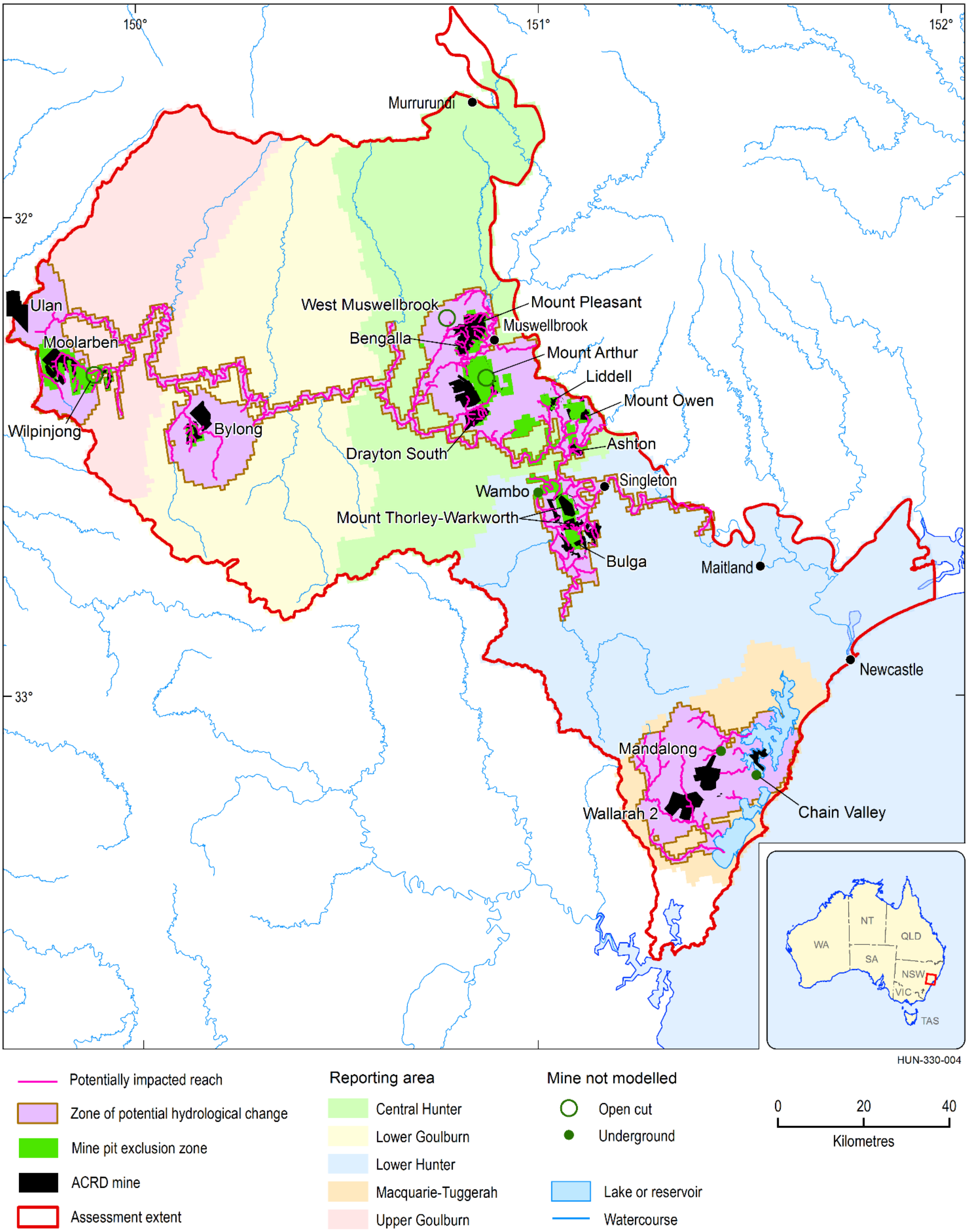

Figure 17 Zone of potential hydrological change for the Hunter subregion

Additional coal resource developments (ACRDs) that were not modelled in one or both of the hydrological models are shown to identify where, had they been included, the zone of potential hydrological change might differ. The reporting areas show where results are summarised as part of the impact and risk analysis.
Data: Bioregional Assessment Programme (Dataset 2, Dataset 3, Dataset 4, Dataset 5)

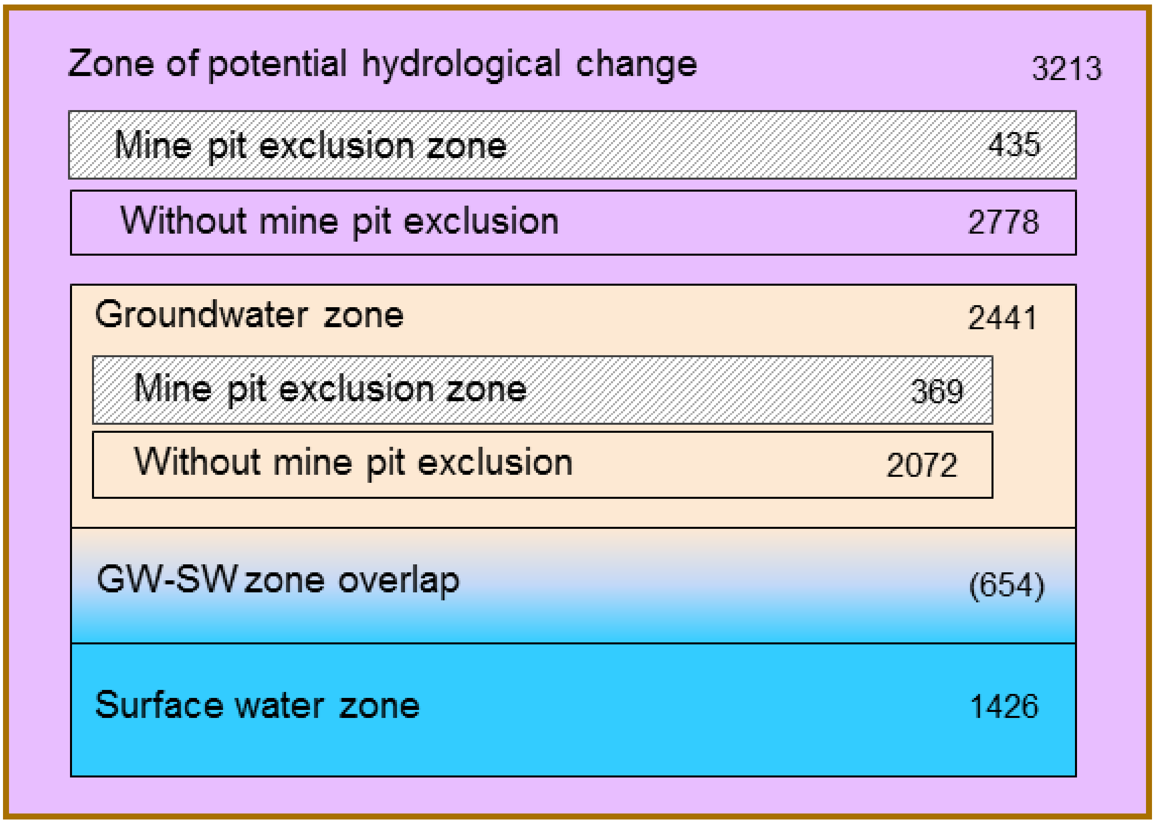

Figure 18 Summary of the areas (km^2) of the zone of potential hydrological change and its surface water and groundwater components for the Hunter subregion

3.3.2 Potential groundwater changes

In assessing potential impacts on groundwater, changes are summarised by the hydrological response variable, *dmax*, which is the maximum difference in drawdown, obtained by choosing the maximum of the time series of differences between two futures. These *dmax* values are presented for the baseline (difference from a 'no-development' model run) and due to additional coal resource development (difference from the baseline run).

In Figure 19, the main panel shows the variation in depth of drawdown within the zone of potential hydrological change for the 50th percentile (median), while the two smaller panels show extents for the 5th and 95th percentiles to illustrate the variability in model predictions due to parameter uncertainty. Table 8 summarises the areas where the additional drawdown is greater than 0.2 m, greater than 2 m and greater than 5 m for the 5th, 50th and 95th percentiles. For additional drawdown greater than 0.2 m, the area associated with the 5th percentile (528 km^2) can be interpreted as representing the extent of drawdown when the model parameters reflect lower pumping rates and/or lower hydraulic conductivities, whereas the area of drawdown associated with the 95th percentile (2441 km^2) also includes the predictions based on higher pumping rates and relatively conductive geological layers. This is a general guide only as the influences of the different parameters can be complex and produce a range of drawdown responses. Groundwater drawdown predictions indicate that drawdowns of greater than 5 m are *very likely* (greater than 95% chance; 5th percentile) due to the additional coal resource developments at Bylong, Mandalong, Ulan and Mount Arthur (Figure 19, top left). Drawdowns exceeding 5 m have at least a 50% chance of occurring at Wallarah 2, Drayton South and Moolarben (Figure 19, main panel).

The spatial distribution of drawdown under the baseline is shown in Figure 20, providing a visual comparison to the potential groundwater drawdown due to additional coal resource development in Figure 19. Under the baseline, the area with at least a 5% chance of drawdown greater than 0.2 m is 4307 km^2. The area of overlap with the groundwater zone is 1619 km^2 and represents the area where drawdowns due to baseline and additional coal resource developments potentially accumulate. Another 260 km^2 overlaps with the surface water zone and defines the area where lagged groundwater drawdown responses from baseline developments could coincide with more instantaneous changes in streamflow due to additional coal resource development. Table 9 summarises the drawdown information in terms of area (km^2) in the zone of potential hydrological change for each drawdown class in each reporting area.

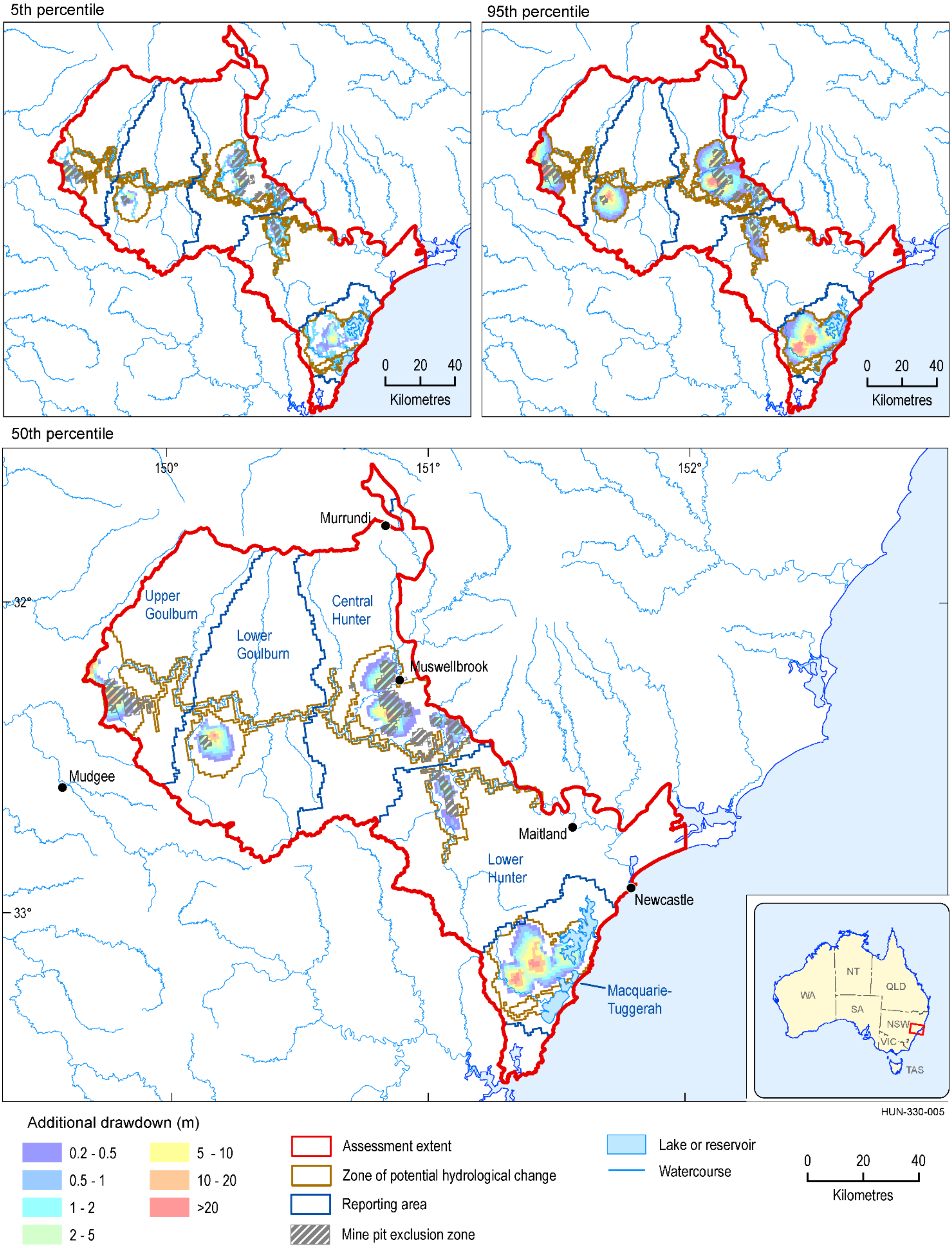

Figure 19 Additional drawdown (m) in the regional watertable (5th, 50th and 95th percentiles)

Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 5, Dataset 9)

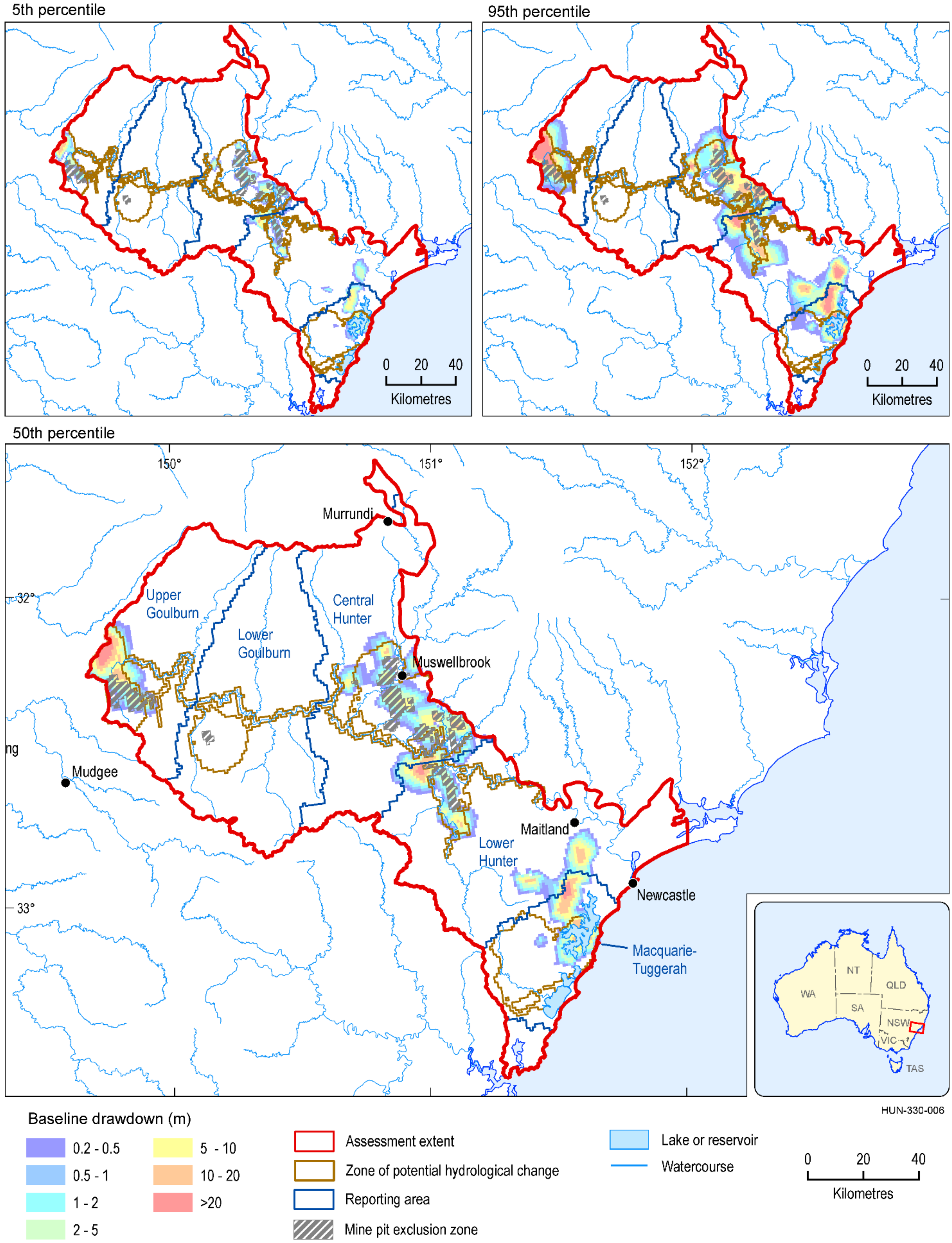

Figure 20 Baseline drawdown (m) in the regional watertable under the baseline (5th, 50th and 95th percentiles)

Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 5, Dataset 9)

Table 8 Area (km²) potentially exposed to varying levels of additional drawdown in the zone of potential hydrological change

Reporting area	Area in zone of potential hydrological change (km²)	Area with additional drawdown ≥0.2 m (km²)			Area with additional drawdown ≥2 m (km²)			Area with additional drawdown ≥5 m (km²)		
		5th	50th	95th	5th	50th	95th	5th	50th	95th
Upper Goulburn	511	80	146	363	35	77	162	12	48	94
Lower Goulburn	494	51	155	343	10	54	129	3	19	64
Central Hunter	1015	157	393	790	24	95	258	10	37	131
Lower Hunter	333	33	82	165	0	5	25	0	0	7
Macquarie-Tuggerah	860	207	453	780	52	230	353	10	123	228
Total	**3213**	**528**	**1229**	**2441**	**121**	**461**	**927**	**35**	**227**	**524**

The area potentially exposed to ≥0.2, ≥2 and ≥5 m additional drawdown for the 5th, 50th and 95th percentile estimates of the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development. Drawdowns in the mine pit exclusion zones cannot be quantified with confidence. Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 9)

Table 9 Area (km²) potentially exposed to varying levels of baseline drawdown in the zone of potential hydrological change

Reporting area	Area in zone of potential hydrological change (km²)	Area with baseline drawdown ≥0.2 m (km²)			Area with baseline drawdown ≥2 m (km²)			Area with baseline drawdown ≥5 m (km²)		
		5th	50th	95th	5th	50th	95th	5th	50th	95th
Upper Goulburn	511	211	310	394	89	208	274	35	143	235
Lower Goulburn	494	0	0	0	0	0	0	0	0	0
Central Hunter	1015	321	597	848	72	237	508	10	88	332
Lower Hunter	333	127	192	255	23	88	178	4	30	131
Macquarie-Tuggerah	860	174	225	381	84	135	178	24	83	125
Total	**3213**	**833**	**1324**	**1879**	**268**	**668**	**1138**	**73**	**344**	**823**

The extent potentially exposed to ≥0.2, ≥2 and ≥5 m baseline drawdown is shown for the 5th, 50th and 95th percentiles. Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Drawdowns in the mine pit exclusion zones cannot be quantified with confidence. Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 9)

Figure 21 summarises the modelled drawdowns under the baseline and due to the additional coal resource development as log-transformed cumulative exceedance plots by area for the 5th, 50th and 95th percentile drawdown distributions. The mine pit exclusion areas are not included. It can be seen that a drawdown of at least 2 m due to the additional coal resource development (right panel) is *very likely* to occur over about 80 km^2, but *very unlikely* to occur over an area exceeding 700 km^2 (as per Table 8). Because the data are not classified, details within the classes can be discerned: drawdowns of at least 1 m due to baseline development are *very likely* over about 300 km^2 and due to additional coal resource development over 150 km^2; drawdowns greater than 50 m are *very unlikely* due to additional coal resource development, but there is a 5% chance of drawdowns between 50 and 100 m over 50 km^2 due to baseline development.

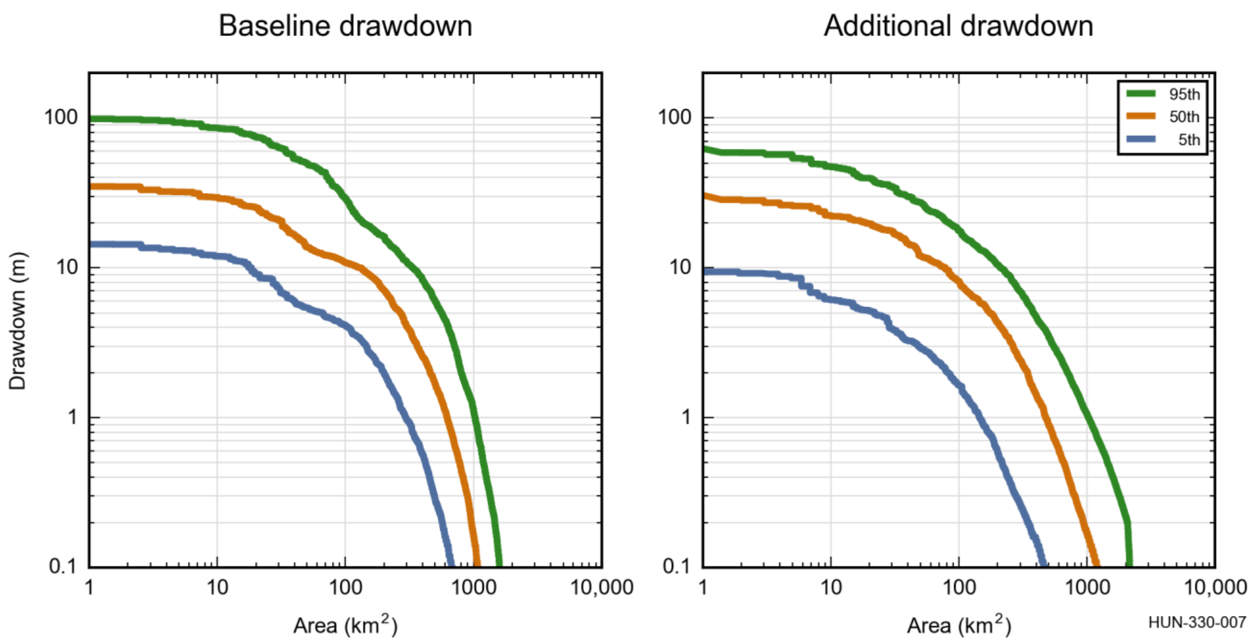

Figure 21 Cumulative exceedance plot of area of drawdown in the zone of potential hydrological change under the baseline and due to the additional coal resource development for the 5th (blue), 50th (orange) and 95th (green) percentiles

Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 9)

When local-scale hydrogeological information is used to constrain model results, the range of predicted drawdown extents can reduce substantially from that predicted using the full set of simulations based on the regional parameter sets. This was illustrated in Section 2.6.2.8 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b) for the area around Wallarah 2 in the Wyong River catchment, where local hydraulic property data from the Wallarah 2 groundwater assessment (Mackie Environmental Research, 2013) were used to constrain model results, and resulted in predictions of drawdown extent, due to the additional coal resource development, at the lower end of the distribution based on the regional parameter sets (see Figure 47 in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)). At the 5th percentile, the modelled area of greater than 0.2 m drawdown in the Wyong River catchment is about 3.5 km^2 (compared with 56 km^2 using regional parameters). Most of this drawdown is associated with the Mandalong Southern Extension project in the adjoining Dora Creek catchment. At the 95th percentile, the area potentially affected by greater than 0.2 m drawdown in the Wyong River catchment is 110 km^2, which, while smaller than the 153 km^2 estimated using the regional parameters (Table 10), corresponds to a 72% overlap. Drawdowns from the Wallarah 2 and Mandalong Southern Extension projects coalesce when the regional parameters are used, but show a more limited connection when results are constrained using local hydrogeological data. The effect on surface water hydrological response variables, of constraining the regional-scale model results based on local-scale information is picked up again in Section 3.3.3. The implications for impacts on GDEs are considered further in Section 3.4.4.

Table 10 Area (km^2) of modelled drawdown in the Wyong River catchment based on regional and locally constrained parameter values

Parameters	Area with drawdown ≥0.2 m (km^2)			Area with drawdown ≥2 m (km^2)			Area with drawdown ≥5 m (km^2)		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
Regional	56	125	153	5.9	85	121	1.1	54	101
Local	3.5	59	110	0.0	3.5	51	0.0	0.2	27

Data: Bioregional Assessment Programme (Dataset 13)

3.3.3 Potential surface water changes

The hydrological response variables generated from the Hunter surface water modelling results are listed in Table 6. Three were chosen to represent changes in low-flow regime (LFD), high-flow regime (FD) and mean annual streamflow (AF) due to additional coal resource development. The additional coal resource development values reflect the maximum difference between streamflow time series of the CRDP and baseline developments from the top 10% of simulations (i.e. 300) for each hydrological response variable.

The Hunter River within in the subregion is regulated by the Glenbawn and Glennies Creek dams. While the AWRA-R modelling of the regulated river includes some aspects of river regulation, it was never intended to be a river operations model, and does not include the more comprehensive set of rules for representing river regulation in the Hunter River that is part of NSW Department of Primary Industries Water Hunter IQQM. The Hunter AWRA-R model uses a simplified approach to represent dam releases based on current levels of demand, ensures that minimum environmental water requirements are met, and includes some rules for mine water discharges under the Hunter River Salinity Trading Scheme (see companion product 2.6.1 (Zhang et al., 2018) and companion product 2.1-2.2 (Herron et al., 2018a) for the Hunter subregion for details of the AWRA-R implementation). Thus the results summarised below do not assume any changes in dam operations in response to the modelled changes.

3.3.3.1 Low-flow days

As defined in Table 6, a low-flow day is one when streamflow is less than the 10th percentile flow from the simulated 90-year period (2013 to 2102) for that stream. The modelled increases in the number of low-flow days due to additional coal resource development in the Hunter assessment extent are shown for the streams in the surface water zone of potential hydrological change in Figure 22. Streams shown as 'potential hydrological change' are likely to experience an increase in low-flow days due to additional coal resource development, but results from upstream or downstream model nodes cannot be reliably interpolated to these reaches due to changes in hydrology along the reach from tributary inflows or coal mining effects.

At the 95th percentile, 408 km of the stream network in the surface water zone of potential hydrological change is modelled to experience increases of at least 3 days in the number of low-flow days per year (as per definition in Table 6). A further 801 km of non-modelled streams could experience similar increases in low-flow days due to additional coal resource development as they flow through catchments disturbed by open-cut mining or are in the groundwater zone of potential hydrological change (Table 11).

Where changes have been quantified, about 22 km of streams in the Central Hunter, Lower Hunter and the Macquarie-Tuggerah reporting areas are *very likely* (5th percentile) to experience increases of at least 3 days per year. They include parts of the Wyong River, Saddlers Creek, Loders Creek, Dry Creek, Swamp Creek and three unnamed creeks draining the Mount Pleasant, Mount Thorley–Warkworth and Liddell additional coal resource developments. There is at least a 5% chance that increases in low-flow days in these six streams will exceed 200 days per year due to additional coal resource development.

In the 'potential hydrological change' reaches where streamflow changes due to the additional coal resource developments have not been quantified, an indication of the potential increases in low-flow days can be inferred from nearby model nodes and stream reaches where potential increases have been quantified, having regard to stream order and proximity to additional coal resource developments.

Increases of more than 80 days per year are *very likely* in the small unnamed creek which drains the northern side of the Mount Pleasant development; and more than 20 days per year in Loders Creek, which drains the Mount Thorley–Warkworth and Bulga developments, and Dry Creek which drains the southern side of the Bengalla development. As identified in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018), these potentially large changes reflect the fact that the mine footprints in these catchments are a large proportion of the total contributing area.

The potentially large changes in some of the small tributary streams of the Hunter River are relatively localised. The much larger Hunter River is not particularly sensitive to the modelled changes in inflows from these tributaries because of its much greater volume of flow and because its flow can be augmented with releases from storage. On the Hunter River, downstream of its junction with Saltwater Creek to just upstream of Singleton, there is a 5% chance of increases of more than 80 days per year in low-flow days. These changes likely reflect the more extreme groundwater drawdown results and associated reductions in baseflow, rather than sensitivity of the river to changes in tributary inflows.

In the Wyong River, results of the modelling indicate a risk of potentially significant impacts from the proposed Wallarah 2 and Mandalong Southern Extension developments. Using the full set of regional parameters, changes in low-flow days of more than 200 days per year are possible (5% chance), which is outside the range of previously experienced low-flow days due to interannual variability. Jilliby Jilliby Creek, which flows through the Wallarah 2 mine lease area and into the Wyong River, and Dora Creek, which drains from the Mandalong Southern Extension, were not represented in the surface water modelling, but could experience similar changes in flow regime to those modelled for Wyong River due to the potentially large drawdowns predicted in the groundwater modelling (Section 3.3.2)

The Wyong River results require further investigation for a number of reasons:

1. Unlike the other streams identified from the regional-scale assessment as 'at risk' of potentially large increases in the number of low-flow days per year, the Wyong River is a perennial river, draining a comparatively larger area, and part of the water supply to the Wyong-Gosford area.
2. Unlike the other 'at risk' streams, which are located close to baseline developments, it is essentially a 'greenfield' area, as hydrological changes from the baseline development at Mandalong in the adjoining Dora Creek catchment are unlikely to have had a significant effect on flows in the Wyong River and its tributary Jilliby Jilliby Creek (see upper panel in Figure 14).
3. Unlike the other 'at risk' streams, which have been assessed as being in poor condition and low recovery potential, the Wyong River has been assessed as being in moderate condition with rapid recovery potential (NSW Office of Water, Dataset 10).
4. The Wallarah 2 development, which is proposed in this catchment, has been controversial due to concerns about potentially adverse impacts on town water supply and ecologically important vegetation communities and habitat.

Given the potentially greater level of risk in the Wyong River catchment, local hydrogeological information was obtained from the Wallarah 2 Environmental Impact Statement (Mackie Environmental Research, 2013) to constrain the groundwater modelling results to the sub-set of simulations (from the full set run as part of the regional-scale assessment) with parameter values consistent with that information (see Section 2.6.2.8 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)). The effect on drawdown predictions of using local information, which indicated that median hydraulic conductivities in this area are about two orders of magnitude lower than the median based on the regional dataset, is shown in Figure 47 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b). The potentially affected area based on a 0.2 m drawdown threshold is smaller across all percentiles (Table 10), and the hydraulic gradient within this area is less steep.

The implications for baseflow to streams and the number of low-flow days per years are dramatic. At the 5th and 50th percentiles, results suggest that the additional coal resource development (predominantly from Wallarah 2, but potentially also affected by the Mandalong Southern Extension) will not have any effect on the number of low-flow days, and that it is *very unlikely* that the increase in the average number of low-flow days per year would exceed 7 days.

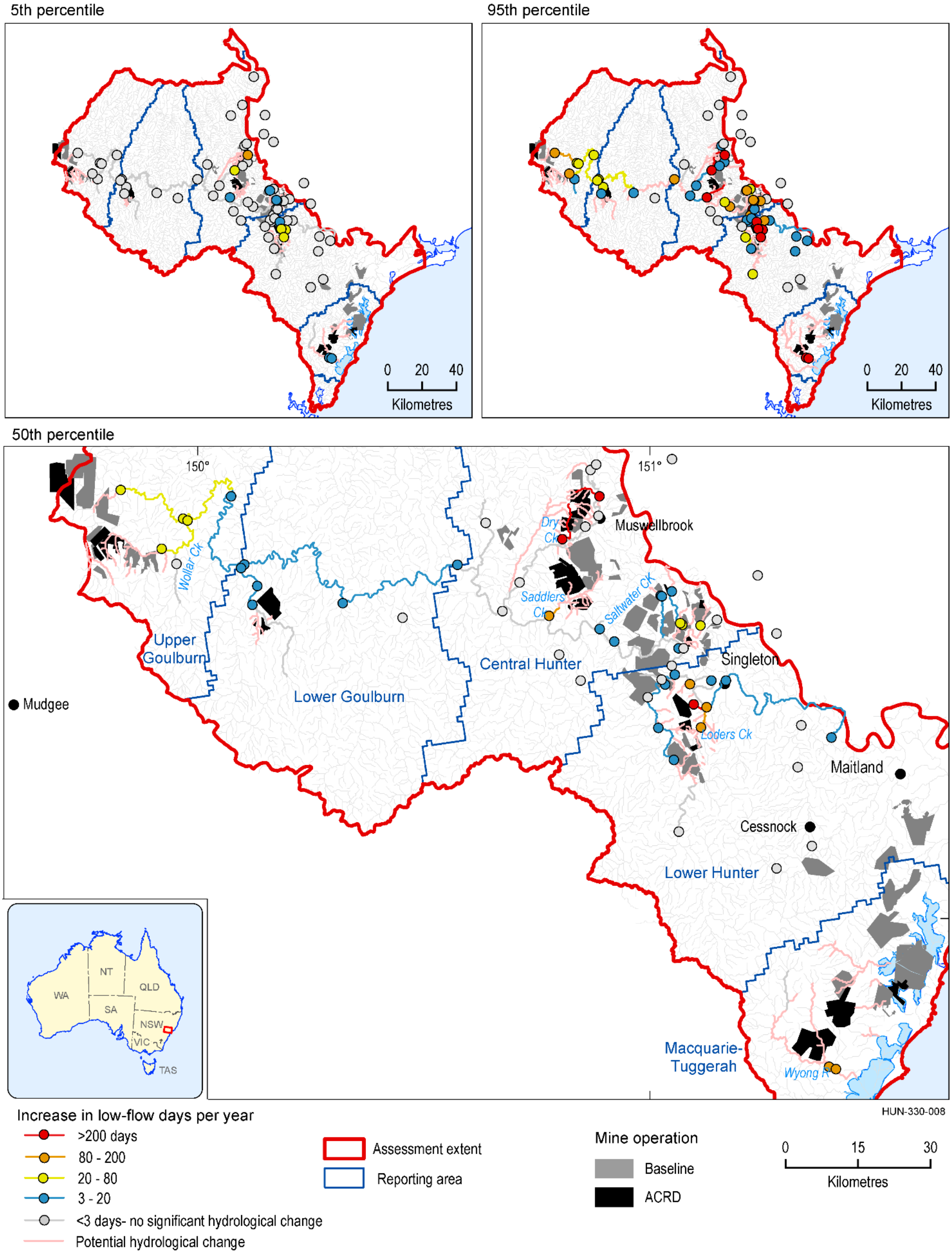

Figure 22 Increases in the number of low-flow days (LFD) due to additional coal resource development (5th, 50th and 90th percentiles)

Data: Bioregional Assessment Programme (Dataset 9)

Table 11 Stream length (km) potentially exposed to varying increases in low-flow days in the zone of potential hydrological change

Reporting area	Length in zone of potential hydrological change (km)	Length potentially impacted but not quantified (km)			Length with increases of ≥3 low-flow days per year (km)			Length with increases of ≥20 low-flow days per year (km)			Length with increases of ≥80 low-flow days per year (km)			Length with increases of ≥200 low-flow days per year (km)		
		5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
Upper Goulburn	192	63	66	79	0	101	113	0	64	101	0	0	26	0	0	0
Lower Goulburn	172	15	16	104	0	105	68	0	0	63	0	0	0	0	0	0
Central Hunter	449	174	186	302	4	42	129	<1	22	50	<1	20	37	0	17	33
Lower Hunter	233	68	87	139	18	93	93	12	9	36	0	9	18	0	4	18
Macquarie-Tuggerah	181	81	118	176	2	2	5	0	2	5	0	2	5	0	0	5
Total	**1228**	**401**	**472**	**801**	**24**	**342**	**408**	**12**	**98**	**255**	**0**	**32**	**86**	**0**	**21**	**55**

Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 9)

To understand the significance of the modelled increases in low-flow days, it is useful to look at them in the context of the interannual variability in low-flow days due to climate. In other words, are the modelled increases due to additional coal resource development within the natural range of variability of the longer-term flow regime, or are they potentially moving the system outside the range of hydrological variability it experiences under the current climate? The maximum increase in the number of low-flow days due to additional coal resource development relative to the interannual variability in low-flow days under the baseline has been adopted to put some context around the modelled changes. This ratio is shown qualitatively for each surface water model node in Figure 23. Table 12 provides the ratio ranges for LFD, FD and AF adopted for each qualitative ratio class shown in Figure 23. It is important to be aware that the changes shown in Figure 23 represent the maximum change due to additional coal resource development in a single year relative to the interannual variability across 90 years under the baseline. Thus it is not a comparison of distributions, but an assessment of whether the change due to additional coal resource development, in the year of maximum difference between the CRDP and the baseline, is within the range of natural variability. If the maximum change is small relative to the interannual variability due to climate (e.g. an increase of 3 days relative to a baseline range of 20 to 50 days), then the risk of impacts from the changes in low-flow days is likely to be low. If the maximum change is comparable to or greater than the interannual variability due to climate (e.g. an increase of 200 days relative to a baseline range of 20 to 50 days), then there is a greater risk of impact on the landscape classes and assets that rely on this water source. Here changes comparable to or greater than interannual variability are interpreted as presenting a risk. However, the change due to the additional coal resource development is additive, so even a ‘less than interannual variability’ change is not free from risk. Results of the interannual variability comparison should be viewed as indicators of risk.

Table 12 Ratio of increase in the number of low-flow days (LFD), high-flow days (FD) and annual flow volume (AF) due to additional coal resource development to the interannual variability in low-flow days under the baseline

Qualitative ratio class	Ratio range
No significant change	LFD <3 days FD ≥3 days AF ≥1%
Less than interannual variability	<0.5
Comparable to interannual variability	0.5–1.5
Greater than interannual variability	>1.5

FD = high-flow days – in previous products, this is referred to as ‘flood days’

At the 5th percentile (Figure 23, top left), the modelled changes in low-flow days represent no significant change or are less than the interannual variability at all model nodes, except one. The change in low-flow days on the unnamed stream near the Mount Pleasant development is *very likely* to experience a change that is comparable to the interannual variability under the baseline, which indicates a potential risk to water-dependent landscape classes and assets in this vicinity. At the 50th percentile (Figure 23, main panel), the changes at five model nodes – in the Central Hunter, Lower Hunter and Macquarie-Tuggerah reporting areas – are comparable to or exceed the baseline interannual variability, suggesting major changes in flow regime driven by reduced runoff and weaker connections to regional groundwater. At the 95th percentile (Figure 23, top right), the increases in low-flow days at 17 locations across the assessment extent suggest the possibility of widespread flow regime changes, particularly in unregulated streams where river flows cannot be topped up through releases of dam water. As discussed above for the Wallarah 2 mining area, local-scale information is needed to refine the regional-scale estimates in areas identified as at risk. The modelled changes in low-flow days in the Wyong River based on the constrained set of model simulations suggest that any changes in the number of low-flow days due to additional coal resource development are likely to be well within the interannual range due to climate in this area.

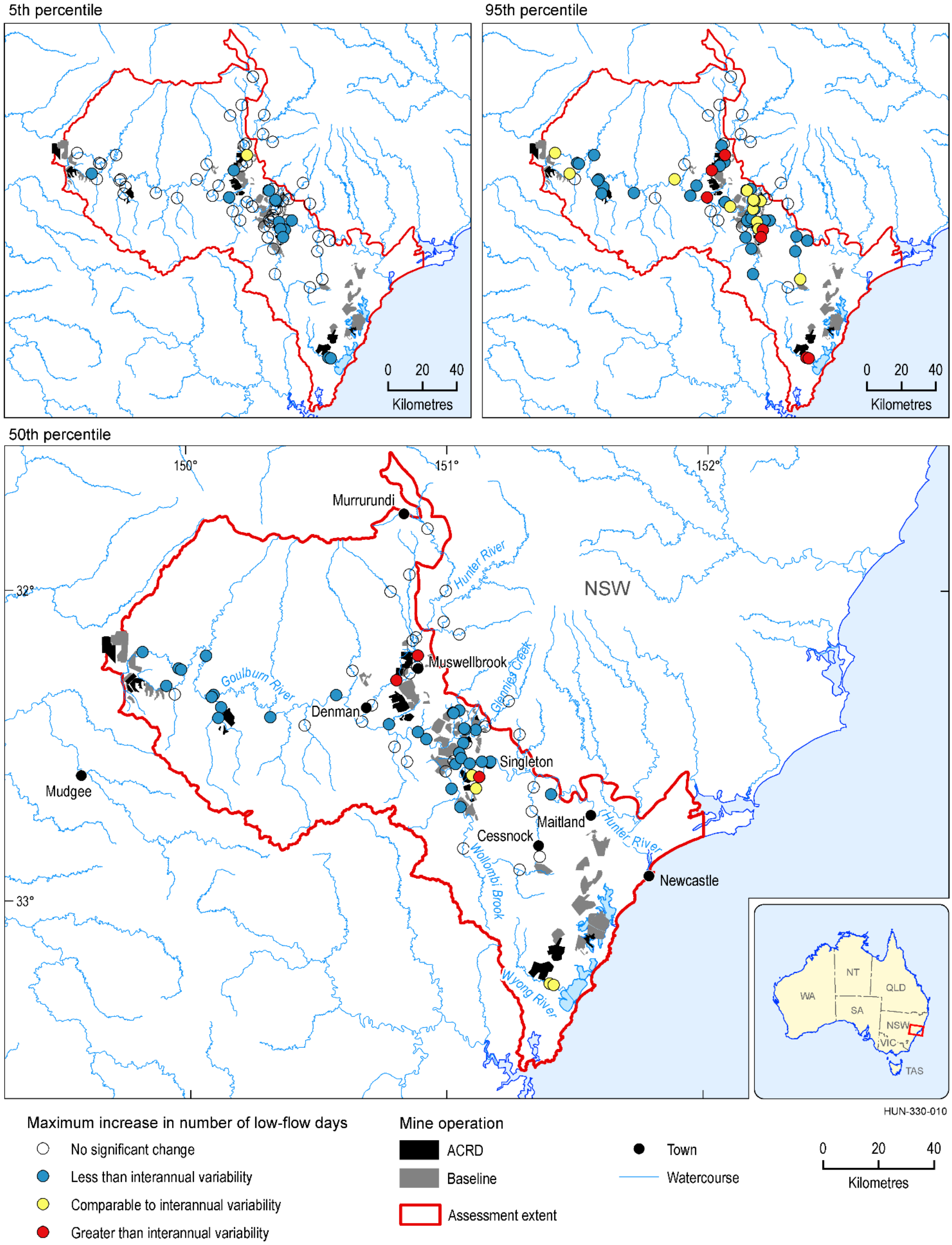

Figure 23 Ratio of change in low-flow days due to additional coal resource development to the interannual variability in low-flow days under the baseline (5th, 50th and 90th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 11)

3.3.3.2 High-flow days

As stated in Table 6, a high-flow day is defined as one in which the streamflow exceeds the 90th percentile flow from the simulated 90-year period (2013 to 2102) for that stream. Reduction in the number of high-flow days due to additional coal resource development in the Hunter subregion is shown in Figure 24, based on results from the regional parameter set. Reductions in high-flow days of at least 3 days per year are *very likely* along lower Wollar Creek, which drains the Moolarben and Wilpinjong mine developments, and in four of the five streams identified as *very likely* to experience above-threshold increases in low-flow days (Figure 22). There is at least a 50% chance that the Wyong River will experience reductions in high-flow days of at least 3 days per year, but is *very unlikely* to experience reductions greater than 20 days per year. However, when the result set is constrained to those simulations with parameter values that are consistent with local hydrogeological information, it appears more likely that the Wallarah 2 development will have a negligible effect on high flows in the Wyong River. It is *very unlikely* that the Hunter Regulated River and most of the Goulburn River will experience reductions in high-flow days of more than 10 days per year.

The total length of stream potentially impacted by reductions in high-flow days is 1116 km, of which the magnitude of change is quantified for 470 km at the flow class level and not quantified for 646 km (Table 13).

The comparison of maximum change in high-flow days due to the additional coal resource development and interannual variability in high-flow days under the baseline (Figure 25) shows that at most nodes, the maximum change is relatively small compared to interannual variability and that the modelled changes are unlikely to increase the stress on these streams. Two streams near Mount Pleasant and Bengalla mines (near Muswellbrook) and in the vicinity of the Mount Thorley–Warkworth and Bulga mines (near Singleton) could potentially experience reductions in high-flow days outside the interannual variability under the baseline. Generally, the impact of additional coal resource development on high-flow days is not as great as it is on low-flow days. In particular, the decrease in number of high-flow days in Saddlers Creek due to the Mount Arthur and Drayton South developments and in the Wyong River due to the Wallarah 2 and Mandalong Southern Extension developments are noticeably less than the increase in number of low-flow days (see Figure 22 and Figure 23).

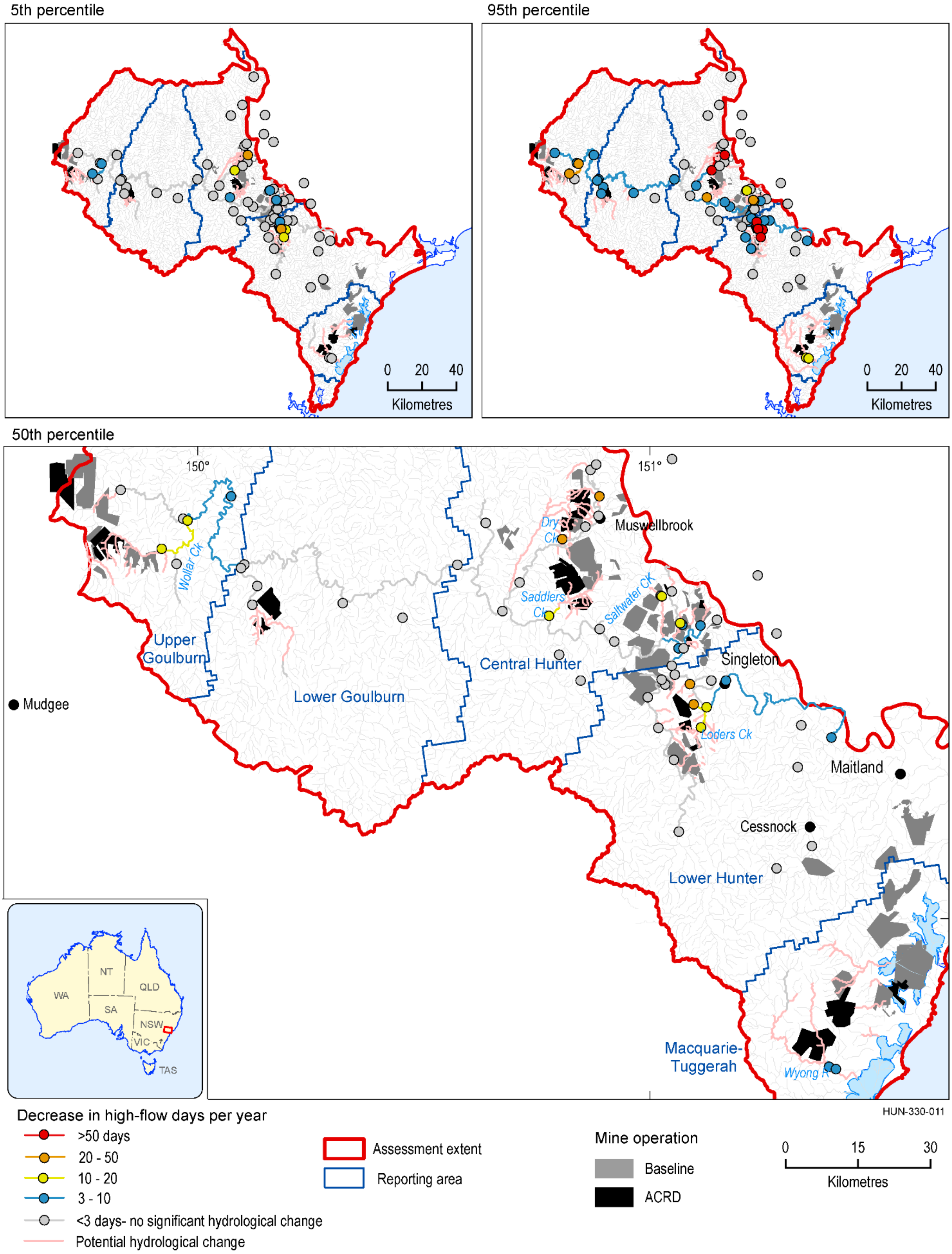

Figure 24 Decrease in the number of high-flow days (FD) due to additional coal resource development (5th, 50th and 90th percentiles)

The 50th percentile map is zoomed in to show detail by excluding those areas that show no significant change.
Data: Bioregional Assessment Programme (Dataset 9)

Table 13 Stream length (km) potentially exposed to varying reductions in high-flow days in the zone of potential hydrological change

Reporting area	Length in zone of potential hydrological change (km)	Length potentially impacted but not quantified (km)			Length with ≥3 day reduction in high-flow days per year (km)			Length with ≥10 day reduction in high-flow days per year (km)			Length with ≥20 day reduction in high-flow days per year (km)			Length with ≥50 day reduction in high-flow days per year (km)		
		5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
Upper Goulburn	192	63	66	79	16	77	101	0	16	16	0	0	16	0	0	0
Lower Goulburn	172	28	38	67	0	0	105	0	0	0	0	0	0	0	0	0
Central Hunter	449	170	197	237	9	26	135	<1	5	22	<1	1	21	0	0	17
Lower Hunter	233	76	77	86	9	61	125	9	9	18	4	0	18	0	0	18
Macquarie-Tuggerah	181	79	116	177	0	4	4	0	0	3	0	0	0	0	0	0
Total	**1228**	**417**	**495**	**646**	**34**	**168**	**470**	**9**	**30**	**58**	**4**	**1**	**55**	**0**	**0**	**35**

Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 9)

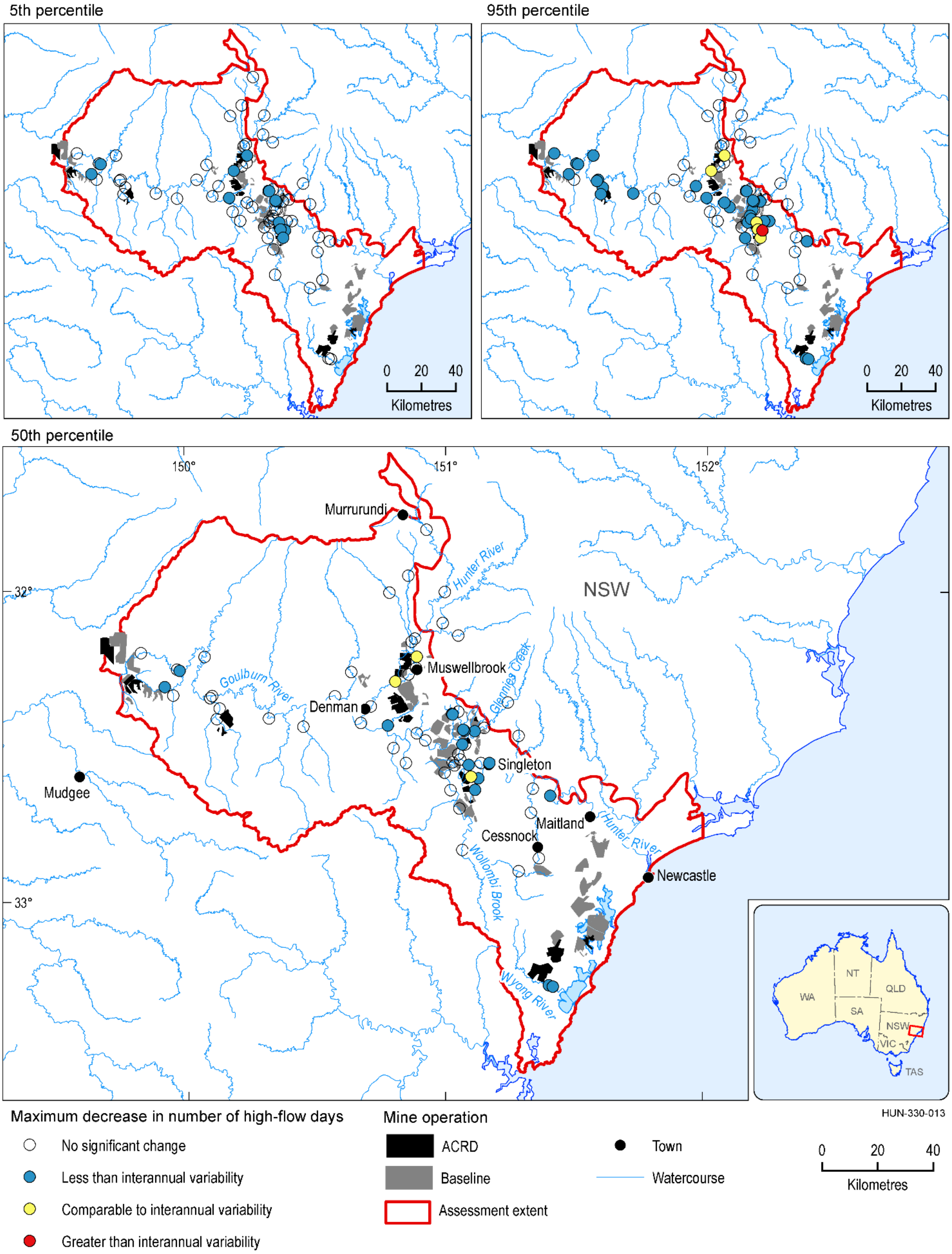

Figure 25 Ratio of change in high-flow days due to additional coal resource development to the interannual variability in high-flow days under the baseline (5th, 50th and 90th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 11)

3.3.3.3 Annual flow

The annual flow (AF) represents the maximum percentage change in the mean annual flow volume (GL/year) over the simulated 90-year period (2013 to 2102) due to additional coal resource development. This is shown in Figure 26 for stream reaches in the surface water zone of potential hydrological change, with summary data presented in Table 14. The extent of stream network that could be subject to at least a 1% reduction in mean annual flow is 1092 km; 441 km of this can be quantified at the flow class level by interpolation of results from surface water model nodes.

Decreases in mean annual flow of at least 5% are *very likely* in lower Wollar Creek, Saddlers Creek, Loders Creek, Dry Creek, Swamp Creek and the three unnamed creeks draining Mount Pleasant, Mount Thorley–Warkworth and Liddell additional coal resource developments, corresponding to 271 km of stream length where results from model nodes can be interpolated to flow classes. Changes in mean annual flow of at least 5% potentially occur more extensively as some of the non-modelled 'potential hydrological change' stream reaches near mining operations are likely to be impacted to a similar degree.

Decreases in mean annual flow of at least 50% are *very likely* in Loders Creek, Dry Creek, Swamp Creek and the unnamed creeks draining Mount Pleasant consistent with the potentially large reductions in high-flow days and shift to greater frequency of low-flow days. These changes are localised as these relatively minor streams feed into the much larger Hunter River, which is largely insensitive to these changes in inflows.

Decreases in mean annual flow of at least 1% are *very likely* along part of the Goulburn River and the Hunter Regulated River, downstream of Saltwater Creek, but decreases of more than 5% are *very unlikely*.

Using the regional parameter set, the effect of additional coal resource development on mean annual flow in the Wyong River is predicted to not be significant (<1% reduction) at the 50th percentile, but there is at least a 5% chance of reductions between 1% and 5% of the baseline mean annual flow. The potentially small effect on mean annual flow relative to the potentially large effect on low-flow days reflects the fact that mean annual flow is strongly influenced by high flows in the river, and that while a small reduction in baseflow to a stream can have a big effect on the number of low-flow days, this does not necessarily result in a big change in annual streamflow volumes. As discussed previously, when the constrained set of simulations is used to assess risk of potentially adverse impacts in the Wyong River, the potential reductions in mean annual flow range from <0.2 GL/year (5th percentile, 2013 to 2042) to about 1.25 GL/year (95th percentile, 2043 to 2072), well below the range predicted using the regional parameter set (0.2 to 5.7 GL/year).

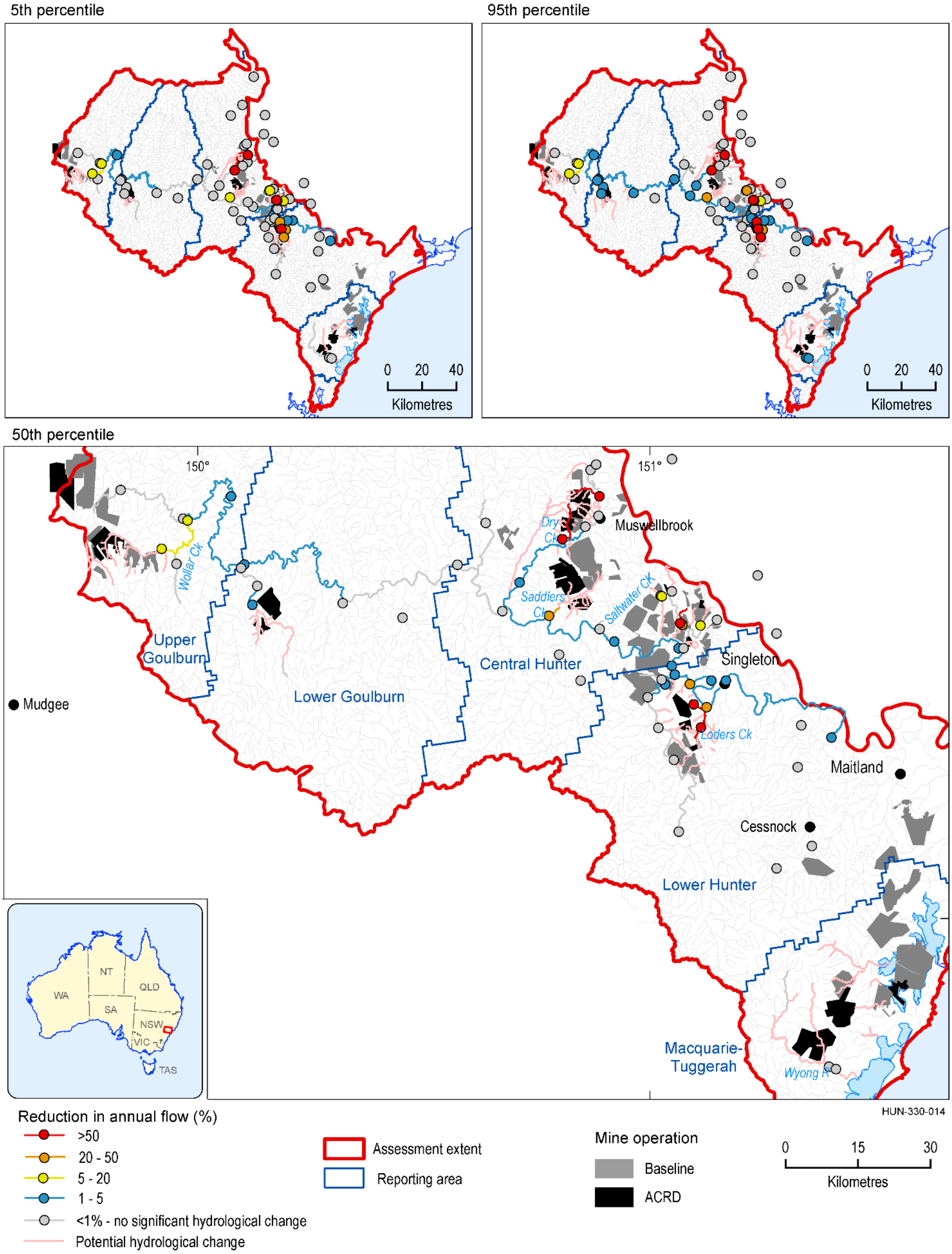

Figure 26 Decrease in annual flow (AF) due to additional coal resource development (5th, 50th and 90th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 9)

The maximum change in annual flow due to additional coal resource development relative to the interannual variability of annual flow under the baseline is shown for each surface water model node in Figure 27. In no case is the maximum change in annual flow due to additional coal resource development greater than the interannual variability under the baseline. There is at least a 50% chance at four locations and at least a 5% chance at another two locations that the changes are comparable to the interannual variability under the baseline. These occur in the Central Hunter and Lower Hunter reporting areas only.

Table 14 Stream length (km) potentially exposed to varying reductions in annual flow in the zone of potential hydrological change

Reporting area	Length in zone of potential hydrological change (km)	Length potentially impacted but not quantified (km)			Length with ≥1% reduction annual flow (km)			Length with ≥5% reduction annual flow (km)			Length with ≥20% reduction annual flow (km)			Length with ≥50% reduction annual flow (km)		
		5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
Upper Goulburn	192	53	56	79	77	77	77	16	16	16	0	0	0	0	0	0
Lower Goulburn	172	28	38	67	56	61	105	0	0	0	0	0	0	0	0	0
Central Hunter	449	154	187	251	54	126	150	26	26	26	22	26	26	22	22	22
Lower Hunter	233	76	74	76	84	100	106	9	12	18	9	12	18	4	12	17
Macquarie-Tuggerah	181	61	116	177	0	0	4	0	0	0	0	0	0	0	0	0
Total	**1228**	373	472	651	271	364	441	51	54	59	32	38	**44**	26	34	39

Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 9)

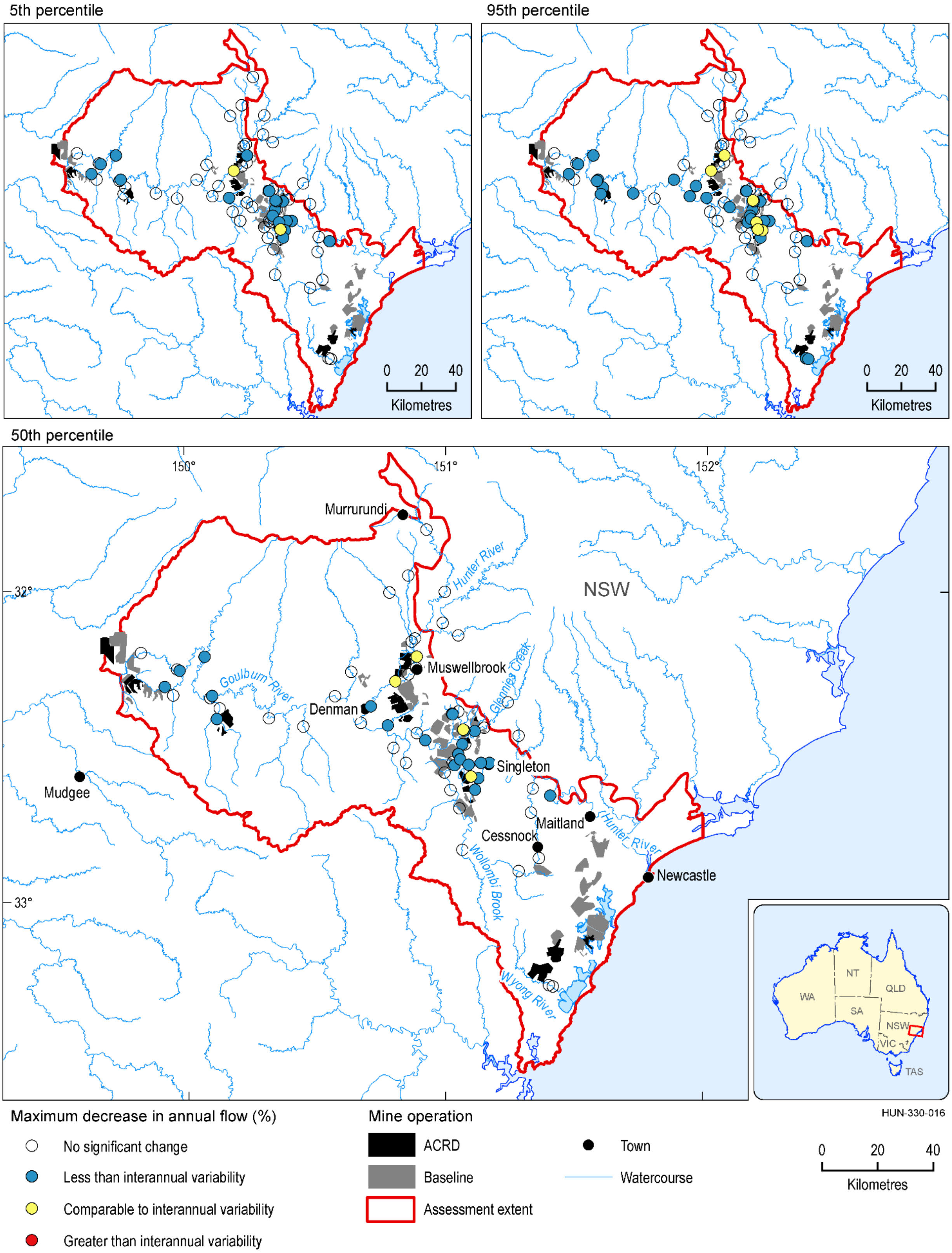

Figure 27 Ratio of change in annual flow due to additional coal resource development to the interannual variability in annual flow under the baseline (5th, 50th and 90th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 11)

3.3.4 Potential impacts on water quality

Regional changes in surface water and groundwater flows due to additional coal resource development could potentially lead to changes in surface water and groundwater quality. While water quality was not modelled as part of this BA, the implications for water quality in the Hunter subregion are considered here in light of the modelled hydrological changes due to additional coal resource development.

Relevant factors for assessing the potential for changes in regional groundwater and surface water quality from the additional coal resource developments in the Hunter subregion are:

- High levels of connate salt in the Greta Coal Measures and Wittingham Coal Measures, which were formed during marine transgressions (Kellett et al., 1989). Estimated salt yields of 30 to 40 T/km^2/year from these measures, compared to 4 to 5 T/km^2/year for Carboniferous and Triassic units have been reported (Creelman (1994) reported in NSW EPA (2013)).
- Areas of high background salinity, including the Jerry Plains area and the Wollombi Brook valley between Broke and Singleton, where Permian rock units occur at the surface (Figure 28). Saline discharges occur from springs associated with geological and geomorphological features, such as the Hunter-Mooki Fault Thrust System and break-of-slope areas.
- Stream salinity is a significant management issue in the Hunter river basin. Sources of salt include rainfall and weathering products, which enter the stream via surface runoff pathways, and groundwater sources, particularly from Permian coal measures. Streams with identified groundwater interactions often have high salinities. Of the surface water salinity observations from across the Hunter subregion, median electrical conductivities exceed 5500 µS/cm in Loders Creek in the Singleton water source, Saddlers Creek and Saltwater Creek in the Jerrys water source, minor creeks around Mount Arthur coal mine in Muswellbrook water source and Big Flat Creek in the Wybong water source. In the Upper Goulburn River and Wollar Creek, median electrical conductivities exceed 2300 µS/cm (Figure 29; NSW EPA, 2013). Coal mining is thought to contribute to stream salinity, although this is difficult to confirm due to lack of long-term monitoring data and a highly variable climate.
- The Hunter River Salinity Trading Scheme (HRSTS) was introduced to manage the discharge of saline water from coal mining and power generation sites along the Hunter Regulated River.
- Some coal resource developments in the subregion are required to manage discharges according to volumes, quality and discharge windows specified in environment protection licences (EPL), which are a condition of their approval to operate.
- There is no CSG development in the CRDP and potential water quality issues from use of fracking chemicals is not relevant; nor can well failure leading to leakage between aquifers be considered a real risk because construction of large numbers of wells is not a feature of open-cut and longwall coal extraction methods.
- None of the additional coal resource developments proposes to re-inject co-produced water into depressurised aquifers.

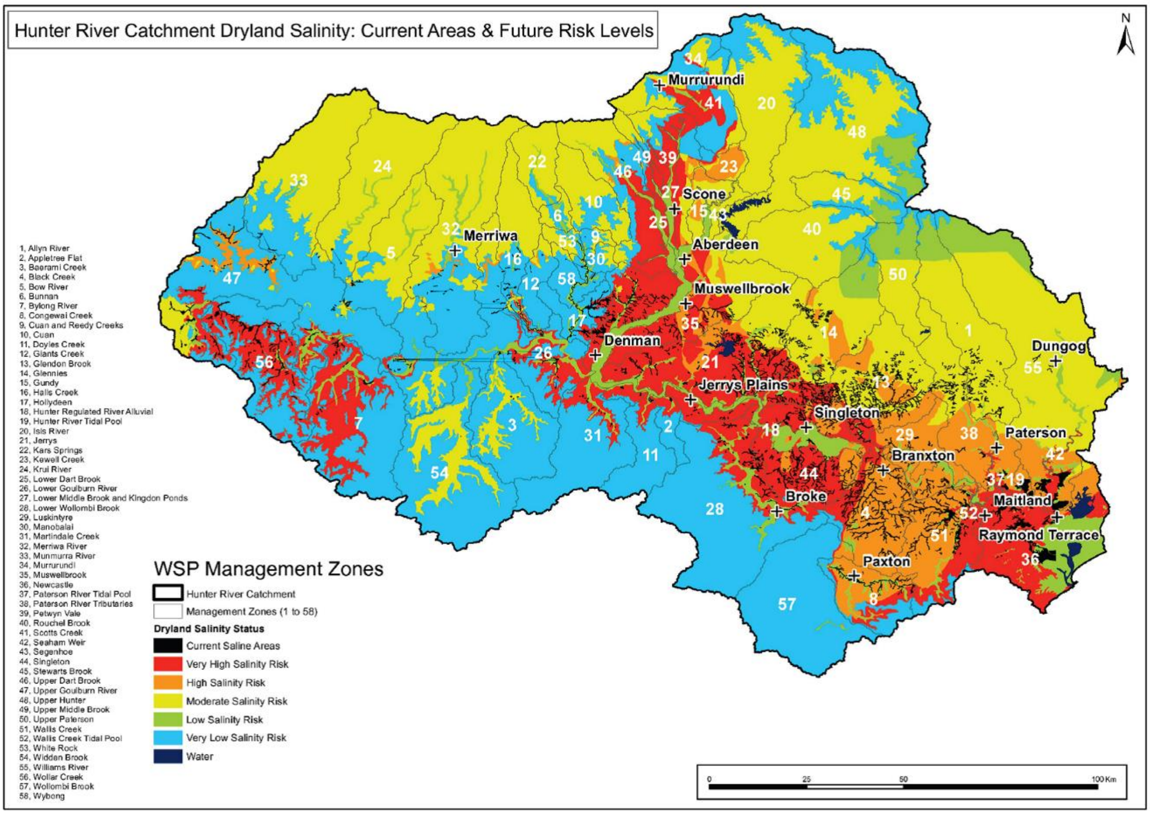

Figure 28 Areas of dryland salinity and salinity risk in the Hunter river basin

Source: NSW EPA (2013)

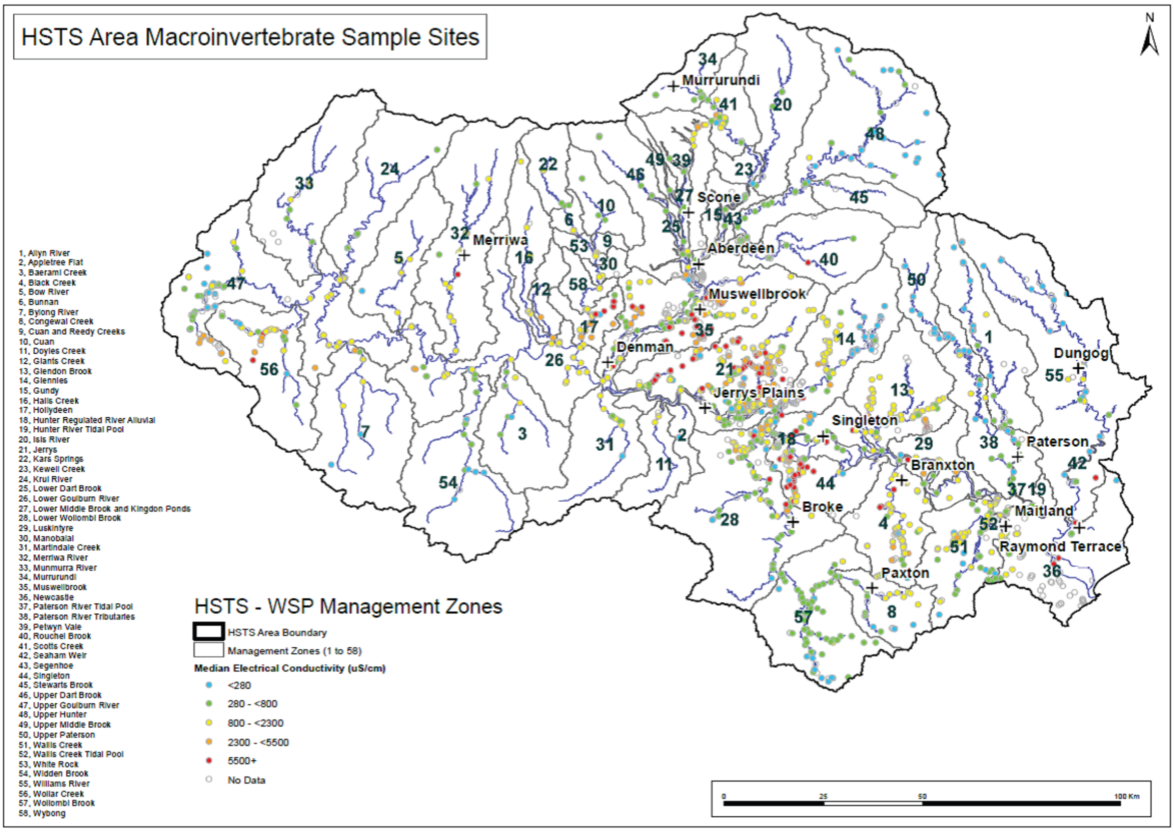

Figure 29 Surface water electrical conductivity (µS/CM) levels in the Hunter river basin

Source: NSW EPA (2013)

In the following sections the groundwater and surface water causal pathways that could potentially lead to regional impacts are identified and the risk of impact is assessed. The extent of influence and existing regulation and management practices are used to inform the assessment of risk.

3.3.4.1 Groundwater quality

Changes in groundwater quality from coal resource development can occur as an indirect result of depressurisation and dewatering of aquifers and changes to subsurface physical pathways between aquifers, which enhance leakage between aquifers of different quality water. Changes in groundwater quality can also occur as a direct result of coal resource development and operational water management, such as when water is deliberately injected into an aquifer or coal seam to manage surplus water or counter the effects of groundwater depressurisation. Unless hydrologically isolated from their surroundings, the creation of coal stockpiles, rock dumps and tailings dams on coal mine sites can result in leaching of contaminants to groundwater. In all these cases, a hazard arises when the quality of the receiving water is changed such that it reduces its beneficial use value. BAs are concerned with the risk from non-accidental changes to water quality off site, which may be cumulative where mining operations are in proximity.

Table 15 lists potential causes of changes in groundwater quality from coal resource development in the Hunter subregion and identifies the potential for off-site impacts. Regional changes in groundwater quality from bore leakage is considered unlikely, as bore construction and maintenance must be undertaken in accordance with state regulation to minimise leakage.

In NSW, a water supply work approval is needed under NSW's *Water Management Act 2000* for a new bore. Construction of a bore must be undertaken by a licensed driller and drillers are expected to meet minimum requirements set out in guidelines developed by the National Uniform Drillers Licensing Committee (NUDLC, 2012). These guidelines detail mandatory requirements and good industry practice for all aspects of the bore life cycle from bore design, bore siting, drilling fluids, casing, maximising bore efficiency, sealing and bore completion. While some leakage from older bores is considered likely, these bores are not part of the potential impact due to additional coal resource development and not within the scope of this BA. Three of the four causal pathways in Table 15 could potentially have off-site impacts. In the remainder of this section, the likelihood of impacts is considered in the context of existing regulatory controls.

The potential impacts on watertable level, water pressure and groundwater quality from environmentally relevant activities such as coal mining are managed through the *NSW Aquifer Interference Policy* (DPI Water, 2012). This policy requires that all water taken from an aquifer is properly accounted for; minimal impact considerations on the watertable, water pressure and water quality are addressed; and remedial measures are planned for in the event that actual impacts are greater than predicted. For aquifers in the Hunter subregion, no change in the beneficial use category of a groundwater source farther than 40 m from the activity is permitted, unless studies can demonstrate that the change in groundwater quality will not affect the long-term viability of any water sharing plan, GDE, culturally significant site or water supply work. An increase of more than 1% per activity of the long-term average salinity is not permitted in a highly connected water source at the nearest point to the activity. As part of their groundwater monitoring and modelling plans, mining companies must demonstrate to the satisfaction of the NSW Department of Primary Industries Water, that the proposed development is undertaken in accordance with the policy. Given this, the potential for significant changes in regional groundwater quality are likely to be low.

Table 15 Potential causes of changes in groundwater quality and potential for off-site impacts in the Hunter subregion

Causal pathway	Water quality concern	Scale	Off-site impacts in Hunter subregion
Groundwater pumping enabling coal extraction	Leakage between aquifers that diminishes the beneficial use value due to changes in water quality	Local to regional	Potential for off-site impacts from changes in the hydraulic gradients between connected aquifers of differing water quality
Failure of bore integrity	Leakage between aquifers that diminishes the beneficial use value due to changes in water quality	Local	Off-site impacts are unlikely. State regulation and best practice guidelines are in place to minimise potential impacts from bore construction and use.
Subsurface fracturing above longwall panels	Leakage between aquifers that diminishes the beneficial use value due to changes in water quality	Local to regional	Potential for off-site impacts from changes in the hydraulic gradients between connected aquifers of differing water quality
Leaching from stockpiles, rock dumps, tailings dams, storage dams	Leaching of contaminants into aquifers that reduce their beneficial use	Local to regional	Potential for off-site impacts, but regulatory controls in place to minimise risk

Changes in tensile and compression forces in the overburden above longwall panels following their collapse can lead to fracturing above longwall panels and hydraulic enhancement of the goaf, with the potential for freer movement of water between aquifers of potentially different water quality. Hydraulic enhancement was modelled in the Hunter groundwater model (companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)) and was shown to affect the extent of drawdown zone and surface water – groundwater exchanges, but implications for groundwater quality were not modelled. Sometimes groundwater assessments undertaken by mines represent changes in hydraulic properties above longwall panels in their modelling, but sometimes these changes are ignored because the scale of influence is deemed too local to affect larger-scale drawdown predictions. If hydraulic enhancement of the goaf is ignored, the hydraulic properties of the interburden may be overestimated to compensate for the lack of groundwater flowing into the mine. Invariably the groundwater models do not represent changes in groundwater quality or surface water quality due to changes in hydraulic properties. The effect of coal resource development on the water quality of nearby aquifers and streams in the Hunter subregion remains largely a knowledge gap.

In relation to leaching of contaminants from mining-related contaminant sources, the Department of Industry Resources and Energy (DIRE), under NSW's *Mining Act 1992*, requires mines to have an approved mining operations plan (MOP). The MOP provides details of how the mining operation will be carried out, including details of management of stockpiles, rock dumps and tailings dams. Mining companies, as part of best practice management, are required to design storages that are secure and stable over their life and have a low risk of spills.

3.3.4.2 Surface water quality

Changes in surface water quality from coal resource development can occur as a result of disruptions to surface drainage from the removal of vegetation and disturbance of soil in construction of roads, site facilities, excavation of open-cut pits and landscaping of the site during production and rehabilitation. Bare surfaces increase the risk of erosion with potential to increase total suspended solids (TSS) in waterways. The discharge of mine water into the stream network as part of operational water management is potentially hazardous if the quality of the discharged water lowers the quality of the receiving water below its current beneficial use level. Groundwater pumping and subsurface fracturing above longwall panels can lead to changes in baseflow to streams and potentially affect the water quality of the stream. Table 16 lists potential causes of changes in surface water quality from coal resource development and identifies the potential for off-site impacts in the Hunter subregion, having regard to the likely scale of the effect and existing management. One causal pathway is considered unlikely to lead to significant off-site water quality impacts; three could potentially have off-site impacts on water quality.

Table 16 Potential causes of changes in surface water quality and potential for off-site impacts

Causal pathway	Water quality concern	Scale	Off-site impacts in Hunter subregion
Altering surface water system	Increased total suspended solids in waterways from soil eroded off mine site; changes in stream salinity	Local	Off-site impacts are unlikely. Managed through regulatory requirements attaching to mining operations plans.
Discharging extracted water into surface water system	Discharge water diminishes the beneficial use value due to changes in water quality	Local to regional	Potential for off-site impacts. Managed through Hunter River Salinity Trading Scheme and environment protection licence conditions.
Groundwater pumping enabling coal extraction	Change in baseflow to stream diminishes the beneficial use value due to changes in water quality	Local to regional	Potential for off-site impacts. Managed through *NSW Aquifer Interference Policy.*
Subsurface fracturing above longwall panels	Change in baseflow to stream diminishes the beneficial use value due to changes in water quality	Local to regional	Potential for off-site impacts. Managed through *NSW Aquifer Interference Policy.*

The likelihood of off-site soil loss and sedimentation impacts from altering the surface water system on the mine sites is considered unlikely. There is a long history of soil erosion management in NSW, which has its origins in the agricultural sector, but has been extended to minimise the generation and mobilisation of sediments in all developments where disturbance of the soil occurs. NSW DIRE requires mines to provide details of how the mining operation proposes to minimise soil loss at all life stages of the mine and post-mining as part of an approved MOP. EPLs, issued by DIRE under NSW's *Protection of the Environment Operations Act 1997*, may also specify erosion control conditions. Furthermore, DIRE requires authorised mines to develop, implement and report on environmental monitoring programs. In annual environmental management reports (AEMR), the coal mining companies must publish their monitoring data in order to demonstrate that they are meeting their environmental objectives under their licence to operate.

3.3.4.2.1 Stream salinity

Reductions in catchment runoff can increase the salinity of a receiving stream, where the runoff is less saline than the receiving stream. Catchment runoff occurs during and shortly after significant rainfall events and is typically the main contributor of fresher water to peaks in the streamflow hydrograph. Where the mine footprint (which for surface water includes areas where runoff is intercepted by mine pits and storages, and is retained on site) is small relative to the contributing area of the stream into which it drains, the risk of large increases in stream salinity from reducing catchment runoff is likely to be very low; where the opposite is true, the salinity of peak flows could become increasingly biased towards the salinity of baseflow. If, at the same time, groundwater drawdown has contributed to a reduction in baseflow or a disconnection between the stream channel and groundwater, then stream salinity will reflect the changes in the relative contributions from catchment runoff, baseflow and streamflow from up catchment.

3.3.4.2.1.1 Discharges to regulated river

There are many competing demands on water resources in the rivers of the Hunter subregion and water needs to be of a quality to support a diverse range of agricultural uses, town water supply and environmental needs. Background salt levels are naturally high in some parts of the subregion where geological layers, such as the Permian coal measures, which formed under marine transgressions, outcrop at the surface (Figure 28). In addition, discharge of saline water from coal mining and power generation operations has been identified as a significant source of salt, and concerns about increasing stream salinities in the Hunter River led to the introduction of the HRSTS in the late 1990s. The scheme introduced a capped system of tradeable salinity credits to limit annual discharges of salt to the Hunter River, and established rules to govern the timing of discharges from participants in the scheme to ensure water quality is maintained at an acceptable level for other users. Dartbrook, Mount Arthur, Bengalla, Hunter Valley Operations, Liddell, Ravensworth, Wambo and Mount Thorley–Warkworth coal mines are all participants of the scheme. Discharges are permitted during high-flow and flood-flow windows when the natural salinity of the river decreases in response to the influx of relatively fresh surface runoff and the river can accommodate extra salt from industrial discharges without exceeding salinity thresholds. Discharges are monitored and reported in an annual statement by the NSW EPA, which summarises the flow and salinity of the river at three locations over the year and details the mine discharges that occurred (see NSW EPA (n.d.)). These monitoring reports indicate that HRSTS is operating as intended and mine discharges are not leading to periods of unacceptable salinity.

Results from the hydrological modelling of additional coal resource development can be used to assess whether the modelled changes in Hunter River flows are likely to impact upon the opportunities the mines and power generators have to discharge saline water to the river under the scheme. Flow rate thresholds are defined at model nodes 6, 20 and 51 for each of the three river reaches making up the HRSTS. Table 17 summarises the discharge thresholds at each node. Industry discharges to the river are permitted when flow rates are above these thresholds. Table 18 summarises the mean annual change in discharge opportunities in the Hunter Regulated River due to additional coal resource development for each 30-year period. The modelled number of discharge days under the baseline are provided to show the interannual variability in discharge days due predominantly to climate. In the most downstream reach of the HRSTS (model node 6), there is a greater than 95% chance of greater than 26 discharge days and a 5% chance of greater than 99 discharge days; in the upstream reach, represented by model node 51, there is a 95% chance of greater than 34 discharge days and a 5% chance of greater than 151 discharge days. Discharge days tend to be fewer in the middle reach. The modelling results suggest that there is *very unlikely* to be an impact upon discharge days under the HRSTS due to additional coal resource development. At the two upstream model nodes (20 and 51), additional coal resource development has no impact on discharge opportunities, with average reductions of less than 1 day per year in all three periods. At the Singleton gauging station (model node 6), additional coal resource development could potentially cause an average reduction of 1 to 2 days in discharge days.

Table 17 Flow rate threshold (ML/day) for mine discharges to the Hunter River under the Hunter River Salinity Trading Scheme

Model node	Gauge ID	Name	Flow rate threshold (ML/d)
6	210001	Hunter R at Singleton	2000
20	210127	Hunter R upstream Glennies Ck	1800
51	210055	Hunter R at Denman	1000

Table 18 Number of days per year when Hunter River streamflow rates are above the discharge threshold under the baseline and reduction in discharge days due to additional coal resource development (ACRD)

Model node	Discharge days under the baseline 2013–2102			Reduction in discharge days due to ACRD 2013–2042			Reduction in discharge days due to ACRD 2043–2072			Reduction in discharge days due to ACRD 2073–2102		
	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
6	26	49	99	0.43	0.77	1.62	0.33	0.60	1.40	0.19	0.45	1.06
20	13	26	52	0.17	0.37	0.85	0.03	0.13	0.33	0.03	0.10	0.24
51	34	68	151	0.07	0.23	0.50	0.03	0.16	0.30	0	0.07	0.24

Discharge day = a day when flow rates at the model node exceed the flow rate threshold for discharge under the Hunter River Salinity Trading Scheme
Data: Bioregional Assessment Programme (Dataset 12)

3.3.4.2.1.2 Discharges to unregulated river

Some of the Hunter subregion mines are not part of the HRSTS and occur along unregulated rivers in the Hunter river basin and Macquarie-Tuggerah lakes basin. These coal mines are required to hold an EPL, which specifies conditions attaching to the mine's licence to operate, including those relating to the management of mine water. Some examples for the Hunter subregion additional coal resource developments are:

- At the proposed Bylong Mine, the condition of operation is that the mine is not permitted to discharge mine water off site.
- The Ulan, Moolarben and Wilpinjong mines in the upper Goulburn River catchment are permitted under their respective EPLs to discharge 30, 10 and 5 ML/day, respectively, but discharges must not exceed electrical conductivities of 810 to 1000 µS/cm at Ulan (depending on discharge site), 800 to 900 µS/cm at Moolarben and 500 µS/cm at Wilpinjong. In addition, these three mines have entered into a water sharing arrangement, which allows a surplus of water at one site to meet the deficit of water at another, thereby reducing the need for the mines to take more water from the environment and reducing the volume of mine water make discharge from the sites.
- At Mandalong mine, the salinity of water discharged from the mine site is picked up in a general clause of EPL 365, whereby any pollutant not specified in the table/s in the EPL is not allowed to be discharged if it will pollute the waters. The mine is licensed to discharge up to 5 ML/day.

- Wallarah 2 is a new mine and does not yet have an EPL. Modelled estimates of Wallarah 2 surplus water requirements, and hence mine discharges to Wallarah Creek, range from 52 ML/year in year one to median discharge of 250 ML/year (90th percentile of 370 ML/year; maximum discharge of around 500 ML/year). Under their proposal, mine water will be treated to background water quality levels prior to discharge, with the salt in the brine to be disposed underground.

In conclusion, due to a high level of regulation and monitoring of discharges of mine water to surface drainage network in the Hunter subregion, the risk to stream water quality from this causal pathway is considered to be minimal.

3.3.4.2.1.3 Depressurisation, dewatering and hydraulic enhancement

The risk to regional stream water quality caused by changes in baseflow following depressurisation and dewatering of mines and/or changes in subsurface physical flow paths (e.g. from hydraulic enhancement of the goaf) will depend on the magnitude of the hydrological changes and the salinity of the groundwater relative to the salinity of the water in the stream into which it discharges. Modelling of the hydrological changes due to additional coal resource development in the Hunter subregion predicts a probable reduction in baseflows to Hunter subregion streams. If, as is usually the case, the salinity of the groundwater is higher than that of the stream into which it discharges, a reduction in baseflow would be expected to lead to a reduction in stream salinity.

Companion product 1.1 for the Hunter subregion (McVicar et al., 2015) provides details on groundwater and surface water quality. The saline water associated with the Permian coal measures and the intervening marine sequence is thought to have a controlling influence on the overall water quality of the Hunter River (Kellett et al., 1989). Groundwater quality is generally brackish to saline (Mackie Environmental Research, 2006), with electrical conductivity (EC) records in the range 4,000 to 12,000 μS/cm in the hard rock aquifers associated with the Hunter coal seams. In the alluvial aquifers of the Hunter River, the mean total dissolved salts varies from 650 mg/L (~1000 μS/cm) upstream of the Hunter-Goulburn rivers confluence to 840 mg/L (~1300 μS/cm) in the aquifers downstream of the confluence. It is reported that groundwater extractions from alluvial aquifers can lead to upward fluxes from more saline water in the underlying Permian units such as occurred during the 2001 to 2004 drought years (NSW Department of Planning, 2005). Mining operations in some locations have led to reversal of groundwater gradients and decreases in groundwater salinity in alluvial aquifers (Australasian Groundwater and Environmental Consultants Pty Ltd, 2013). Groundwater modelling results from this BA suggest that baseflow reductions are the likely outcome from coal resource development, which could result in reductions in salinity in connected streams. For example, the potentially large reductions in streamflow modelled for Loders Creek and Saddlers Creek, which both have high stream salinities (>5500 μS/cm), are likely to mean less salt is exported from these catchments to the Hunter River due to additional coal resource development.

In all the streams identified from the regional-scale modelling as at risk of potentially large changes in flow regime, the impact on local stream salinity will depend on the relative reductions in catchment runoff and baseflow over time. Reductions in catchment runoff are more likely to affect runoff peaks, while baseflow reductions have a more noticeable effect on low flows. The implications for stream salinity at any given time will depend on how the relative contributions from the quick and slower flow pathways change over time. In streams, such as Loders Creek, Saddlers Creek and the unnamed creeks near the Mount Pleasant and Mount Thorley-Warkworth mines, where modelling results suggest increasing numbers of zero-flow days, it is likely that channel pools will be subject to longer periods of salt concentration by evaporation and less efficient flushing, conditions that favour increasing the salinity of these water bodies.

Increases in baseflow, potentially leading to increases in alluvial aquifer and stream salinity, cannot be ruled out, but this is not an outcome that has been reported in the literature and remains an area for further investigation. The magnitude and extent of water quality changes cannot be determined without specifically representing water quality parameters in the modelling. This remains a knowledge gap.

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3.4 Impacts on and risks to landscape classes

Summary

The heterogeneous natural and human-modified ecosystems in the Hunter subregion were classified into 26 landscape classes, and then aggregated into five landscape groups based on water dependency: riverine, groundwater-dependent ecosystem (GDE), coastal lakes and estuaries, non-GDE vegetation and economic land use.

Landscape classes that are unlikely to be impacted

Within the 'Riverine' landscape group, the 'Highly intermittent or ephemeral' landscape class is unlikely to be impacted by drawdown because, by definition, ephemeral streams are not connected to regional groundwater. Ephemeral streams that are directly affected by disruptions to their drainage from excavations at the mine site are likely to be impacted.

All landscape classes in the 'Coastal lakes and estuaries' landscape group, except saline wetlands, are *very unlikely* to be impacted: drowned valleys do not occur within the zone; regulations are in place to limit impacts to seagrass beds from subsidence; and creeks are upstream of developments.

In the 'Non-GDE vegetation' landscape group, the 'Native vegetation' landscape class is ruled out from impacts because it is not considered water dependent for the purposes of bioregional assessments (BAs).

'Riverine' landscape group

The potentially large hydrological changes modelled in some permanent or perennial streams of the Hunter subregion could result in significant ecological impacts. Results from the perennial stream receptor impact model, which uses changes in the probability of presence of riffle-breeding frogs and density of riffle-dwelling Hydropsychidae larvae due to hydrological changes as indicators of change in instream habitats, indicate a potentially significant impact on instream habitat of the Wyong River, and by extension Dora Creek, in the Macquarie-Tuggerah lakes basin. However, when local hydrogeological information is used to constrain the hydrological change predictions in this area, the likelihood of potentially significant changes in instream habitat is low. Elsewhere in the subregion, it is *very unlikely* that instream habitats of permanent or perennial streams are impacted.

Potentially large hydrological changes are modelled in the intermittent Saddlers and Loders creeks in the Central Hunter and Lower Hunter reporting areas. Results from the intermittent stream receptor impact model, which models changes in the probability of presence of riffle-breeding frog and hyporheic taxa richness in response to changes in zero-flow days, indicate a risk of adverse impacts upon instream habitats in these intermittent systems. Local

information is needed to determine the actual risk, having regard to stream condition, habitat diversity, other catchment stressors and recovery potential.

'Groundwater-dependent ecosystem (GDE)' landscape group

Potentially large drawdowns are possible in the Macquarie-Tuggerah lakes basin with potential for ecological impacts on wet and dry sclerophyll forests. Around 5.6 km^2 of wet and dry sclerophyll forest have a 50% chance of experiencing drawdown of more than 2 m. There is little likelihood of impacts on wet and dry sclerophyll forests, based on receptor impact modelling, which predicted only minor reductions in projected foliage cover based on modelled drawdown. There is at least a 5% chance that 10 to 15 km^2 of dry sclerophyll forests in the Macquarie-Tuggerah lakes basin will be impacted. It is *very unlikely* that more than 8.6 km^2 of wet sclerophyll forests or dry sclerophyll forests experience drawdown of more than 2 m. It is *very unlikely* that more than 5.2 km^2 of wet sclerophyll forests or dry sclerophyll forests experience drawdown of more than 5 m. The potentially impacted areas are smaller and associated with smaller drawdowns, when local hydrogeological information from the Wyong River catchment is used to constrain the hydrological predictions.

Potentially significant hydrological changes due to additional coal resource development are possible in some areas of forested wetlands. Regional hydrological modelling found that nearly all the riverine forested wetlands in the Hunter and Goulburn basins will potentially experience drawdown of up to 2 m, with about 2.6 km^2 of the coastal forested wetlands at risk of drawdowns of more than 2 m. It is likely that only small areas (<1 km^2) of forested wetlands for which surface water modelling is available are impacted by changes in overbench and overbank flows. Results from receptor impact modelling, which are based on predicted changes in projected foliage cover, indicate little likelihood of impacts on riverine forested wetlands. Riverine forested wetlands along the Goulburn River are identified as 'more at risk of ecological and hydrological changes', but the significance of this risk can only be determined through more local information. The ecological impact on the coastal forested wetlands in the Macquarie-Tuggerah lakes basin was not represented in the receptor impact model.

Most of the GDE rainforests are unlikely to be impacted, because if they are dependent on groundwater at all, it is local groundwater sources. The exception is rainforest along the Wyong River and Jilliby Jilliby Creek, the water dependency of which requires further study at a local scale to assess water dependency and potential for impact.

The freshwater wetlands within the zone of potential hydrological change are represented entirely by Keith's (2004) 'Coastal freshwater lagoons' vegetation class. Experts were uncertain about the water dependencies of these systems and their sensitivity to hydrological changes caused by coal mining. The potential for ecological impacts on this landscape class is a knowledge gap.

Semi-arid woodlands, heathlands and grassy woodlands are *very unlikely* to be impacted because they are located almost exclusively outside the zone of potential hydrological change.

Springs are represented by four assets in the water-dependent asset register. None of these four assets intersects the zone and thus this landscape class is *very unlikely* to be impacted due to additional coal resource development.

Experts were uncertain about the sensitivity of saline wetlands to drawdown due to additional coal resource development. The potential for ecological impacts on this landscape class is a knowledge gap.

3.4.1 Overview

This section describes the potential impacts on ecosystems that result from hydrological changes due to additional coal resource development. Ecosystems are represented by landscape classes, which are organised into five landscape groups that reflect their water dependencies: riverine, GDE, coastal lakes and estuaries, non-GDE vegetation and economic land use (Table 19). The basis for the landscape groups and classes is described in companion product 2.3 for the Hunter subregion (Dawes et al., 2018). Landscape classes that intersect the 3213 km^2 zone of potential hydrological change are considered potentially impacted due to additional coal resource development and are the focus of this section. Landscape classes that are not water dependent can be 'ruled out' from potential impacts. Landscape classes that do not intersect the zone are *very unlikely* to be impacted (less than 5% chance) due to additional coal resource development (see Section 3.4.2).

About 3,136 km (21%) of the 14,659 km of river length in the Hunter assessment extent is in the zone of potential hydrological change (Figure 30). About 1232 km of perennial streams, 1450 km of intermittent streams and 8840 km of ephemeral streams are outside the zone. Most (63%) of the stream length in the zone comprises ephemeral streams (1985 km), with a further 634 km of perennial streams and 518 km of intermittent streams (Figure 30).

Potential impacts on permanent or perennial streams and lowly to highly intermittent streams were assessed using both qualitative models and quantitative receptor impact models developed for the Hunter subregion (Table 19; also see companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)), with results presented in Section 3.4.3. Most (1346 km) of the ephemeral streams within the zone are considered unlikely to be affected due to additional coal resource development and are ruled out (see Section 3.4.2; also see companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)). Thus, about 1228 km of streams within the zone are considered potentially impacted. Section 3.4.3 provides an assessment of the potential impacts on and risks to the landscape classes in the 'Riverine' landscape group.

There are about 102 km^2 of the 'GDE' landscape group in the zone of potential hydrological change (Figure 30). Five landscape classes in the 'GDE' landscape group are described by qualitative models, of which three are also described by quantitative receptor impact models. Details of these models are reported in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a). These models are used to assess the potential for impacts on and risks to the landscape classes in the 'GDE' landscape group (see Section 3.4.4).

Receptor impact modelling converts the potentially abstract information about hydrological changes to quantities that stakeholders care about and can more readily understand and interpret. In particular, outcomes of the modelling relate more closely to their ecological values and beliefs and therefore support community discussion and decision making about acceptable levels of coal resource development (see companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018b)). Receptor impact models are not intended to make site-specific predictions but rather to quantify the range of possible responses of selected receptor impact variables to a given change in hydrology. It is beyond the scope of a BA to make precise predictions at exact locations.

Receptor impact variables represent biological components of the ecosystem that experts have chosen as indicators of ecosystem condition, and which are considered likely to be sensitive to changes in the hydrology of that system (see companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018b)). Changes in hydrology are represented in the model by hydrological response variables, chosen to reflect particular water requirements of the ecosystem. The magnitude of change in the chosen receptor impact variables to changes in one or more hydrological response variables, captured through an expert elicitation process, is an indicator of the magnitude of risk to the ecosystem as a result of hydrological perturbation. For example, a prediction that the number of riffle-breeding frog species is likely to decrease in a particular reach where zero-flow days are predicted to increase does not necessarily mean that there are riffle-breeding frogs present and that they will be impacted. Rather, it means that given the magnitude of hydrological change predicted in that reach, there is a specific risk to the habitat requirements of riffle-breeding frogs, and more generally a risk to the ecosystems represented by the landscape class the riffle-breeding frog inhabits. The receptor impact modelling results are provided at a landscape scale and should not be interpreted as exactly representing the local conditions of a particular site.

In the following sections, the results from receptor impact models should be treated as indicating the experts' pooled knowledge as to the likelihood and magnitude of ecological impacts in an ecosystem given a known hydrological change. Results also capture the uncertainties arising from lack of knowledge, the variability inherent in landscapes across short and long distances and the variability in response pathways over short and long time frames.

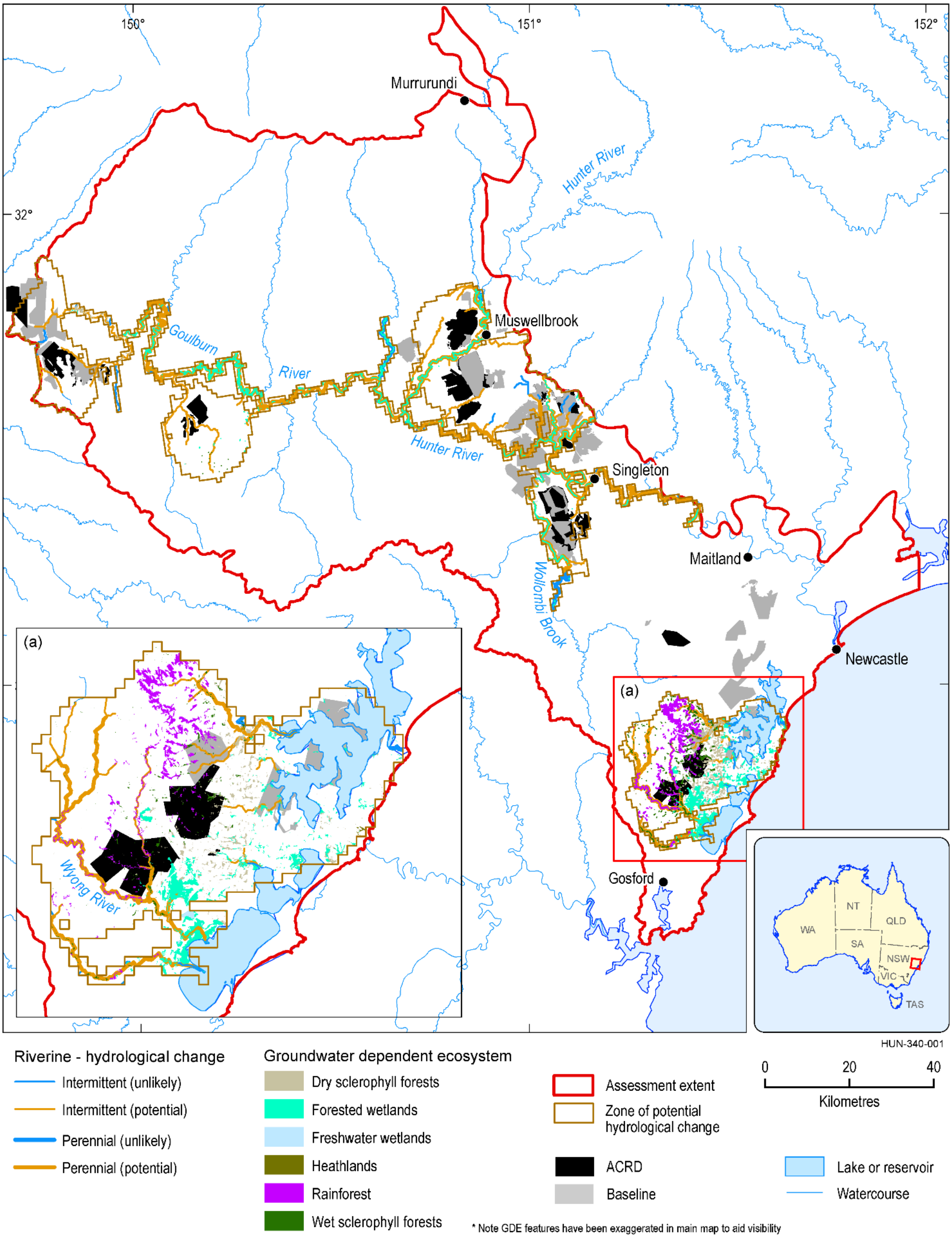

Figure 30 Landscape classes in the zone of potential hydrological change

Landscape classes are shown from the 'Groundwater-dependent ecosystem (GDE)' landscape group and the 'Riverine' landscape group. The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD). Groundwater-dependent ecosystems (GDEs) are exaggerated (not to scale) for clarity.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3, Dataset 4)

Table 19 Length (km) or area (km^2) of all landscape classes in the assessment extent and the zone of potential hydrological change, and associated qualitative models and receptor impact models

Landscape group	Landscape class	Extent in assessment extent	Extent in the zone	Qualitative model	Receptor impact model
Riverine (km)	Permanent or perennial	1,866	634	Perennial streams	1. Perennial streams – riffle-breeding frogs 2. Perennial streams – Hydropsychidae larvae
	Lowly to moderately intermittent Moderately to highly intermittent[a]	1,968	518	Intermittent streams	1. Intermittent streams – riffle-breeding frogs 2. Intermittent streams – hyporheic invertebrate taxa
	Highly intermittent or ephemeral	10,825	1985	Ephemeral streams	No
GDE (km^2)	Rainforest	40.2	23.9	Rainforests	No
	Wet sclerophyll forest	14.2	4.5	Wet and dry sclerophyll forests	Wet and dry sclerophyll forests – projected foliage cover
	Dry sclerophyll forest	91.1	14.6		
	Freshwater wetland	35.5	1.1	Freshwater wetlands	No
	Forested wetland	150.8	57.8	Forested wetlands	Forested wetland – riverine forest – projected foliage cover
	Grassy woodland	12.6	0.2	No	No
	Heathland	14.0	0.2	No	No
	Semi-arid woodland	0.6	<0.1	No	No
	Spring	na	na	No	No

Landscape group	Landscape class	Extent in assessment extent	Extent in the zone	Qualitative model	Receptor impact model
Coastal lakes and estuaries (km²)	Lakes	172	76.2	Intertidal wetlands	No
	Lagoons	9	3.8		
	Seagrass	39	15.6	Subtidal benthos	No
	Saline wetlands	30	1.5	Intertidal wetlands	No
	Creeks	<1	<0.1	No	No
	Barrier river	13	0.4	No	No
	Drowned valleys	<1	na	No	No
Non-GDE vegetation (km²)	Native vegetation	10,414	1633	No	No
Economic land use (km²)	Dryland agriculture	3,819	768	No	No
	Irrigated agriculture	252	106	No	No
	Intensive use	1,068	322	No	No
	Plantation or production forestry	726	133	No	No
	Water	142	50	No	No

[a]The 'Lowly to moderately intermittent' and 'Moderately to highly intermittent' landscape classes were collapsed into a single 'Intermittent' landscape class in developing the qualitative models (companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)).
GDE = groundwater-dependent ecosystem, na = not applicable
Data: Bioregional Assessment Programme (Dataset 5)

3.4.2 Landscape classes that are unlikely to be impacted

The majority (3012 km^2 or 94%) of the zone of potential hydrological change comprises landscape classes from 'Non-GDE vegetation' and 'Economic land use' landscape groups (Table 19). The 'Native vegetation' landscape class is ruled out from potential impacts, because it is classified in the 'Non-GDE vegetation' landscape group and is therefore not considered water dependent for the purposes of BAs. While some landscape classes in the 'Economic land use' landscape group are water dependent (e.g. 'Irrigated agriculture'), impacts on economic assets are not evaluated by landscape class. Potential impacts on economic assets are considered in Section 3.5.

The 'Highly intermittent or ephemeral' landscape class in the 'Riverine' landscape group is *very unlikely* to be impacted by drawdown. By definition ephemeral streams flow in response to rainfall, and do not have a baseflow component from connection with groundwater. Ephemeral streams can be impacted through disruption to their natural drainage, for example through creek diversions or alterations due to land surface disturbance, as part of mining operations. The 1228 km of stream network used to define the surface water zone of potential hydrological change includes only those ephemeral streams likely to have disruptions to their natural drainage. A total of 1908 km of streams within the zone are unlikely to be impacted.

The 'Rainforest' landscape class within the 'GDE' landscape group is *very unlikely* to be impacted, because if they are dependent on groundwater at all, it is likely to be on local, rather than regional, groundwater sources. The exception are the riparian rainforests of the Wyong River catchment, which, given they occupy the same landscape position as the 'Forested wetland' landscape class (i.e. alluvium along perennial streams), are likely to have a dependency on streamflow and alluvial groundwater. They are potentially impacted by changes in groundwater levels and streamflow due to the proposed Wallarah 2 and Mandalong Southern Extension developments, but are not explicitly represented in any of the qualitative or quantitative models developed for the landscape classes.

The 'Semi-arid woodland', 'Heathland' and 'Grassy woodland' landscape classes within the 'GDE' landscape group are *very unlikely* to be impacted because they are located almost exclusively outside the zone of potential hydrological change. Only small areas of the 'Heathland' (0.2 km^2), 'Grassy woodland' (0.2 km^2) and 'Semi-arid woodland' (<0.1 km^2) landscape classes were within the zone. In addition, their use of groundwater tends to be opportunistic or facultative, rather than obligate (see Section 2.7.2.1 of companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)).

The 'Spring' landscape class is based on the four assets within the Hunter subregion register of water-dependent assets. None of these four assets intersects the zone; hence, this landscape class is judged *very unlikely* to be impacted.

The 'Freshwater wetland' landscape class within the zone of potential hydrological change is represented entirely by Keith's (2004) 'Coastal freshwater lagoons' vegetation class. A qualitative model was developed for Keith's 'Coastal freshwater lagoons' vegetation class, but experts at the workshop were unable to agree on whether groundwater dependence of these lagoons was regional or local, and whether hydrological changes from underground coal mining higher up in the catchment would affect lagoon hydrology. It was thought that tidal fluctuations influence water levels in the lagoons and that any drawdown would be compensated by the inflow of seawater intrusion, leading to no change in water levels, but potential changes in salinity of the wetland water. Given the lack of certainty about the key driving processes, a quantitative model was not developed for this landscape class (see Section 2.7.2.3 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)).

The ‘Lakes’, ‘Lagoons’ and ‘Seagrass’ landscape classes within the ‘Coastal lakes and estuaries’ landscape group are *very unlikely* to be impacted because the risk to seagrass beds from coal mining is from subsidence, rather than changes in lake inflows and drawdown from mines in the contributing area to the lakes (see Section 2.7.5 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)). Subsidence causes base-level lowering of the lake floor which reduces light penetration and can reduce the habitable area for seagrass beds. The establishment of a high water mark subsidence barrier around Lake Macquarie and Tuggerah Lakes, within which maximum vertical subsidence is limited to 20 mm, and the requirement of coal mines to prepare extraction plans, which include details of how subsidence will be managed to minimise impacts, are important regulatory controls intended to avoid or limit impacts to seagrass beds from subsidence (see Section 2.3.4 in companion product 2.3 for the Hunter subregion (Dawes et al., 2018)).

The ‘Creek’ landscape class within the ‘Coastal lakes and estuaries’ landscape group is *very unlikely* to be impacted because it is upstream of development. The ‘Drowned valleys’ landscape class is *very unlikely* to be impacted because it does not occur within the zone. The ‘Barrier river’ landscape class within the ‘Coastal lakes and estuaries’ landscape overlaps with the ‘Riverine’ landscape group and impacts on this are evaluated with the ‘Riverine’ landscape group. The ‘Saline wetland’ landscape class within the ‘Coastal lakes and estuaries’ landscape was not evaluated because it was judged that any potential impacts from drawdown due to additional coal resource development would be too fine scale for a BA (see Section 2.7.5 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)).

3.4.3 'Riverine' landscape group

3.4.3.1 Description

Four landscape classes were defined in the 'Riverine' landscape group for the Hunter subregion, based on an unpublished flow regime classification approach from NSW Department of Primary Industries Water (companion product 2.3 for the Hunter subregion (Dawes et al., 2018)):

- permanent or perennial
- lowly to moderately intermittent
- moderately to highly intermittent
- highly intermittent or ephemeral.

Of the 3136 km of river in the zone of potential hydrological change, 634 km were determined to be permanent or perennial streams; 518 km lowly to moderately intermittent streams or moderately to highly intermittent streams; and 1985 km highly intermittent or ephemeral streams. During the development of qualitative and quantitative models via expert elicitation (see companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)), the 'Lowly to moderately intermittent' landscape class and 'Moderately to highly intermittent' landscape class were collapsed into a single 'Lowly to highly intermittent' landscape class, which represents rivers that are variably connected to groundwater, irrespective of the frequency and duration of connection.

The 'Permanent or perennial' landscape class broadly corresponds to the 'stable baseflow' classes from Kennard et al. (2010; Classes 1, 2 and 3), while the 'Lowly to moderately intermittent' landscape class and 'Moderately to highly intermittent' landscape class (dealt with together as 'Lowly to highly intermittent' streams; see Table 4 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) correspond broadly to the 'unpredictable baseflow' and 'intermittent' classes from Kennard et al. (2010; Classes 4 and 5–8). Permanent or perennial streams have flow at least 80% of the year, and an appreciable contribution of groundwater to baseflows. Kennard et al. (2008) report baseflow indices in the range of 0.15 to 0.40 for perennial streams. Lowly to highly intermittent streams are characterised by streams that cease flowing more often than perennial streams and have a smaller baseflow contribution (0.07 to 0.25) due to an intermittent connection with groundwater (Kennard et al., 2008). Highly intermittent streams are characterised by an infrequent connection to groundwater and large numbers of zero-flow days.

River basins in the Hunter subregion include the Hunter, Macquarie-Tuggerah lakes, Upper Namoi and Lower Karuah. Only the Hunter river basin and Macquarie-Tuggerah lakes basin intersect the zone of potential hydrological change. The Hunter River is the largest river in the subregion and is fed by a number of significant tributaries, including Pages River, Dart Brook, Goulburn River (Figure 31), Glennies Creek, Wollombi Brook, Glendon Brook, Paterson River and Williams River. The total Hunter river basin area is 21,437 km^2, of which 14,886 km^2 is in the subregion. The Hunter River descends 1397 m over its 468 km course from its upper reaches in the Barrington Tops (outside the subregion), through the Hunter Valley, and out to sea.

Figure 31 The Goulburn River near Coggan

Source: Martin Krogh (2017). This figure is covered by a Creative Commons Attribution licence.

The Macquarie-Tuggerah lakes basin includes three main river basins: Dora Creek, Wyong River and Ourimbah Creek. The Macquarie-Tuggerah lakes basin covers an area of 1836 km^2 and is bordered by the Hunter river basin in the north. Dora Creek runs south-east for 25 km to meet Lake Macquarie at the township of Dora Creek. The major tributaries of Dora Creek include Moran, Tobins, Jigadee, Blarney and Deep creeks. Wyong River runs south-east for 48 km to meet Tuggerah Lake at Tacoma. The Wyong River's main tributaries include Jilliby Jilliby and Cedar Brush creeks. Ourimbah Creek runs south-east for 31 km to meet Tuggerah Lake at Chittaway. Ourimbah Creek's major tributaries include Elliots, Bumbles, Toobys, and Bangalow creeks, which drain the southernmost corner of the subregion.

Ecologically important components of the hydrograph can be broadly summarised (Dollar, 2004; Robson et al., 2009) as cease-to-flow periods, periods of low flow, freshes, and periods of high flow (including overbench and overbank flows) as illustrated in Figure 32. Longitudinal, lateral and vertical connectivity is enhanced with increasing flow. Increasing flow increases connectivity between habitats and enables greater movement of aquatic biota, and water-borne nutrients and fine and coarse particulate organic matter. Flow regimes determine natural patterns of connectivity, which are essential to the persistence of many riverine populations and species (Bunn and Arthington, 2002). High flows are especially important for lateral connectivity and channel maintenance. Low flows are critical to maintaining vertical and longitudinal connectivity, and water quality of inundate habitat including pools. Freshes can trigger fish spawning, maintain water quality in inundate habitats, and cleanse and scour the riverbed. A lack of vertical connection to groundwater can result in cease-to-flow periods during periods of little or no rainfall. Cease-to-flow events dry out shallow habitats and can create chains of pools, isolated pools or completely dry riverbeds, depending on riverbed morphology (Robson et al., 2009). The limited lateral, vertical and longitudinal connectivity associated with the zero-flow condition is illustrated in Figure 33, where an isolated pool persists between dry riffle beds and the groundwater level is below the channel bed.

During periods of low flow (Figure 34), lateral connectivity is likely to be limited; however, low flows are important for maintaining vertical connectivity to the hyporheic zones of the streambeds (Ward, 1989; Kondolf et al., 2006), and for maintaining longitudinal connectivity within the landscape by linking instream habitats and allowing dispersal of instream biota (Dollar, 2004; Robson et al., 2009; Marsh et al., 2012; Boulton et al., 2014). Interactions between hydrological, ecological, and biogeochemical processes in the hyporheic zone influence key stream ecosystem processes in the surface stream, such as primary productivity and nutrient cycling (Boulton et al., 2010). The hyporheic sediments harbor microbes and invertebrates and are used by some fish for spawning.

Low flows provide seasonal habitat for many species and can maintain refugia for other species during droughts (Dollar, 2004). In regions with seasonal rainfall, low flows are maintained by baseflow, which is generally considered to be groundwater contribution to the hydrograph, hence the importance of the vertical connection of the riverbed to groundwater. A lack of vertical connection to groundwater can result in cease-to-flow periods during periods of little or no rainfall. Cease-to-flow events dry out shallow habitats and can create chains of pools, isolated pools or completely dry riverbeds, depending on riverbed morphology (Figure 33; Robson et al., 2009). In a synthesis of case studies Marsh et al. (2012) concluded that increasing durations of low flow are correlated with declining water quality (increased temperature and salinity and reduced dissolved oxygen), and that this a primary driver of ecological responses, especially in pools.

Riffle habitats are not only affected by changes in water quality but also reduced habitat area, as riffles dry out and contract. For example, Chessman et al. (2012) reported that aquatic macroinvertebrate assemblages that had been exposed to severe flow reduction or cessation during the period prior to sampling would be dominated by taxa tolerant of low oxygen concentrations, low water velocities and high temperatures, whereas assemblages not exposed to very low flows would be dominated by taxa that favour cool, aerated, fast-flowing conditions. Riffle habitats that are characterised by faster flowing, well-oxygenated water tend to be the first habitat type to be impacted by reduced river discharge. Marsh et al. (2012) also concluded that communities in streams that are usually perennial but cease to flow for short periods (weeks) will mostly recover the following season, but that the community composition will decline if cease to flow recurs over consecutive years.

Although lateral connectivity is limited under no- and low-flow conditions, riparian vegetation may directly access alluvial groundwater, in addition to perched watertables within the stream bank, or riverine water. The contribution of groundwater to evapotranspiration is likely important for maintaining function of the riparian vegetation (Dawson and Ehleringer, 1991) and may be higher during periods of low flow (Lamontagne et al., 2005).

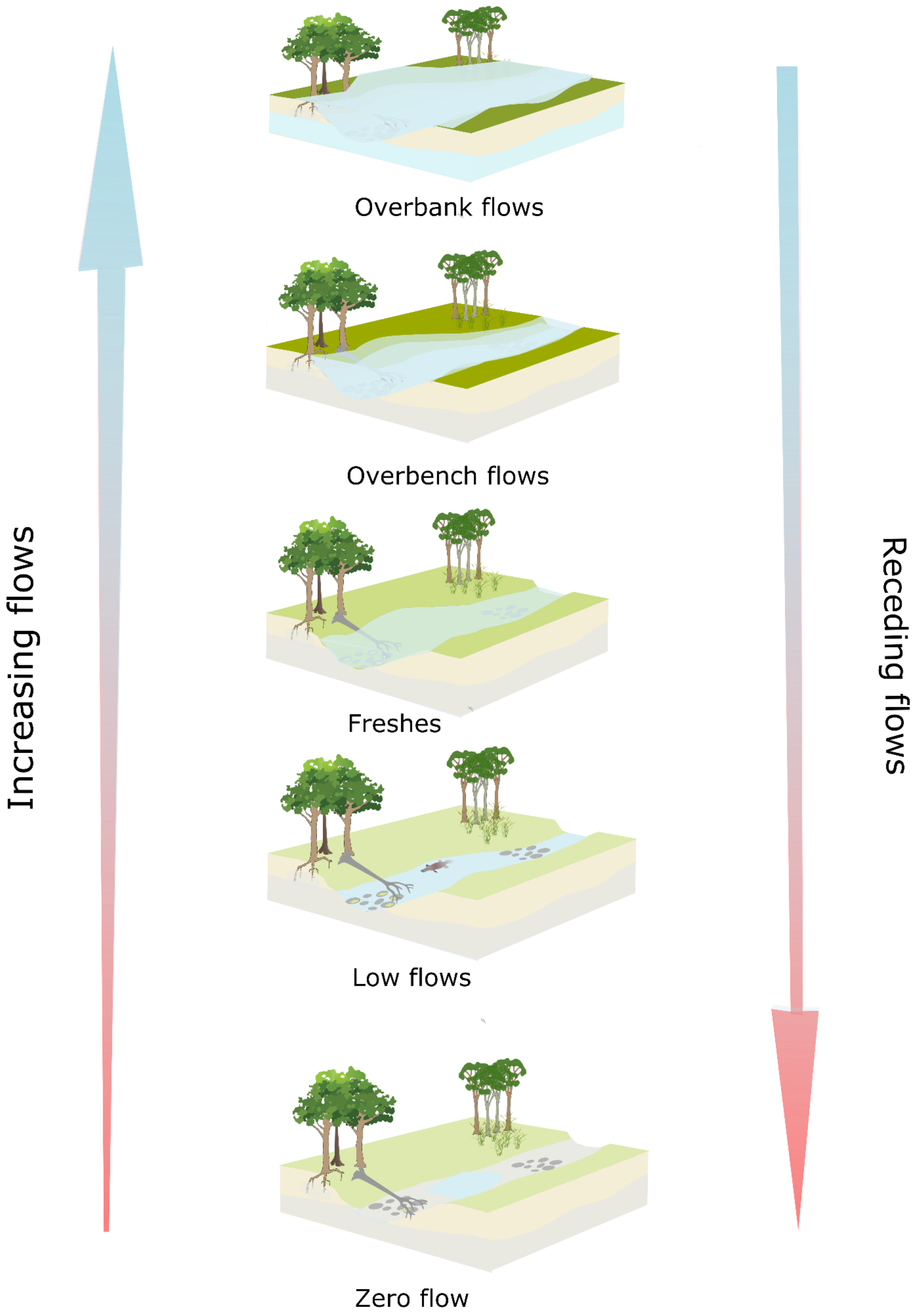

Figure 32 Conceptual representation of components of the hydrograph during wetting and drying cycles in streams

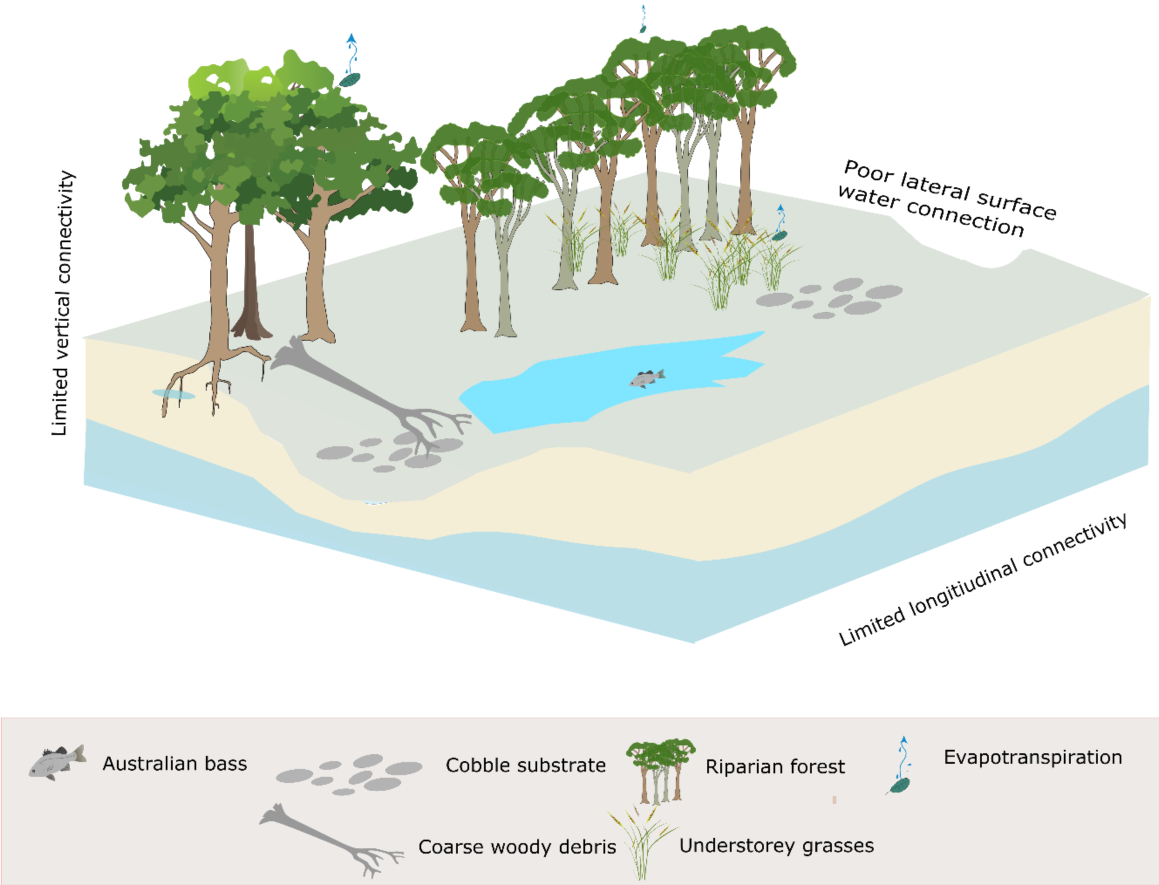

Figure 33 Conceptual model of streams during periods of zero flow when the connection to groundwater is broken

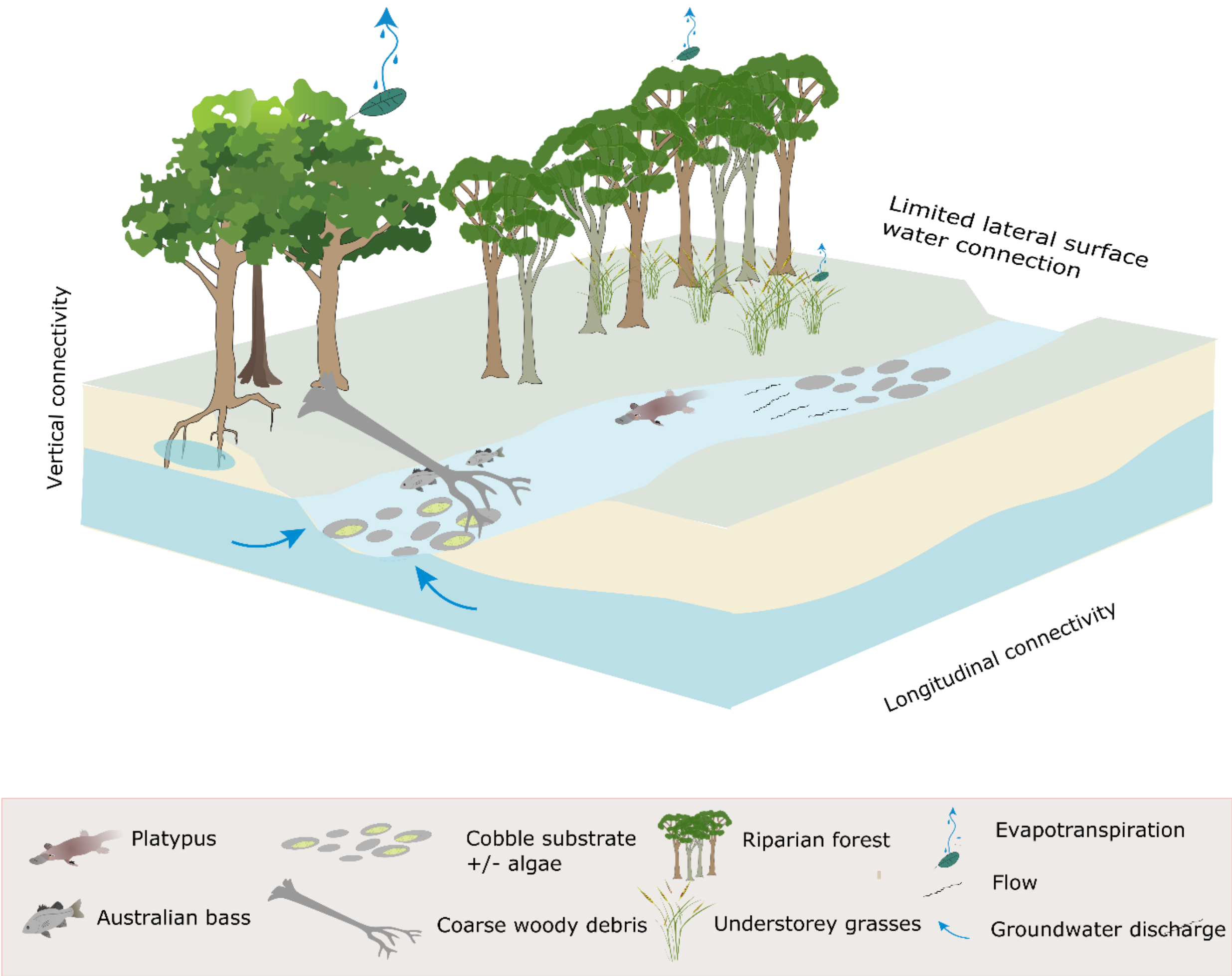

Figure 34 Conceptual model of streams during periods of low flow when baseflows predominate

Freshes (Figure 35) are defined as flows greater than the median for that time of the year (Robson et al., 2009). They can last for several days and typically increase the flow variability within the stream as well as play an important role in the regulation of water quality through inputs of freshwater. Freshes can mobilise sediment, inundate larger areas of potential habitat, and connect in-channel habitats, thereby permitting migration of aquatic fauna (Robson et al., 2009). Freshes can increase vertical connectivity between the streambed and the hyporheic zone by scouring and cleansing the riverbed (Hancock and Boulton, 2005) and can also trigger spawning in some fish (King et al., 2009). Freshes increase lateral connectivity beyond that of low flows, and increase soil water availability in stream banks through increased bank recharge, helping to support the health and vigour of woody and herbaceous vegetation.

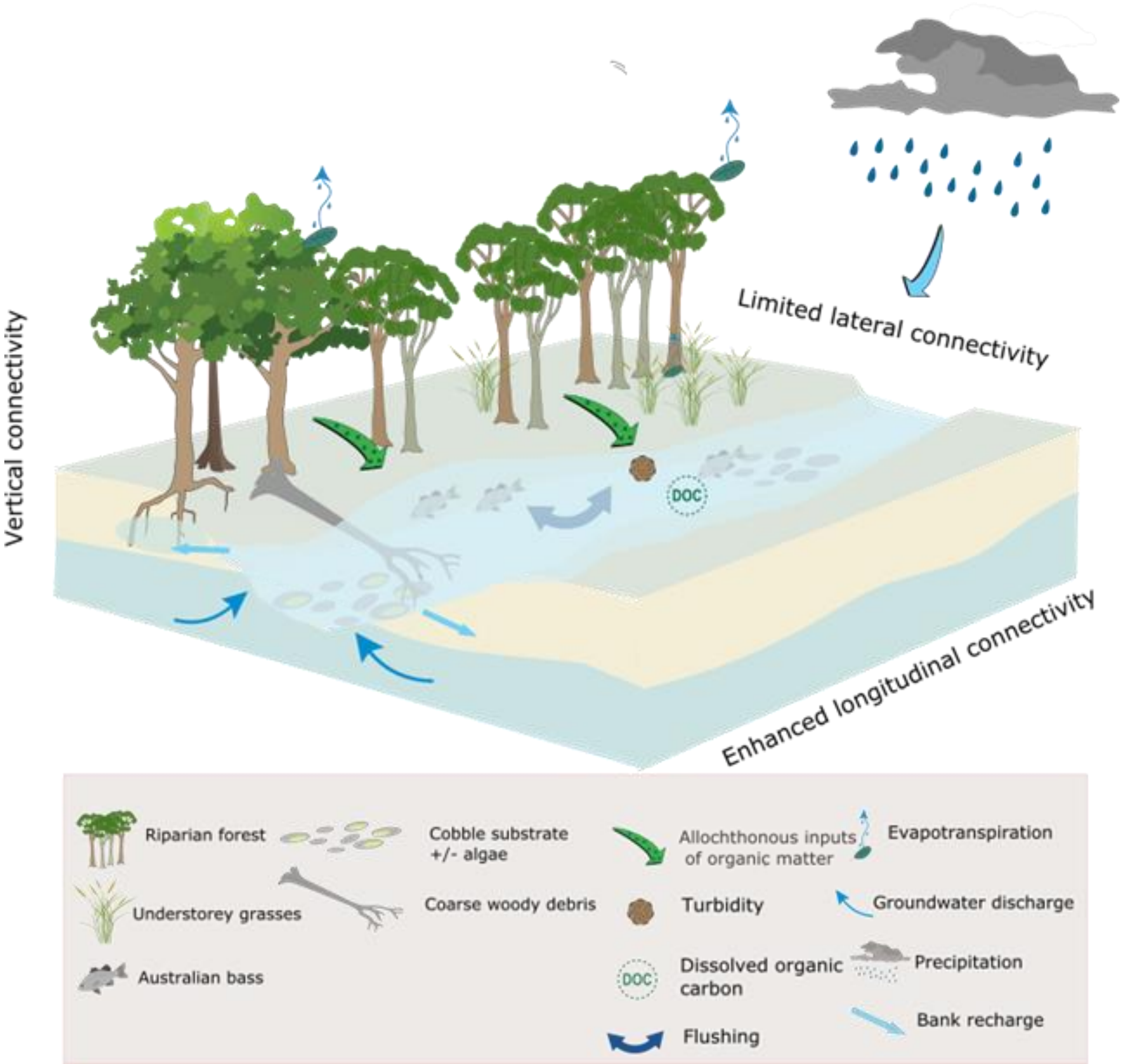

Figure 35 Conceptual model of streams during periods of freshes flow

The longitudinal connectivity is enhanced when compared to the low-flow conceptual model (Figure 34).

High flows (Figure 36 and Figure 37) inundate specific habitats and restore riverbed morphology (Robson et al., 2009). In the event of flooding they can also reconnect floodplains to the rivers and streams, fill wetlands, improve the health of floodplain trees and trigger waterbird breeding (Robson et al., 2009). High flows are often categorised 'wet season baseflows', 'bank-full flows' and 'overbank flows' (e.g. Robson et al. (2009)). For consistency with terminology used by experts during elicitation workshops (see Section 2.7.3.2 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)), 'overbench flow' is used to represent both wet season baseflows and bank-full flows. A bench is bank-attached, narrow, relatively flat sediment deposit that develops between the riverbed and the floodplain.

Overbench flows partially or completely fill the channel for longer periods than freshes; typically weeks to months. Practically all habitat components within the river channel will be wetted, including boulders, logs and lateral benches (if present), and the entire length of the channel is connected with relatively deep water, allowing movement of biota along the river (Department of Sustainability and Environment, 2003). As for freshes, some native fish species rely on seasonal high flows during winter and spring as cues to start migration and prepare for spawning (Department of Sustainability and Environment, 2003), such as the diadromous and potamodromous species listed earlier.

Increased flow rates, such as during bank-full flows, scour banks and river substrate, and increase stream bank erosion. Bank erosion is accentuated under high discharge (bank-full condition), with the effectiveness of these erosional forces being a function of bank condition and the health of the riparian vegetation (Brierley and Fryirs, 2005), in addition to factors such as particle shape, density, packing, and biological activity such as algal growth (Boulton et al., 2014). Bank slumping or undercutting can create new habitats and contribute additional coarse woody debris to streams. Logs, sticks and root masses in the channel create depositional areas for sediment and for fine particulate organic matter. Localised increases in velocity profiles around snags scour out pools or undercut banks that provide habitat for large fish and other animals such as platypus (Boulton et al., 2014). Scouring of the benthic algal communities, often considered to be the main source of energy for higher trophic levels, can temporarily reduce stream primary production (Davie et al., 2012). Benthic algal communities often recover rapidly and grazing macroinvertebrates are able to feed preferentially on early succession benthic algal taxa, whereas late succession algae are less palatable or physically difficult to consume. High flow rates may also dislodge macrophytes and macroinvertebrates resulting in population drift downstream (Downes and Lancaster, 2010).

Overbank flows (Figure 37) inundate the surrounding floodplains, providing lateral connectivity, freshwater, nutrients and particulate matter to floodplain wetlands. These high-flow events also tend to enhance vertical connectivity providing a source of recharge for alluvial aquifers below the inundated floodplains (Doble et al., 2012) and recharge soil water reserves, which may promote seedling recruitment and promote health of the forested wetlands. However, Chalmers et al. (2009) also note that scouring of the floodplain can substantially increase seedling mortality. Connectivity to off-stream wetlands, via overbank flows, enables replenishment of freshwater in these systems, and migration of riparian floodplain biota to and from the main channel. In some agricultural environments, these processes may lead to high loads of nutrients being imported to the stream environment, which may have deleterious effects on instream habitats through algal blooms (Boulton et al., 2014).

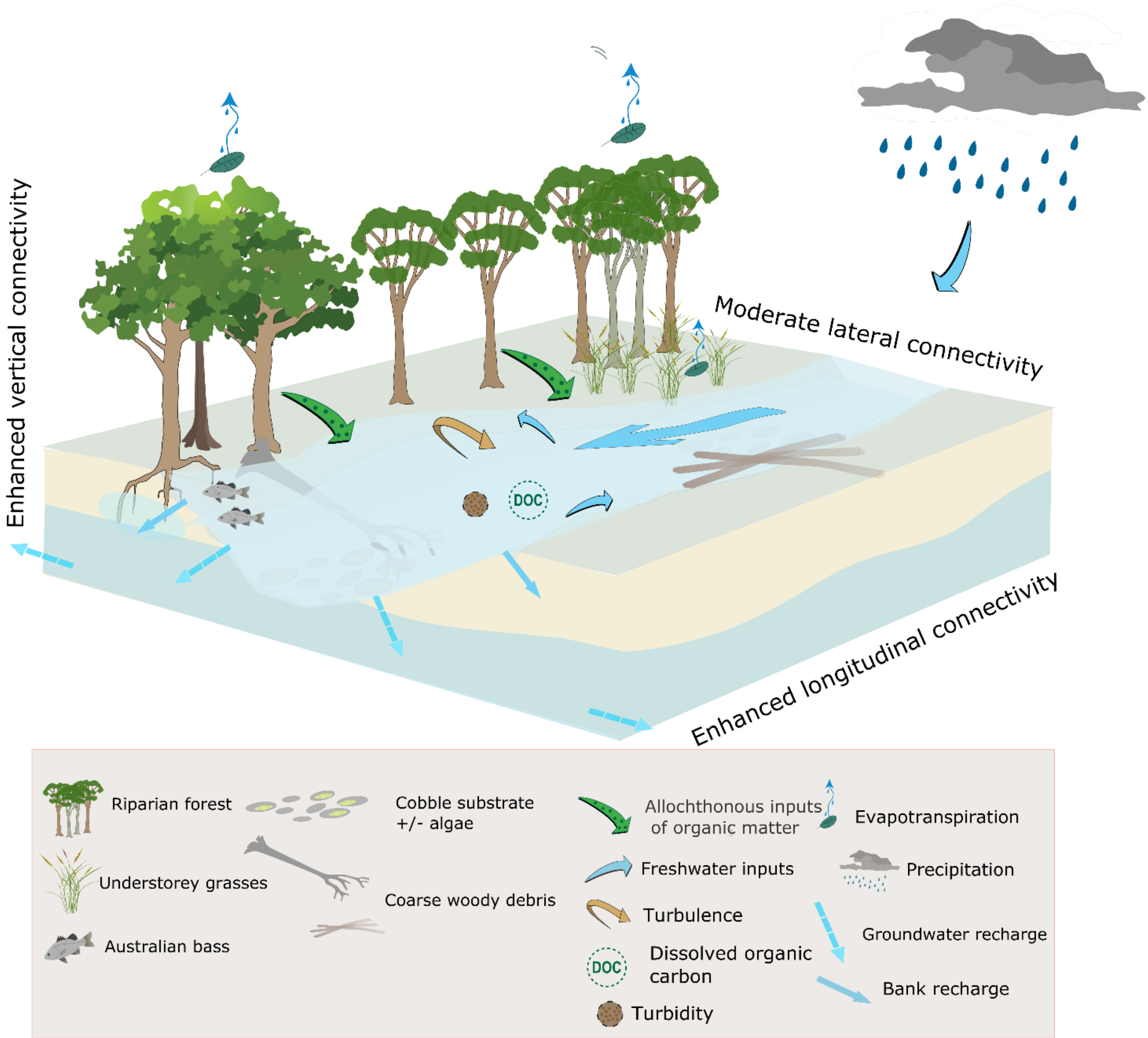

Figure 36 Conceptual model of streams during periods of overbench flow

Dashed arrows represent high uncertainty in relation to the flux. The enhanced connectivity is relative to the freshes flow conceptual model (Figure 35).

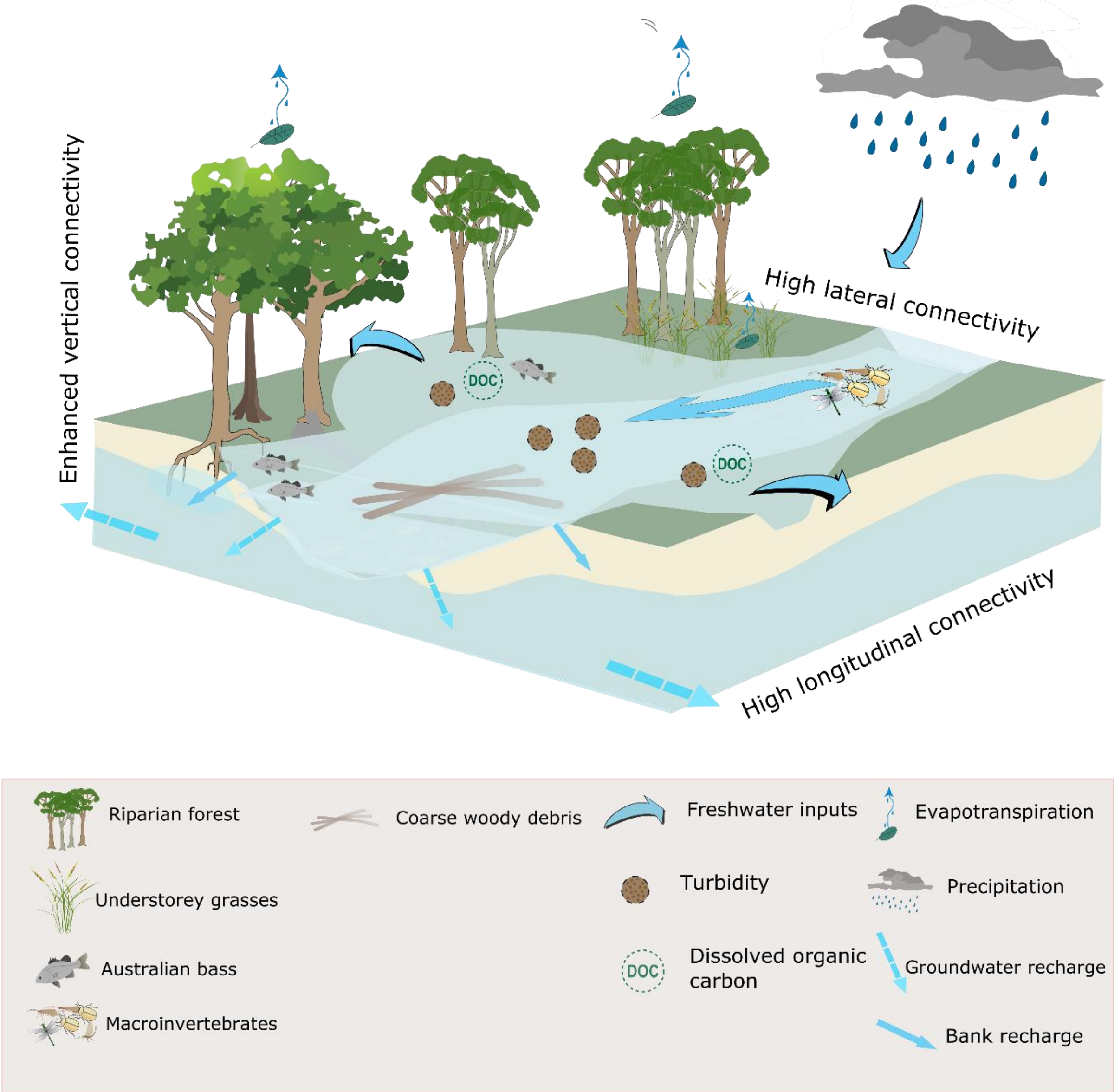

Figure 37 Conceptual model of streams during periods of overbank flow

Dashed arrows represent high uncertainty in relation to the flux. The ‘high’ and ‘enhanced’ connectivity states are relative to the overbench flow (Figure 36).

3.4.3.2 Potential hydrological changes

3.4.3.2.1 ‘Permanent or perennial’ landscape class

The key hydrological determinants of ecosystem function identified by experts in the qualitative modelling workshops (companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) have been interpreted as a set of hydrological response variables. For the ‘Permanent or perennial’ landscape class, these are:

- number of zero-flow days per year, averaged over a 30-year period (ZQD, subsequently referred to in this section as ‘zero-flow days’)
- mean maximum spell duration of zero flow days over a 30-year period (ZME).

For details of these variables, see Section 2.7.3 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a).

There are about 634 km of perennial stream in the zone of potential hydrological change (based on a modelled flow regime classification). The vast majority of the perennial streams are not predicted to experience a change in ZQD of more than 3 days (Figure 38). Along the Hunter Regulated River, the surface water model was constructed to maintain a minimum flow rate of 80 ML/day, broadly consistent with the environmental water requirements under the *Water Sharing Plan for the Hunter Regulated River Water Source 2016*. Thus, results show no change in zero-flow days along the Hunter River. No increase in ZQD of more than 3 days is modelled to occur along the perennial Goulburn River either.

The only perennial stream where the increase in zero-flow days is predicted to exceed 3 days per year is in the Wyong River. Results from the regional hydrological modelling indicate at least a 5% chance that the mean number of zero-flow days per year will increase by fewer than 3 days and at least a 5% chance that increases of greater than 200 days per year will occur, with median estimates indicating increases between 20 and 80 days per year. However, as discussed in Section 3.3.3, when local hydrogeological information is used to constrain the result set from the hydrological modelling, the modelled estimates of increases in zero-flow days are much reduced, with increases of more than 13 days *very unlikely*, and median results indicating no change in the number of zero-flow days per year due to additional coal resource development.

Dora Creek in the Macquarie-Tuggerah reporting area is also potentially impacted. Dora Creek was not included in the surface water modelling network, but is identified in Section 3.6 as likely to experience changes in flow regime similar to what is predicted for Wyong River based on the modelled drawdowns. The hydrogeological information used to constrain model results in the Wyong River catchment might not be appropriate in the Dora Creek catchment, and further assessment of risk in the Dora Creek catchment should be informed by data from that catchment.

Foy Brook and Bayswater Creek are also potentially impacted. Part of Foy Brook flows through an area where there is a chance of drawdown due to additional coal resource development exceeding 2 m (Figure 19 in Section 3.3). It could experience changes in zero-flow days of at least 3 days and requires further investigation. Bayswater Creek flows through areas where the drawdown is *very likely* (greater than 95% chance) to be less than 2 m due to additional coal resource development. No definitive conclusion can be made about the magnitude of potential changes in zero-flow days due to additional coal resource development.

There is no discernible difference between changes in mean annual number of zero-flow days and mean maximum spell duration in ‘Permanent or perennial’ streams in 2042 (Figure 38) and 2102 (Figure 39).

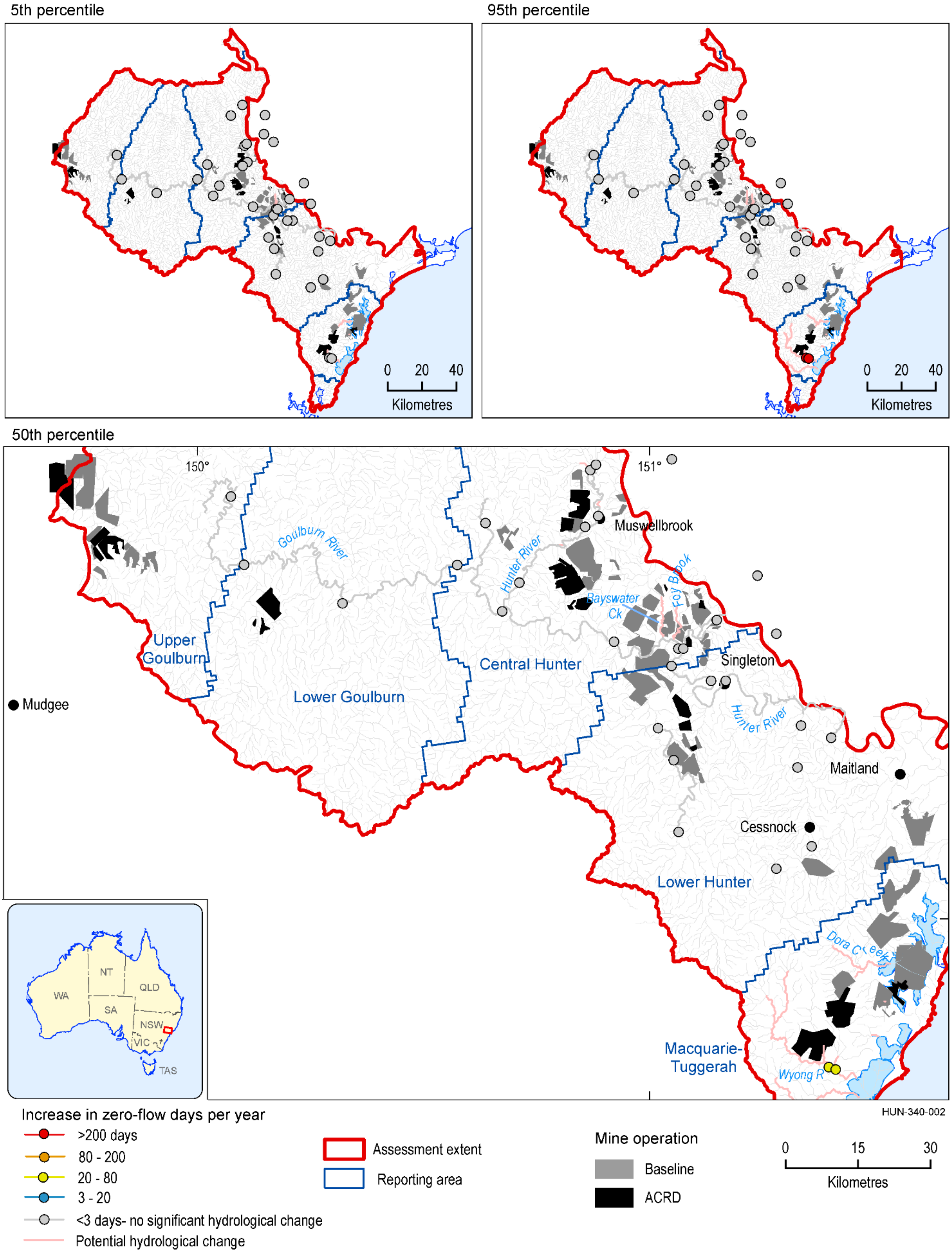

Figure 38 Modelled increase in zero-flow days in permanent or perennial streams in 2042 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

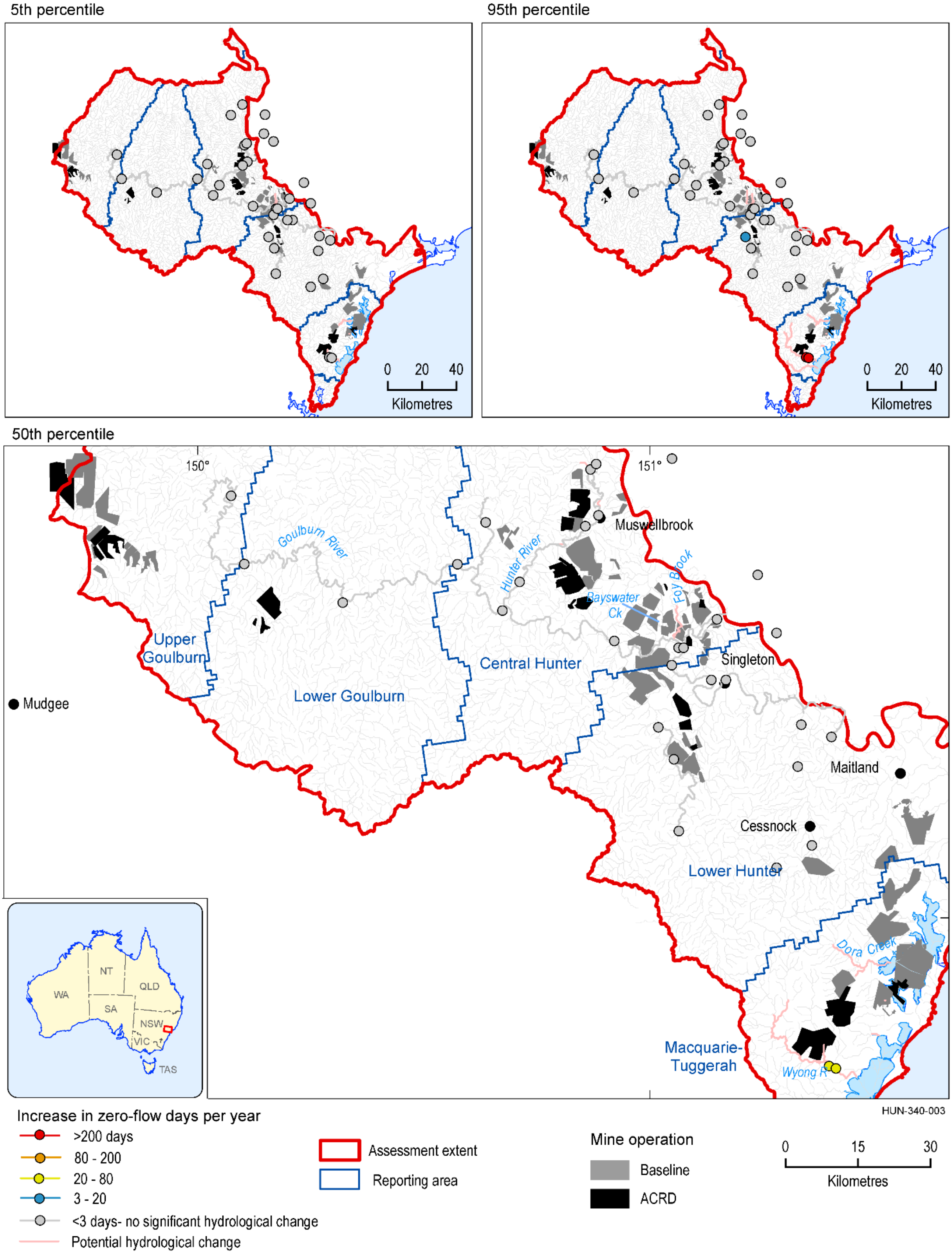

Figure 39 Modelled increase in zero-flow days in permanent or perennial streams in 2102 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

3.4.3.2.2 'Lowly to highly intermittent' landscape classes

Experts in the qualitative modelling workshops (companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) identified the same hydrological determinants of ecosystem function for the 'Lowly to highly intermittent' landscape class as for the 'Permanent or perennial' landscape class.

There are 518 km of intermittent stream in the zone of potential hydrological change (based on a modelled flow regime classification). Figure 40 shows the intermittent streams in the zone of potential hydrological change, classified by the magnitude of modelled change in mean number of zero-flow days (averaged over 30 years) (ZQD). Given the limitations of the interpolation (see Section 3.2.3.2), changes cannot be quantified for much of the intermittent stream network. The surface water model nodes on the intermittent streams are shown to provide the point estimates of modelled changes.

The majority of stream length is either *very unlikely* to be impacted or changes cannot be quantified. The upper Goulburn River and Wollar Creek are *very unlikely* to experience increases in zero-flow days, but the magnitude of potential changes in other intermittent streams are not quantified. Changes in zero-flow days in intermittent streams near all the additional coal resource developments cannot be ruled out.

There is a 50% chance of changes in zero-flow days in Saddlers Creek exceeding 20 days, and exceeding 3 days in Loders Creek and in an unnamed creek in the Bayswater Creek catchment. There is a 5% chance that increases in zero-flow days in Saddlers and Loders Creek will exceed 100 days. The regional-scale modelling identifies a risk in these streams. Local hydrogeological and catchment information, including water quality data, stream condition, habitat diversity, recovery potential and other catchment stressors (such as from baseline mines and other land uses) are needed to inform the true nature of the risk from the additional coal resource development.

There are small differences in the mean number of zero-flow days in 'Lowly to highly intermittent' streams in 2042 (Figure 40) and 2102 (Figure 41). Model nodes in Saddlers Creek and a tributary of Bayswater Creek indicate smaller changes in 2102.

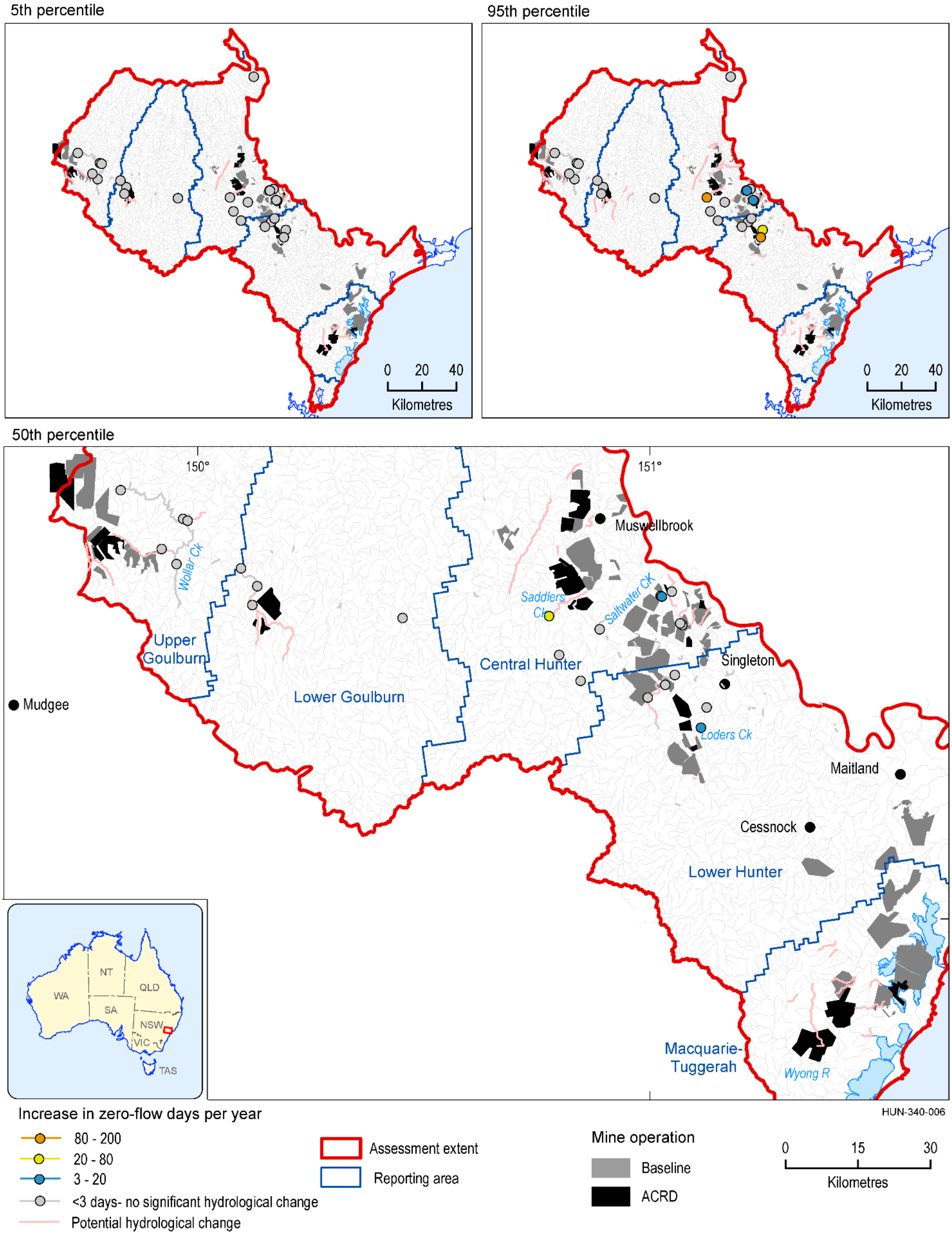

Figure 40 Modelled increase in zero-flow days in lowly to highly intermittent streams in 2042 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

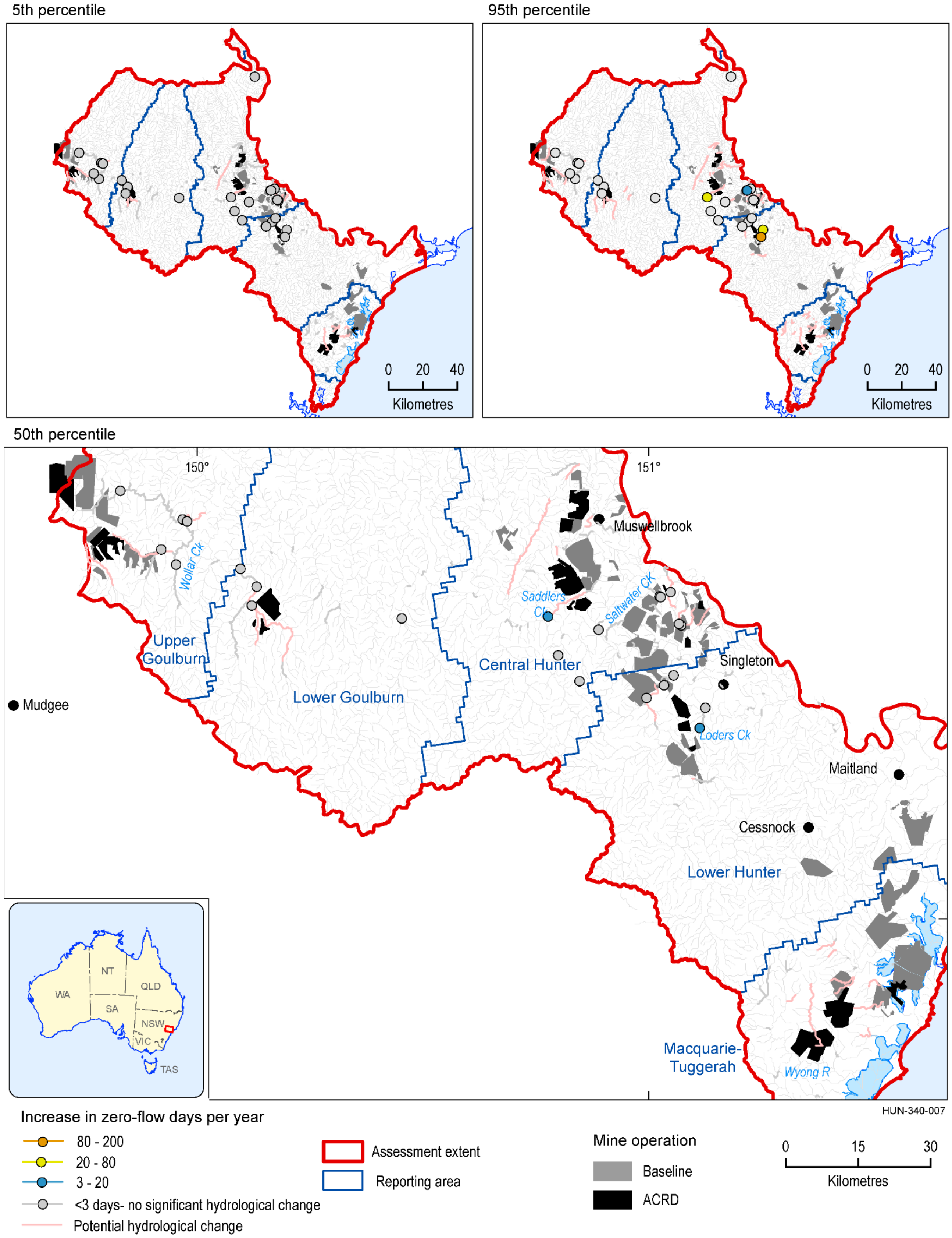

Figure 41 Modelled increase in zero-flow days in lowly to highly intermittent streams in 2102 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 4, Dataset 5)

3.4.3.3 Potential ecosystem impacts

As described in Section 3.4.2, most of the 'Highly intermittent or ephemeral' landscape class within the 'Riverine' landscape group is *very unlikely* to be impacted because it is assumed to not be connected to regional groundwater. In this section the potential ecosystem impacts on 'Permanent or perennial' streams and 'Lowly to highly intermittent' streams are discussed.

3.4.3.3.1 'Permanent or perennial' landscape class

The receptor impact models for 'Permanent or perennial' streams are constructed around relationships between:

- mean abundance of larvae of the Hydropsychidae (net-spinning caddisflies) in a 1 m^2 sample of riffle habitat and changes in zero-flow days (averaged over 30 years) (ZQD) and the mean maximum spell duration of zero flow days (ZME)
- mean probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in a 100 m transect and changes in zero-flow days (ZQD) and the mean maximum spell duration of zero-flow days (ZME).

Hydropsychid caddisflies live in riffles because they rely on flowing water to feed. They play an important trophic role in many stream ecosystems, especially as a key food item for many fish. Median estimates of density of larvae of the Hydropsychidae under the baseline and coal resource development pathway (CRDP) ranged from 0 to 50 m^{-2} in a sample of riffle habitat (Figure 42). There is considerable uncertainty surrounding absolute values of density of larvae of the Hydropsychidae; there was a 90% chance that density could be in the range of 0 to more than 10,000 m^{-2} in both periods.

The median estimates of the difference in density of larvae of the Hydropsychidae due to additional coal resource development in the 30-year periods preceding 2042 and 2102 indicate no change from density under the baseline (Figure 42).

Based on the modelled 5th and 95th percentiles, potential increases or decreases in density of larvae of the Hydropsychidae are possible in some streams due to additional coal resource development. Potentially large changes in mean annual number of zero-flow days due to additional coal resource development in perennial streams are modelled to occur in Wyong River (Figure 38 and Figure 39) and, while not represented in the surface water modelling, potentially also Dora Creek where there is also a risk of extensive groundwater drawdown (Figure 19). The 5th percentile difference in Figure 42 reflects the risk to larvae of the Hydropsychidae from the modelled hydrological changes in Wyong River. Results indicate a 90% chance the impact on Hydropsychidae larvae will range between increases of up to 166 and decreases of up to 4100 caddisfly larvae per square metre of riffle habitat. The large range in predicted response indicates a high degree of uncertainty because other site factors influence the response to this perturbation.

In other perennial streams of the subregion, the modelled hydrological changes are *very unlikely* to impact larvae of the Hydropsychidae.

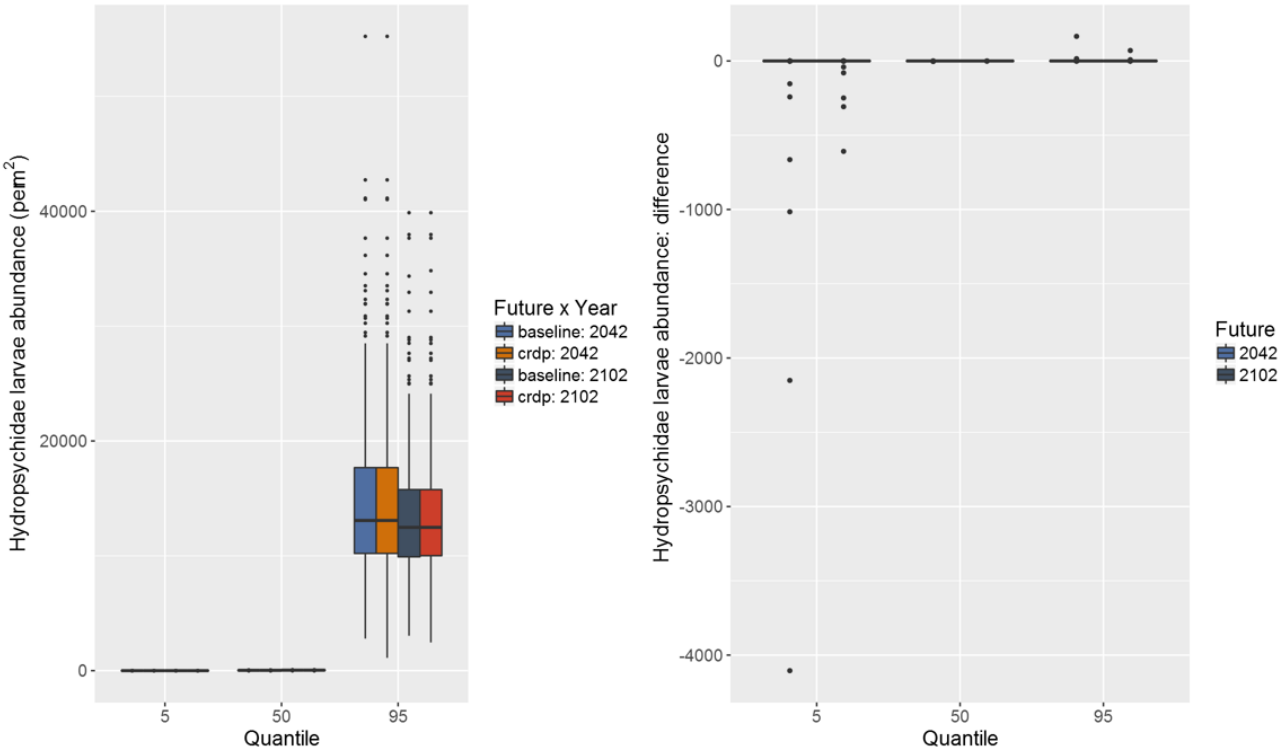

Figure 42 (Left) Modelled change in density of larvae of the Hydropsychidae in 2042 and 2102 across the 'Permanent or perennial' landscape class under both baseline and coal resource development pathway (CRDP) futures. (Right) Predicted change of density of larvae of the Hydropsychidae due to additional coal resource development

Data: Bioregional Assessment Programme (Dataset 6)

The stuttering frog (*Mixophyes balbus*) is a riffle-breeding frog, which breeds in streams during summer after heavy rain. Its eggs are laid on rock shelves or shallow riffles in small, flowing streams. The tadpoles are free-swimming benthic grazers, foraging amongst stones and leaf litter in riffle and pool sections of the stream channel (Anstis, 2002). As the tadpoles grow they move to deep, permanent pools and take approximately 12 months to metamorphose. Median estimates of probability of presence of the riffle-breeding frog (*Mixophyes balbus*) under the baseline and CRDP futures range from less than 0.1 to nearly 0.5 in a 100 m transect of riffle habitat (Figure 43). There is a lot of uncertainty around absolute values of probability of presence of the riffle-breeding frog (range of 0 to nearly 0.7 between 5th and 95th percentiles) in both periods.

The median estimate of change in probability of presence of the riffle-breeding frog due to additional coal resource development in the 30-year periods preceding both 2042 and 2102 indicates no change compared to the baseline period (Figure 43), except potentially in one small section of modelled stream. As for the Hydropsychidae larvae, the 5th and 95th percentiles show potential for increases or decreases in the probability of presence of the riffle-breeding frog in some streams due to additional coal resource development. Again, these large changes relate to the potentially large changes in zero-flow days modelled to occur in the Wyong River. Modelled decreases in the probability of presence of riffle-breeding frogs of up to nearly 0.5 indicate potential losses of instream habitat. The much smaller chance of changes in zero-flow days in the

Wyong River catchment when local-scale hydrogeological data are used to constrain the regional model results (see Section 2.6.2.8 of companion product 2.6.2 for the Hunter subregion, Herron et al., 2018), however, suggest that the likelihood of significant adverse impacts on instream habitat is low.

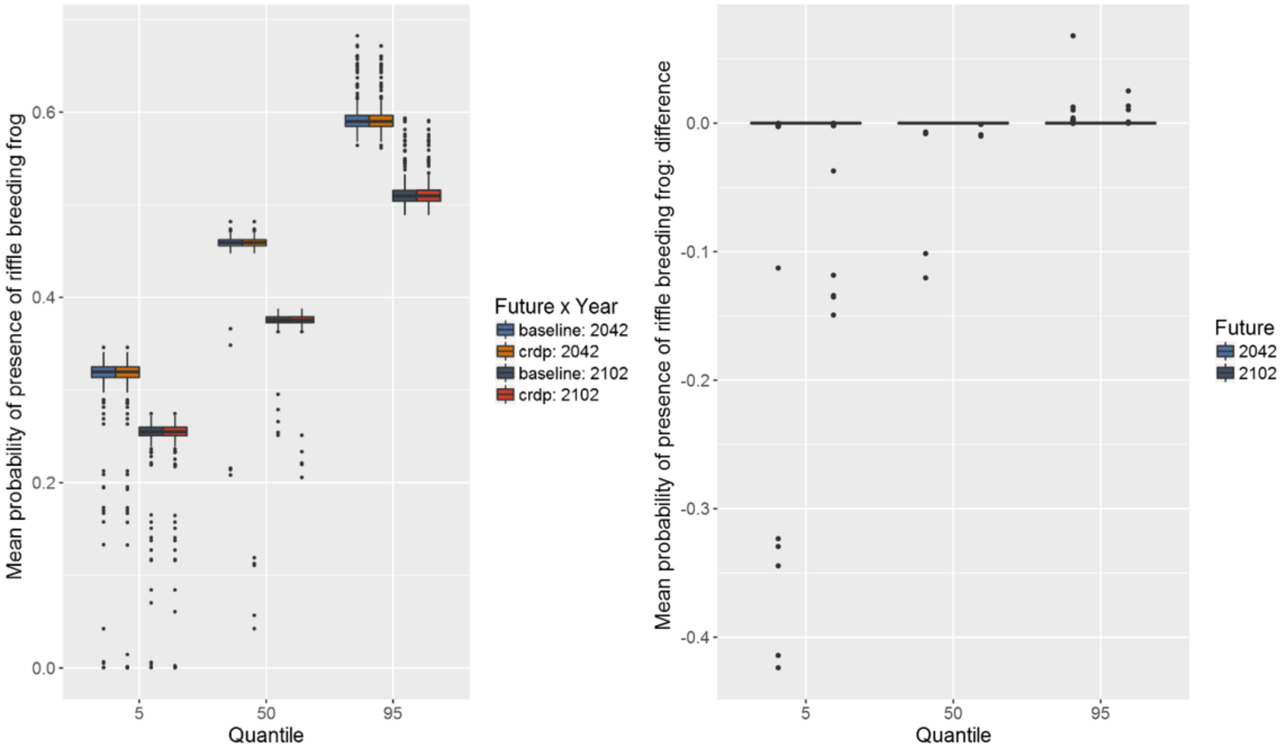

Figure 43 (Left) Modelled change in probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in 2042 and 2102 across the 'Permanent or perennial' landscape class under both baseline and coal resource development pathway (CRDP) futures. (Right) Predicted change of probability of presence of the riffle-breeding frog (*Mixophyes balbus*) due to additional coal resource development

Data: Bioregional Assessment Programme (Dataset 6)

In summary, model results suggest that across the subregion generally, impacts on much of the instream habitat of the 'Permanent or perennial' streams from hydrological changes due to additional coal resource development are *very unlikely*. There is at least a 5% chance that some 'Permanent or perennial' streams in the zone of potential hydrological change will experience adverse ecological impacts. The larger hydrological changes modelled in the Wyong River imply a risk to Hydropsychidae larvae and the probability of presence of riffle-breeding frog populations, and by extension to other components of the ecosystem that have similar water dependencies or depend on the presence of these populations for their persistence. When local information for the Wyong River catchment is incorporated into the groundwater and surface water modelling, the modelled hydrological changes are much smaller and hence the risk to instream habitat could be low. Other local information, relating to the presence and quality of instream habitats, the range of pressures upon them and their recovery potential, is needed to better inform the assessment of risk and guide the appropriate management response.

There is very high uncertainty surrounding estimates of absolute values. Uncertainties reflect not just lack of knowledge, but also the generalisation that is necessary in regional-scale assessments to capture the range of possible changes, which are conditioned on local-scale factors. Based on the qualitative model (see Section 2.7.3.2 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) increases in zero-flow days are likely to result in declines in invertebrates and other subsurface fauna, fish, and riparian and subsurface habitat and carnivores.

3.4.3.3.2 'Lowly to highly intermittent' landscape classes

The receptor impact models for 'Lowly to highly intermittent' streams are constructed around relationships between:

- mean richness of hyporheic invertebrate taxa in 6 L of water pumped from a depth of 40 cm below the streambed (riffle and gravel bars) to changes in zero-flow days (averaged over 30 years) (ZQD) and the mean maximum spell duration of zero-flow days (ZME)
- mean probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in a 100 m transect to changes in zero-flow days (ZQD) and the mean maximum spell duration of zero-flow days (ZME).

Median estimates of richness of hyporheic invertebrate taxa (hereafter referred to as hyporheic taxa) under the baseline and CRDP futures range from 13 to 15 in 6 L of water pumped from a depth of 40 cm below the streambed (Figure 44). There is a lot of uncertainty around absolute values of richness of hyporheic taxa (90% chance that richness of hyporheic taxa could be in the range of less than 4 to more than 40) in both periods.

The median estimate of change in richness of hyporheic taxa due to additional coal resource development in the 30-year periods preceding both 2042 and 2102 indicates that some intermittent streams might experience a reduction in mean richness of up to two taxa compared to the baseline period (Figure 44). Experts were confident that increases in zero-flow days would not result in increases in hyporheic taxa richness. There is at least a 5% chance of reductions in hyporheic taxa of up to ten taxa in some intermittent streams due to additional coal resource development. It is *very unlikely* that there will be decreases in hyporheic taxa richness in the upper Goulburn River and Wollar Creek due to additional coal resource development. There is at least a 50% chance of decreases in hyporheic taxa in Saddlers Creek and at least a 5% chance of decreases in Loders Creek. The condition of these streams, pressures from surrounding land uses and potential to recover are important considerations in determining an appropriate management response.

Hydrological changes were not modelled for many intermittent streams in the assessment extent (Figure 40 and Figure 41). Some are potentially impacted as they are in the groundwater drawdown zone. Impacts on the ecosystems in these streams cannot be ruled out.

Median estimates of probability of presence of the riffle-breeding frog (*Mixophyes balbus*) under the baseline and CRDP futures range from less than 0.12 to nearly 0.75 in a 100 m transect of riffle habitat (Figure 45). There is great uncertainty surrounding absolute values of probability of presence of the riffle-breeding frog; there is a 90% chance that the probability of presence of the riffle-breeding frog is between 0 and 1.

The median estimates from modelled changes in probability of presence of the riffle-breeding frog in the 30-year periods preceding both 2042 and 2102 indicate no change relative to the baseline period (Figure 45) in the majority of intermittent streams in the zone. The 5th and 95th percentiles show potential for increases or decreases in the probability of presence of the riffle-breeding frog in some of the modelled intermittent streams due to additional coal resource development. Based on the hydrological modelling results, the probability of presence of riffle-breeding frogs in Saddlers and Loders creeks is likely to be diminished due to additional coal resource development. Decreases in the probability of presence of riffle-breeding frogs of up to 0.4 are possible, which could mean very low probability of presence of frogs based on the baseline probabilities, or potentially complete loss of habitat. Loders and Saddlers creeks have relatively high stream salinities (medians >5500 µS/cm, Section 3.3.4); their catchments have already been disturbed by baseline and historical mining and agricultural development, and their geomorphic condition has been assessed as poor (Figure 46; NSW Office of Water, Dataset 7). Thus the habitat value of these creeks is likely to already be compromised, and the risk of adverse impacts from additional coal resource development is probably low. Local information on the factors influencing the hydrology of these creeks and the current condition of instream habitats is needed to put the regional-scale assessment into context for informing the appropriate management response.

In summary, the results suggest that for most of the modelled 'Lowly to highly intermittent' streams in the Hunter subregion, impacts on the instream habitat due to additional coal resource development are *very unlikely*. There is at least a 5% chance that some modelled 'Lowly to highly intermittent' streams in the zone will experience adverse ecological impacts, and by extension some of the non-modelled streams that drain or flow close to additional coal resource developments could also be impacted. The potentially large hydrological changes predicted in Saddlers Creek and Loders Creek could have adverse impacts on instream ecosystems, however, local stream salinity (Figure 28 and Figure 29) and geomorphic condition (Figure 46) information suggest they are already degraded.

There is considerable uncertainty surrounding estimates of absolute values. Based on the qualitative model (see Section 2.7.3.3 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) increases in the number of zero-flow days are likely to result in declines in invertebrates and other subsurface fauna, fish, and riparian and subsurface habitat and carnivores.

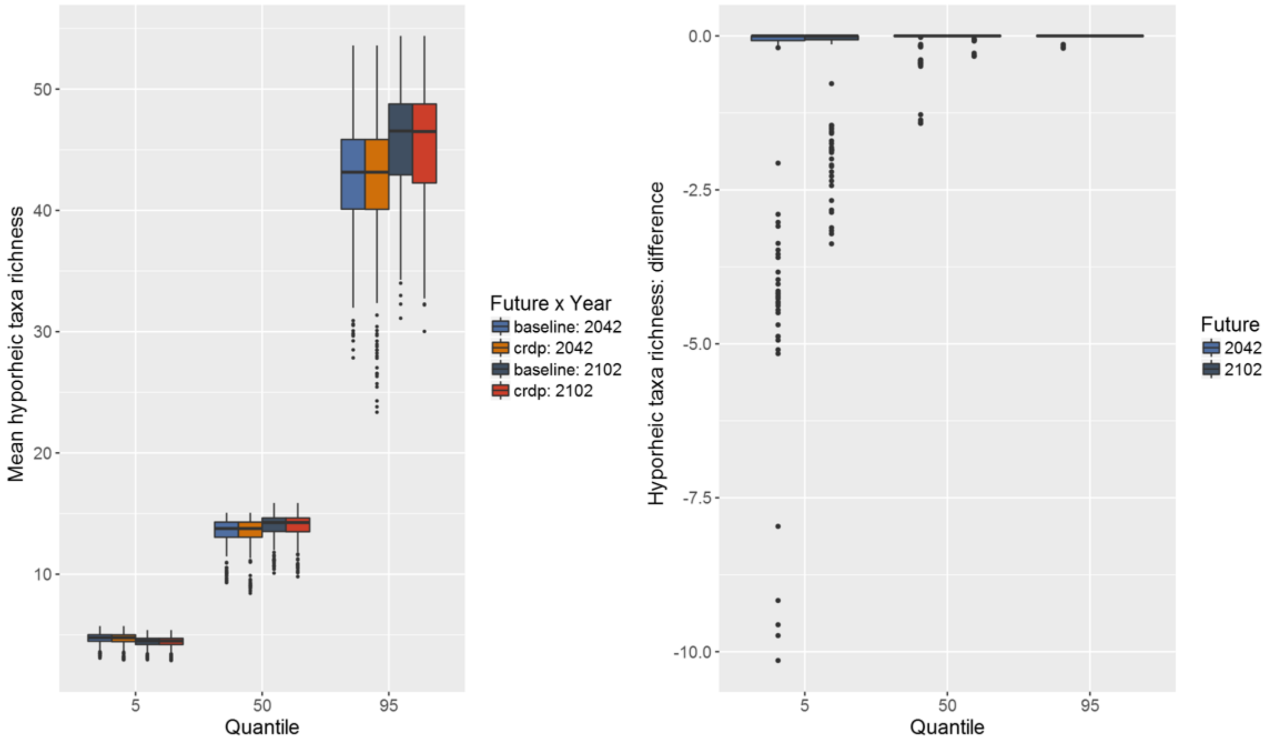

Figure 44 (Left) Modelled change in richness of hyporheic taxa in 2042 and 2102 across the ‘Lowly to highly intermittent’ landscape classes under both baseline and coal resource development pathway (CRDP) futures. (Right) Predicted change of richness of hyporheic taxa due to additional coal resource development

Data: Bioregional Assessment Programme (Dataset 6)

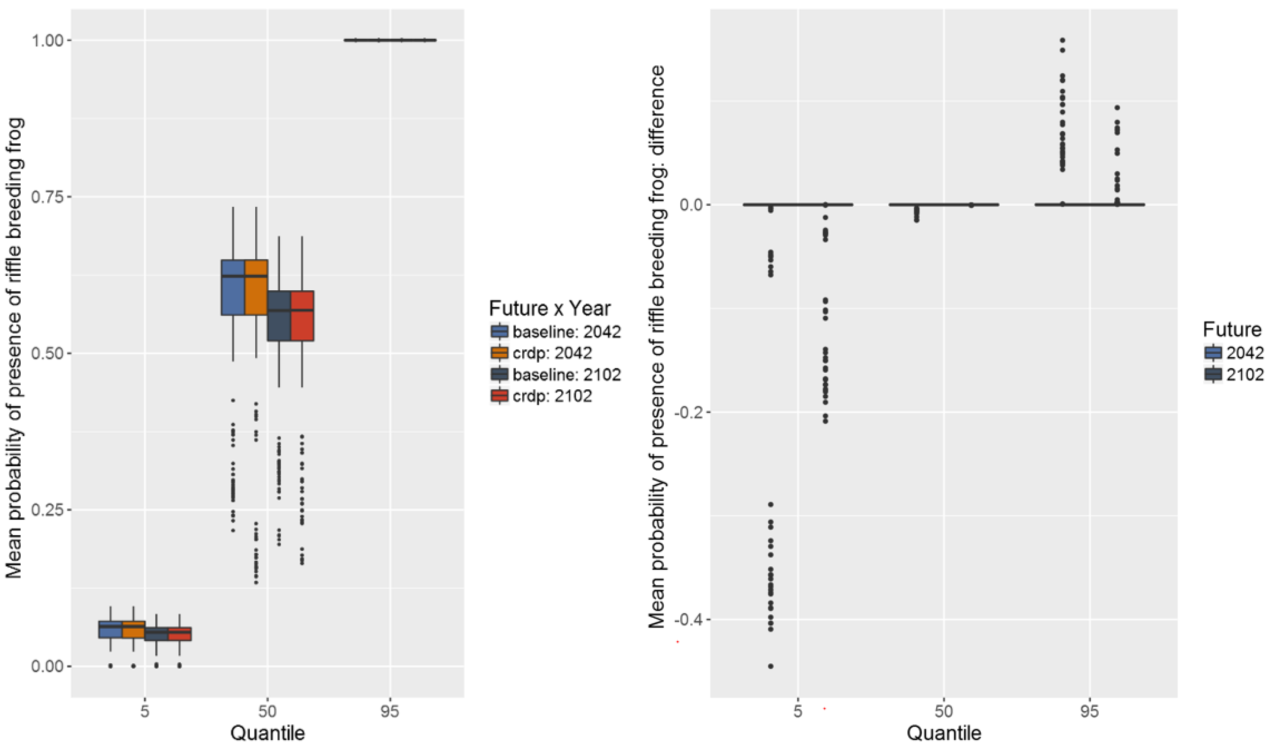

Figure 45 (Left) Modelled change in probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in 2042 and 2102 across the ‘Lowly to highly intermittent’ landscape classes under both baseline and coal resource development pathway (CRDP) futures. (Right) Predicted change of probability of presence of the riffle-breeding frog (*Mixophyes balbus*) due to additional coal resource development

Data: Bioregional Assessment Programme (Dataset 6)

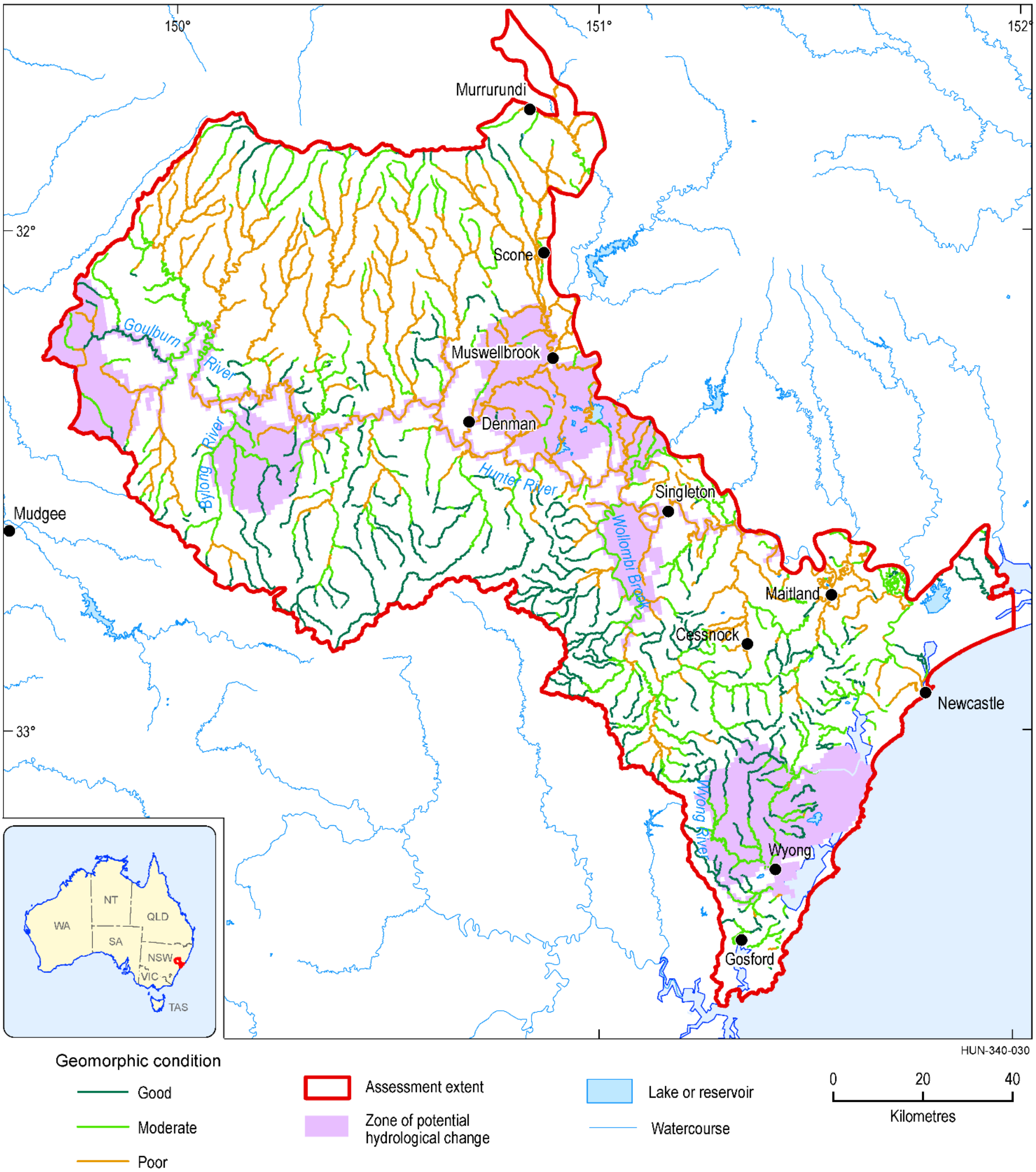

Figure 46 Geomorphic condition of streams in the Hunter assessment extent

Data: Bioregional Assessment Programme (Dataset 3, Dataset 4), NSW Office of Water (Dataset 7)

3.4.4 'Groundwater-dependent ecosystem (GDE)' landscape group

3.4.4.1 Description

GDEs are those ecosystems that rely on the surface or subsurface expression of groundwater to meet all or some of their life-cycle requirements (Eamus et al., 2006). The dependence of GDEs on groundwater varies both spatially and temporally (Eamus et al., 2006). Ecosystems may be obligate GDEs, with a continuous or entire dependence on groundwater, or facultative GDEs, with an infrequent or partial dependence on groundwater (Zencich et al., 2002). Plants that depend solely on moisture held within the soil profile are known as vadophytes and are not groundwater dependent (Sommer and Froend, 2010). In the Hunter subregion, as in much of Australia, there is considerable uncertainty as to the nature of groundwater dependency for much terrestrial vegetation.

The water requirements of GDEs are poorly understood and there is large uncertainty as to the frequency, timing and duration of their groundwater use (Andersen et al., 2016). In general, transpiration of groundwater is expected to decline as the depth to groundwater increases, but there is very limited evidence to support this assumption within Australia. O'Grady et al. (2010) reviewed estimates of groundwater discharge in Australia and concluded that there is considerable variation in the relationship between transpiration of groundwater and depth to groundwater. Factors such as the rooting depth of a particular species (which is usually not known), hydroclimatic environment and groundwater salinity all impact on groundwater use by vegetation. Zolfaghar et al. (2014) examined the structure and productivity of eucalypt forest across a depth to watertable gradient in the Upper Nepean catchment in NSW. They found that where groundwater was shallow, vegetation had significantly higher biomass and productivity than sites where groundwater was deeper than approximately 10 m. The relationships between depth to groundwater and the structural and functional attributes of the vegetation communities were highly non-linear, with steep declines in leaf area index and biomass over a range of 5 to 10 m depth to groundwater. However, it is important to note that the study was largely correlative in nature and did not quantify the groundwater requirements of the vegetation. Specific studies of GDEs within the Hunter subregion are limited. Existing mapping of GDEs is based on a multiple-lines-of-evidence approach that incorporated existing vegetation mapping, modelled groundwater levels and remote sensing (Kuginis et al., 2016). Modelled depths to groundwater (Summerell and Mitchell, 2011) for the subregion are generally shallow (within 16 m of the ground surface). However, there is likely to be uncertainty in the mapping owing to the sparse network of monitoring bores over much of the subregion.

The hydroclimatic environment of the Hunter subregion is subtropical in the eastern part, and bordering on temperate in the western part of the subregion. Average annual rainfall ranges from 600 to 1440 mm/year, with higher values associated with higher elevations and coastal areas. Precipitation is summer dominated when potential evaporation is also highest (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). Hence, the region is classified as being water limited in as much as potential evaporation (1250 to 1950 mm/year) exceeds rainfall in most months of the year. In areas that experience a rainfall deficit, vegetation may be dependent to varying extents on groundwater within the Hunter subregion.

The geomorphology and hydrogeology of the Hunter subregion is described in companion product 1.1 (McVicar et al., 2015) and only a brief summary is presented here as context. The hydrogeological systems in the Hunter subregion are associated with Permian-Triassic rock aquifers, alluvial aquifers along major rivers and creeks and aeolian sands aquifers in the coastal zone of the subregion. The Hunter Valley represents a regional groundwater discharge zone and a dividing streamline for groundwater flow. The main regional surface water – groundwater fluxes largely follow the subregion topography from the upland towards the river channels with overall discharge towards the Tasman Sea. From a surface water perspective, the Hunter subregion is primarily composed of the Hunter river basin (87.5% of the subregion) and the Macquarie-Tuggerah lakes basin (10.7% of the subregion) (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)).

The subregion has three main hydrogeological units (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)) relevant to sustaining GDE structure and function, which provide a useful conceptual framework for examining landscape classes that are dependent on groundwater:

- alluvial aquifers along major rivers and creek lines
- fractured rock aquifers of the Hunter subregion
- coastal aquifers in the coastal area.

3.4.4.1.1 Alluvial aquifers

Alluvial aquifers form in sediments such as gravel, sand, silt and/or clay deposited by physical processes in river channels or on floodplains (Figure 47). These unconsolidated sedimentary aquifers may be layered and/or discontinuous due to the presence of deposits of low permeability silt and clay within the alluvia (Queensland Government, 2013a). Alluvial aquifers are generally shallower than sedimentary and fractured rock aquifers and water levels often fluctuate due to varying recharge and pumping rates (Geoscience Australia, 2016). Alluvia may be underlain by impermeable layers, which separate the unconfined sedimentary aquifer from other groundwater aquifers. Alluvia may support a range of ecosystems (Queensland Government, 2013a). Palustrine (e.g. swamps) and lacustrine (e.g. lakes) wetlands and riverine (e.g. streams and rivers) water bodies on alluvial deposits may depend on the surface expression of groundwater, while terrestrial vegetation may depend on subsurface groundwater that is typically accessed through the capillary zone above the watertable. Unconsolidated sedimentary aquifers in alluvial deposits may also support ecosystems within the aquifer itself, such as stygofauna.

The alluvial aquifer of the Hunter subregion is considered a regional discharge zone for the aquifers within the region (EPA, 2013), implying an interaction from the groundwater to surface water system through the alluvial aquifer. The connection between the alluvial aquifer and underlying fractured rocks is considered bi-directional (EPA, 2013). Groundwater discharge contributes to baseflow throughout the subregion, but is more persistent in the main Hunter alluvial systems than in the elevated areas, where there is a permanent connection to groundwater. The main recharge mechanisms for the alluvial aquifer are river leakage to the alluvium (particularly during flooding), direct rainfall recharge and upward flow from Permian fractured rocks (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)).

River leakage is generally considered to be the largest recharge component, and in various modelling studies it has been fitted as up to four times greater than diffuse rainfall recharge (Worley Parsons, 2009; Heritage Computing, 2012).

GDE landscape classes, which are based on vegetation forms from Keith (2004) that are likely to be associated with alluvial aquifers, include forested wetlands, and some freshwater wetlands, rainforests and semi-arid wetlands.

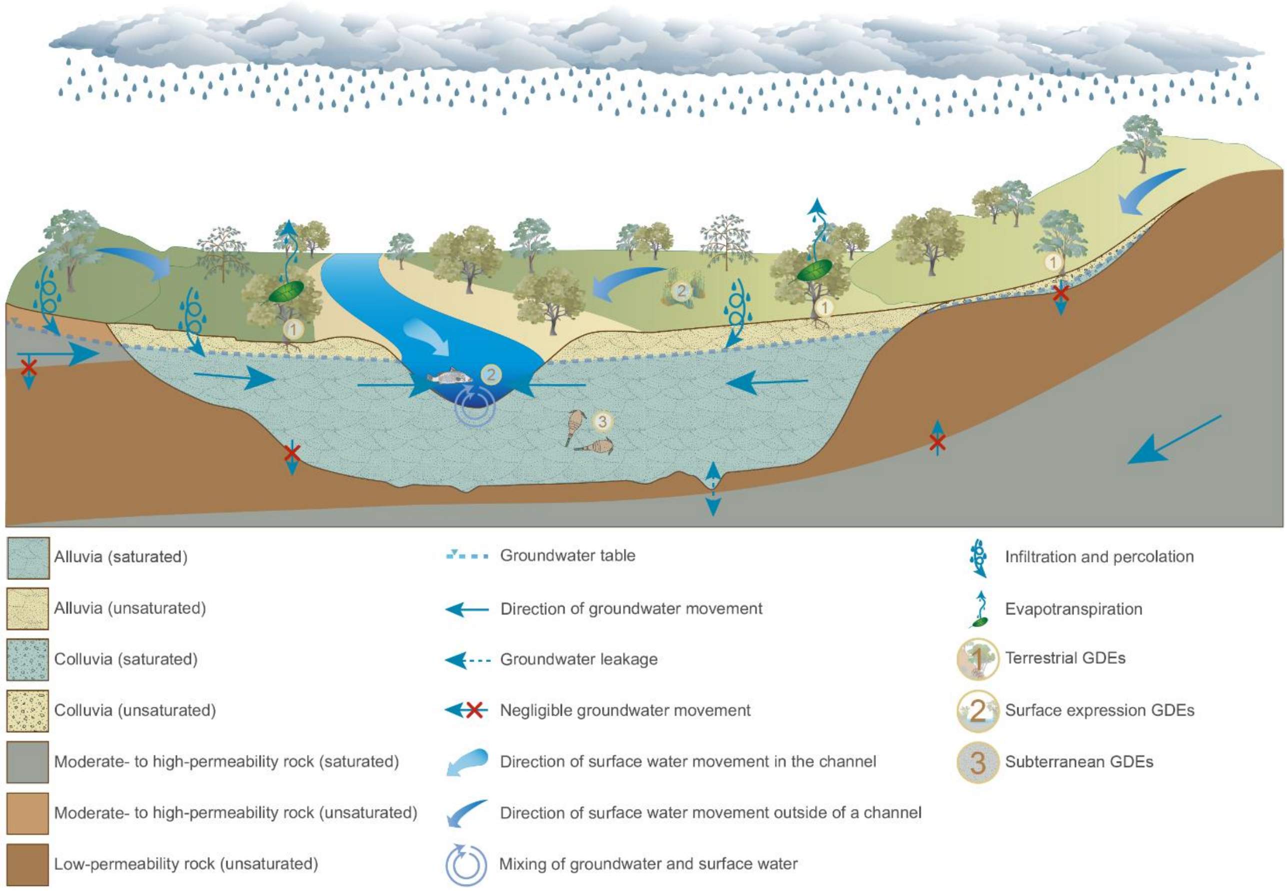

Figure 47 Conceptual model of the major groundwater processes in alluvia along major rivers and creeks in lower catchments

Source: adapted from Queensland Government (2013a); Queensland Department of Science, Information Technology and Innovation (Dataset 8)

3.4.4.1.2 Fractured rock

In fractured rock aquifers (Figure 48), groundwater is stored in the fractures, joints, bedding planes and cavities of the rock mass (Geoscience Australia, 2016) and transmitted through fractures within the otherwise low-permeability rock (Queensland Government, 2015). Fractured rock aquifers may discharge groundwater into channels largely in the lower parts of the landscape while channels in upper parts of the landscape usually transmit surface water runoff only. Groundwater diffuse recharge from Permian sedimentary rock units in the Hunter subregion is estimated at less than 2% of annual rainfall, with high values associated with areas of the enhanced regolith permeability.

GDE landscape classes most likely to be associated with fractured rock aquifers include some rainforests, wet and dry sclerophyll forests, grassy woodlands and semi-arid woodlands.

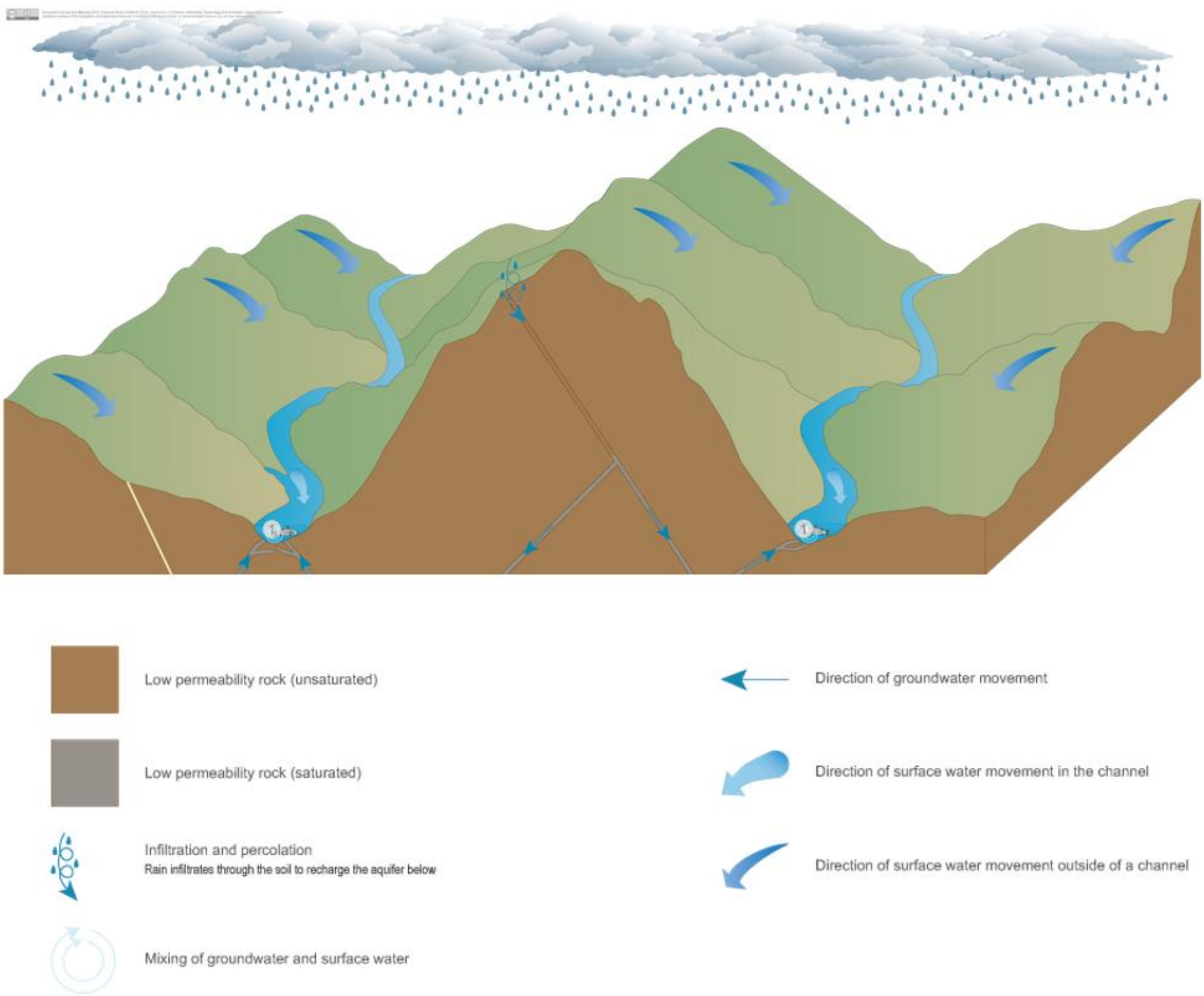

Figure 48 Conceptual model of the major groundwater processes in fractured rock systems

The number '1' indicates a surface expression groundwater-dependent ecosystem (GDE).
Source: Queensland Government (2015); Queensland Department of Science, Information Technology and Innovation (Dataset 8)
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3.4.4.1.3 Coastal aquifers

Coastal sands typically support a single, unconsolidated sedimentary aquifer, in which groundwater forms a freshwater lens in the intergranular voids of the coastal sand mass (Figure 49). Perched aquifers may also occur over low permeability layers within the sand mass (Queensland Government, 2013b). Palustrine (e.g. swamps) and lacustrine (e.g. lakes) wetlands and riverine (e.g. streams and rivers) water bodies on coastal sand masses may depend on the surface expression of groundwater from these unconsolidated sedimentary aquifers, while terrestrial vegetation may depend on subsurface groundwater that is typically accessed through the capillary zone above the watertable. Unconsolidated sedimentary aquifers may also support subterranean ecosystems within the aquifer itself, indicated by the presence of stygofauna.

In the Hunter subregion, dunal and/or coastal (of aeolian origin) sands of medium-grain size form a highly permeable unconfined aquifer, and rainfall rapidly infiltrates through the unsaturated zone to recharge the saturated zone (companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). This type of aquifer experiences the highest diffuse recharge rate in the subregion. Transmissivity was estimated between 400 m/day to more than 600 m/day (Crosbie, 2003), with a specific yield of about 0.2. The groundwater level is very responsive to rainfall events, with groundwater level rises over a metre observed on an event basis (Crosbie, 2003).

GDE landscape classes most likely to be associated with coastal aquifers include some freshwater wetlands, forested wetlands, heathlands and rainforests. Estuarine and near-shore marine ecosystems located adjacent to coastal sand masses may also depend on the discharge of groundwater from these unconsolidated sedimentary aquifers (note that ‘Coastal lakes and estuarine systems’ are covered in Section 2.7.5 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)).

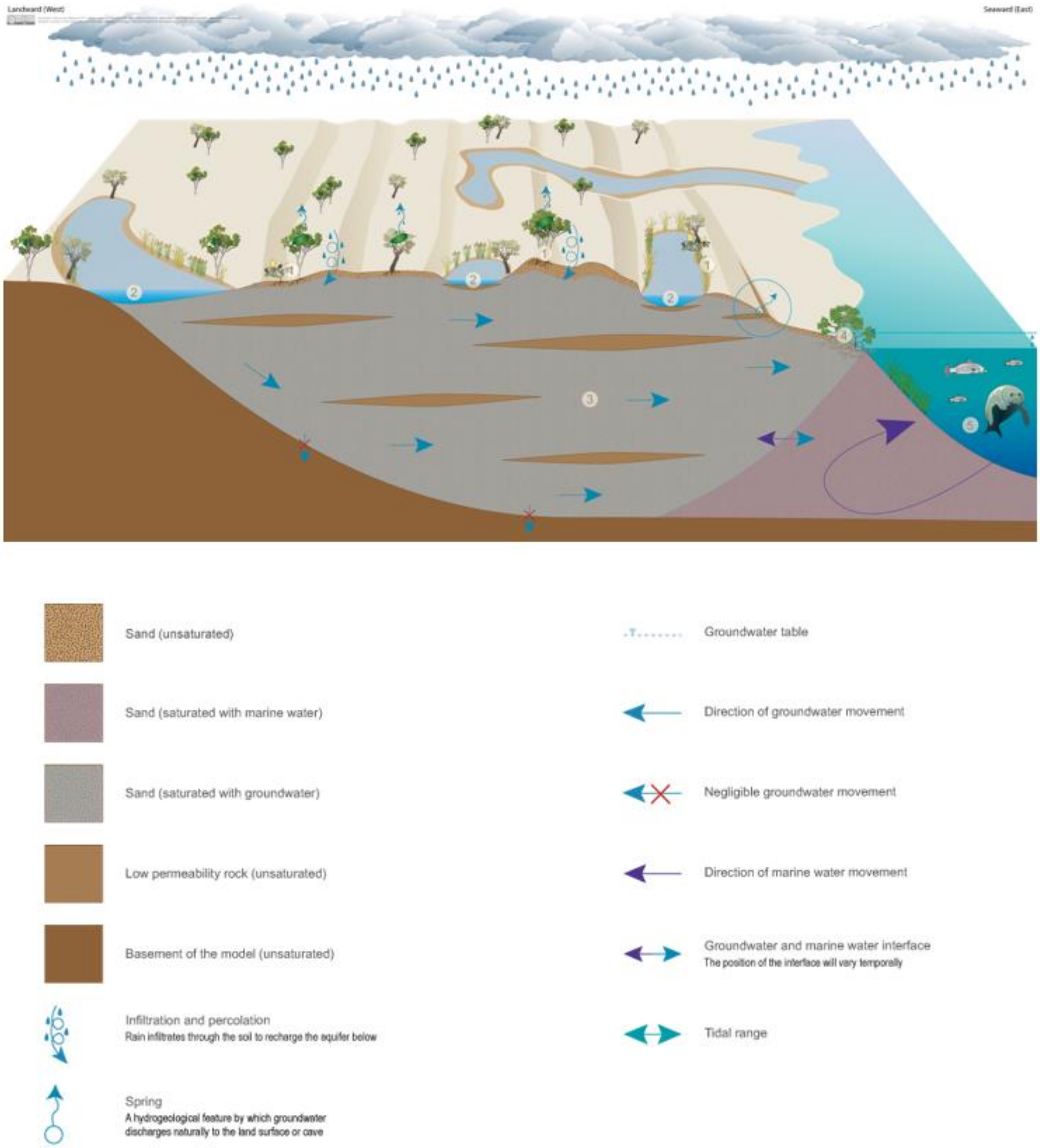

Figure 49 Conceptual model of the major groundwater processes on coastal areas

Numbers refer to types of groundwater-dependent ecosystems (GDEs) as follows: 1 = terrestrial GDEs, 2 = surface expression GDEs, 3 = subterranean GDEs, 4 = surface expression GDEs (estuarine systems), 5 = surface expression GDEs (near-shore marine systems).
Source: Queensland Government (2013b); Queensland Department of Science, Information Technology and Innovation (Dataset 8)
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3.4.4.2 Potential hydrological changes

The area of GDE landscape classes within the zone of potential hydrological change is 102 km^2 of which 1.8 km^2 is in the mine pit exclusion zone (Table 20). This represents 28% of the total area of GDEs within the Hunter assessment extent (Table 20). Only small percentages (<3%) of the total areas of 'Freshwater wetland', 'Grassy woodland', 'Heathland' and 'Semi-arid woodland' are present in the zone. Instead, 16% of 'Dry sclerophyll forest', 38% of 'Forested wetland', 60% of 'Rainforest' and 31% of 'Wet sclerophyll forest' landscape classes are present in the zone (Table 20).

All the 'Rainforest' (24 km^2) and 'Wet sclerophyll forest' (4.5 km^2) in the zone are present in the Macquarie-Tuggerah lakes basin, as is the majority of the 'Dry sclerophyll forest' (13.2 km^2); small areas of 'Dry sclerophyll forest' (1.2 km^2) are present in the Upper Goulburn. Forested wetlands are most concentrated in the Macquarie-Tuggerah (28.8 km^2) and Central Hunter (13.2 km^2), with smaller areas in the Lower Goulburn (9.2 km^2), Lower Hunter (4.7 km^2) and Upper Goulburn (1.9 km^2).

The hydrological factors identified by experts in the qualitative modelling workshops (see companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) have been interpreted as a set of hydrological response variables. The hydrological factors and associated hydrological response variables for the 'GDE' landscape group are the:

- maximum difference in drawdown under the baseline future or under the coal resource development pathway future relative to the reference period (1983 to 2012) (dmaxRef)
- year that the maximum decrease of groundwater occurs (tmaxRef)
- mean annual number of events with a peak daily flow exceeding the volume of flow that is assumed to result in 'overbench' flow (EventsR0.3)
- mean annual number of events with a peak daily flow exceeding the volume of flow that is assumed to result in 'overbank' flow (EventsR3.0).

For details of these variables see Section 2.7.3 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a). Drawdown is a hydrological response variable for both the 'Forested wetland' and 'Wet and dry sclerophyll forest' receptor impact models, while the overbench and overbank flow hydrological response variables are only used in the 'Forested wetland' receptor impact model.

3.4.4.2.1 Groundwater

Of the 100 km^2 of GDEs outside the mine pit exclusion zone, 39 km^2 are potentially subject to drawdown of more than 0.2 m under the baseline (95th percentile); this reduces to 14 km^2 at the 50th percentile and 7 km^2 at the 5th percentile (Table 20). The majority of the GDE area potentially subject to drawdown under the baseline future is 'Forested wetland', 'Rainforest' or 'Dry sclerophyll forest' (Figure 50). Approximately half of the 'Forested wetland' is riverine forest (29.1 km^2) and half is coastal forest in the Macquarie-Tuggerah lakes basin (28.7 km^2). For the majority of the GDE area predicted to experience drawdown under the baseline drawdown, the predicted drawdown is less than 2 m. For GDEs, 9 km^2 will potentially experience a drawdown of more than 2 m under the baseline, most of which is 'Forested wetland' or 'Dry sclerophyll forest'.

As a result of additional coal resource development, 62 km^2 of GDEs are potentially subject to additional drawdown of at least 0.2 m (95th percentile); this reduces to 41 km^2 at the 50th percentile and 16 km^2 at the 5th percentile (Table 21; Figure 51). The majority of the GDE area potentially subject to additional drawdown is 'Forested wetland', 'Rainforest' or 'Dry sclerophyll forest'. Twenty-eight km^2 of GDEs are predicted to experience an additional drawdown of more than 2 m and 17 km^2 are potentially subject to additional drawdown of greater than 5 m.

'Rainforest' is potentially subject to greater drawdowns than either 'Forested wetland' or 'Dry sclerophyll forest'.

The vast majority of 'Wet sclerophyll forest', 'Dry sclerophyll forest' and 'Rainforest' landscape classes potentially subject to 0.2 m of drawdown due to additional coal resource development is in the Macquarie-Tuggerah reporting area (Figure 51); 5.6 km^2 of 'Wet sclerophyll forest' or 'Dry sclerophyll forest' are potentially subject to drawdown of more than 2 m.

Nearly all of the riverine 'Forested wetland' in the Hunter and Goulburn river basins is potentially subject to drawdown of less than 2 m (median estimate); 2.6 km^2 of the coastal 'Forested wetland' are potentially subject to drawdown of more than 2 m (median estimate).

When local geological and hydrogeological data are used to constrain model results based on the regional parameter set, the area potentially at risk of drawdowns exceeding 0.2 m can be smaller than predicted using the full set of simulations. This is illustrated for the Wyong River catchment in Figure 47 in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018), and in Table 10 of this product. The areas of the potentially impacted GDE landscape classes in the Wyong River catchment based on the regional and local parameter sets are provided in Table 22 and Table 23. Using the locally-constrained parameter set, the area of GDEs identified as potentially at risk (at least 5% chance of greater than 0.2 m drawdown) due to additional coal resource development is just over 0.6 km^2, about half the area (1.18 km^2) estimated using the regional parameter result set. The biggest reductions in potentially impacted area are for the 'Forested wetland' GDEs, followed by 'Rainforest' GDEs.

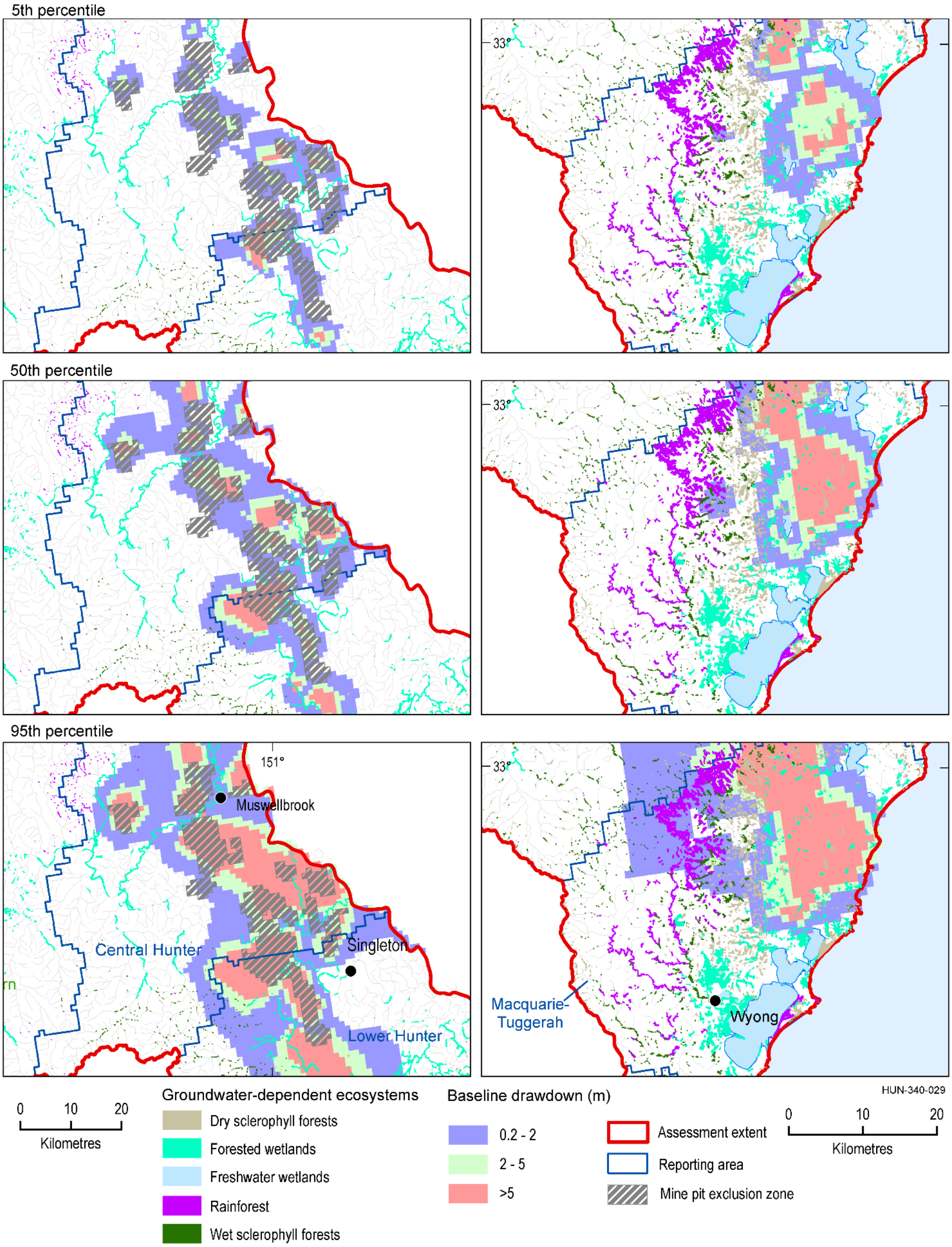

Figure 50 'Groundwater-dependent ecosystem (GDE)' landscape classes in areas of baseline drawdown in Central Hunter, Lower Hunter (left panels) and Macquarie-Tuggerah (right panels) reporting areas (5th, 50th and 95th percentiles)

Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 3, Dataset 4, Dataset 5)

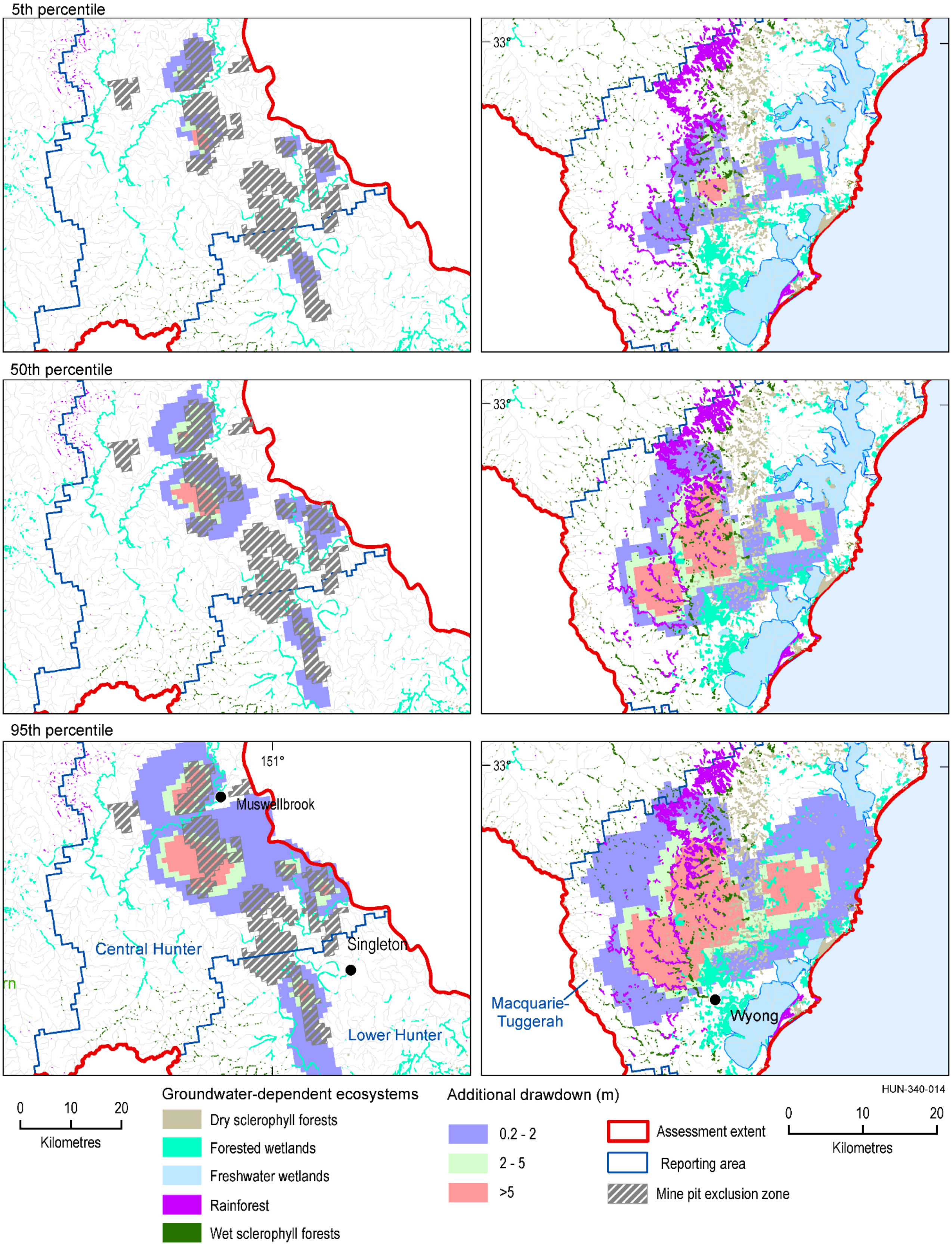

Figure 51 'Groundwater-dependent ecosystem (GDE)' landscape classes in the area of additional drawdown in Central Hunter, Lower Hunter (left panels) and Macquarie-Tuggerah (right panels) reporting areas (5th, 50th and 95th percentiles)

Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 3, Dataset 4, Dataset 5)

Table 20 Area (km^2) of landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group potentially exposed to varying levels of baseline drawdown in the zone of potential hydrological change

Landscape class	Area in assessment extent (km^2)	Area in zone of potential hydrological change (km^2)	Area in mine pit exclusion zone (km^2)	Area with baseline drawdown ≥0.2 m (km^2)			Area with baseline drawdown ≥2 m (km^2)			Area with baseline drawdown ≥5 m (km^2)		
				5th	50th	95th	5th	50th	95th	5th	50th	95th
Dry sclerophyll forest	91.1	14.6	0.0	1.8	3.7	6.7	0.8	1.0	2.0	0.3	0.8	1.0
Forested wetland – riverine forests	150.8	29.1	1.8	1.5	4.4	10.1	0.2	1.0	3.6	0.0	0.1	2.0
Forested wetland – coastal forests		28.7	0.0	3.2	4.2	4.6	0.7	1.4	2.9	0.1	0.7	0.9
Freshwater wetland	35.5	1.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0
Grassy woodland	12.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heathland	14.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Rainforest	40.2	23.9	0.0	0.5	1.5	15.5	0.0	0.0	0.5	0.0	0.0	0.0
Semi-arid woodland	0.6	<0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wet sclerophyll forest	14.2	4.5	0.0	0.1	0.4	1.4	0.0	0.0	0.2	0.0	0.0	0.0
Total	**359**	**102**	**1.8**	**7.1**	**14.3**	**38.6**	**1.8**	**3.4**	**9.3**	**0.4**	**1.7**	**3.9**

The area potentially exposed to ≥0.2, ≥2 and ≥5 m baseline drawdown is shown for the 5th, 50th and 95th percentiles. Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Areas within mine pit exclusion zones are excluded from further analysis. Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5)

Table 21 Area (km²) of landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group potentially exposed to varying levels of drawdown due to additional coal resource development

Landscape class	Area in assessment extent (km²)	Area in zone of potential hydrological change (km²)	Area in mine pit exclusion zone (km²)	Area with additional drawdown ≥0.2 m (km²)			Area with additional drawdown ≥2 m (km²)			Area with additional drawdown ≥5 m (km²)		
				5th	50th	95th	5th	50th	95th	5th	50th	95th
Dry sclerophyll forest	91.1	14.6	0.0	4.4	8.1	11.6	0.7	3.5	5.9	0.0	1.2	2.9
Forested wetland – riverine forests	150.8	29.1	1.8	0.1	0.8	5.9	0.0	0.0	0.1	0.0	0.0	0.0
Forested wetland – coastal forests		28.7	0.0	2.2	8.4	17.6	0.3	2.6	5.4	0.0	0.4	2.5
Freshwater wetland	35.5	1.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.1
Grassy woodland	12.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heathland	14.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Rainforest	40.2	23.9	0.0	7.3	20.2	23.5	1.5	10.4	14.2	0.2	5.8	9.8
Semi-arid woodland	0.6	<0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wet sclerophyll forest	14.2	4.5	0.0	2.0	3.1	3.8	0.8	2.1	2.6	0.1	1.6	2.3
Total	**359**	**102**	**1.8**	**16.0**	**40.6**	**62.5**	**3.3**	**18.7**	**28.3**	**0.3**	**9.0**	**17.5**

The area potentially exposed to ≥0.2, ≥2 and ≥5 m additional drawdown is shown for the 5th, 50th and 95th percentiles. Additional drawdown is the maximum difference in drawdown (*dmax*) due to additional coal resource development relative to the baseline. Areas within mine pit exclusion zones are excluded from further analysis. Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5)

Table 22 Area (km²) of 'Groundwater-dependent ecosystem (GDE)' landscape classes in the Wyong River catchment potentially exposed to varying levels of drawdown due to additional coal resource development, based on regional parameter values

Landscape class	Area with additional drawdown ≥0.2 m (km²)			Area with additional drawdown ≥2 m (km²)			Area with additional drawdown ≥5 m (km²)		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
Dry sclerophyll forest	0.05	0.10	0.13	0.01	0.08	0.11	0	0.04	0.09
Forested wetland	0.01	0.19	0.50	0	0.11	0.24	0	0	0.14
Rainforest	0.15	0.40	0.43	0	0.26	0.35	0	0.16	0.29
Wet sclerophyll forest	0.07	0.10	0.12	0.01	0.08	0.11	0	0.05	0.10
Total	**0.27**	**0.79**	**1.18**	**0.02**	**0.53**	**0.81**	**0**	**0.25**	**0.62**

The area potentially exposed to ≥0.2, ≥2 and ≥5 m additional drawdown is shown for the 5th, 50th and 95th percentiles. Additional drawdown is the maximum difference in drawdown (*dmax*) due to additional coal resource development relative to the baseline. Areas within mine pit exclusion zones are excluded from further analysis. Some totals due not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5)

Table 23 Area (km²) of 'Groundwater-dependent ecosystem (GDE)' landscape classes in the Wyong River catchment potentially exposed to varying levels of drawdown due to additional coal resource development, based on locally-constrained parameter values

Landscape class	Area with additional drawdown ≥0.2 m (km²)			Area with additional drawdown ≥2 m (km²)			Area with additional drawdown ≥5 m (km²)		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
Dry sclerophyll forest	0.01	0.06	0.10	0	0	0.05	0	0	0.03
Forested wetland	0	0.03	0.13	0	0	0.02	0	0	0.01
Rainforest	0	0.15	0.28	0	0	0.16	0	0	0.09
Wet sclerophyll forest	0	0.08	0.11	0	0	0.09	0	0	0.04
Total	**0.01**	**0.33**	**0.61**	**0**	**0**	**0.32**	**0**	**0**	**0.17**

The area potentially exposed to ≥0.2, ≥2 and ≥5 m additional drawdown is shown for the 5th, 50th and 95th percentiles. Additional drawdown is the maximum difference in drawdown (*dmax*) due to additional coal resource development relative to the baseline. Areas within mine pit exclusion zones are excluded from further analysis. Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5)

3.4.4.2.2 Surface water

Surface water hydrological response variables that represent change in the recurrence interval of overbench and overbank flows were used in the receptor impact model for 'Forested wetland – riverine forest'. This model applies to riverine forests along unregulated rivers in the Hunter River basin, and is not considered appropriate for riverine forests along the regulated river. It is also not applicable to coastal swamp forested wetlands in the Macquarie-Tuggerah lakes basin, which comprise different tree species and could respond differently to changes in hydrology. There are 28.7 km^2 of coastal 'Forested wetland' within the zone.

Overbench flows and overbank flows form part of the high flow end of the flow regime and enhance the hydrological connectivity between the floodplain and alluvial aquifers (Section 3.4.3.1). For the purposes of the 'Forested wetland – riverine forest' receptor impact model, overbench flows are assumed to occur on average about 3 times a year, which corresponds to a recurrence interval of 0.33 years; and overbank flows are flood flows and assumed to occur on average once every 3 years (recurrence interval of 3 years). At each surface water model node, the flow rates corresponding to these recurrence intervals define the thresholds for assessing the impact of additional coal resource development on the recurrence interval of overbench and overbank flows.

Most of the riverine forests potentially subject to changes in overbench or overbank flows due to additional coal resource development are located along the Goulburn River, Wollombi Brook and the Hunter Regulated River. Of the 29.1 km^2 of 'Forested wetland – riverine forest' within the zone, changes in projected foliage cover cannot be quantified for 15.4 km^2 because the changes in hydrology due to additional coal resource development were not able to be quantified in the reaches along which they occur.

For the reaches where surface water modelling results are available, 8.5 km^2 of riverine forest are predicted to experience decreases in overbench and overbank flows. The predicted changes are generally small (i.e. fewer than 0.2 events per year decrease for overbench and fewer than 0.1 events per year decrease for overbank). A reduction of 0.2 means one fewer event every 5 years; a reduction of 0.1 is one fewer event every 10 years. Based on the median estimates from the modelling, it is unlikely that the frequency of overbench or overbank flows will change due to additional coal resource development (Figure 52, Figure 53, Figure 54, Figure 55) over the short or long term. The area of riverine forest potentially subject to a decrease in overbench flows of one event every 5 years, based on the median result, is 0.3 km^2 in the 30-year period preceding 2042 (Table 24) and 0.2 km^2 in the 30-year period preceding 2102 (Table 24). None of the riverine forest, for which changes can be quantified, is predicted to experience decreases in overbank flows of one event every 5 years due to additional coal resource development, but 0.2 km^2 could experience a loss of one overbank flow event every 10 years (Table 25).

Overall, there is only a small chance in a few areas that riverine forests along unregulated rivers in the Hunter river basin will be impacted by changes in overbench or overbank flow due to additional coal resource development. The risk to riverine forests along the Hunter Regulated River cannot be determined with much certainty, although modelling results do show similar changes in the overbench (Figure 52 and Figure 53) and overbank (Figure 54 and Figure 55) hydrological response variables along the regulated reaches. The uncertainty associated with streamflow in a regulated river is reflected by greying out these reaches.

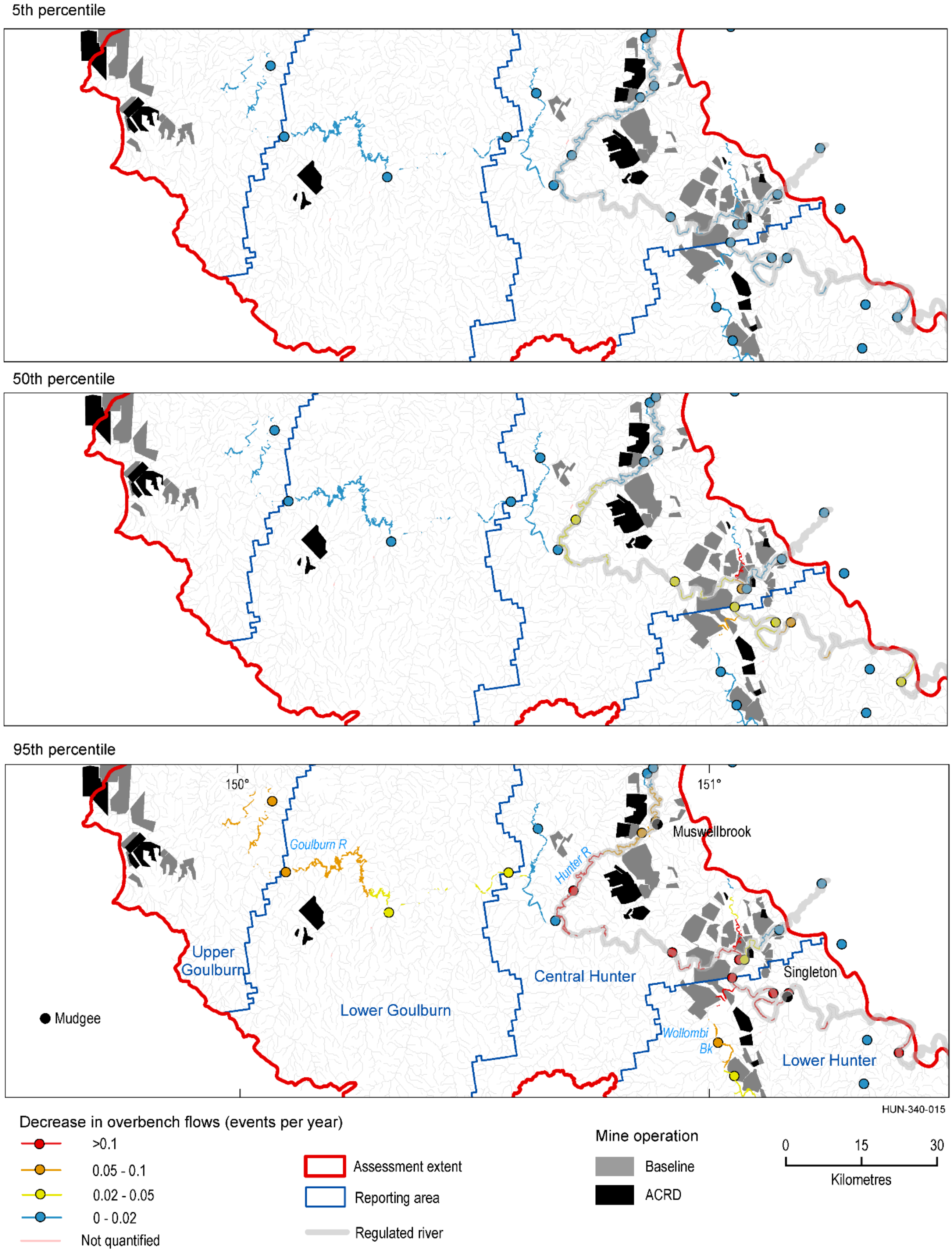

Figure 52 Modelled change in overbench flow in forested wetlands in 2042 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The Hunter Regulated River is greyed out because the receptor impact model was explicitly developed for riverine forests on unregulated rivers in the Hunter river basin.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 4, Dataset 5)

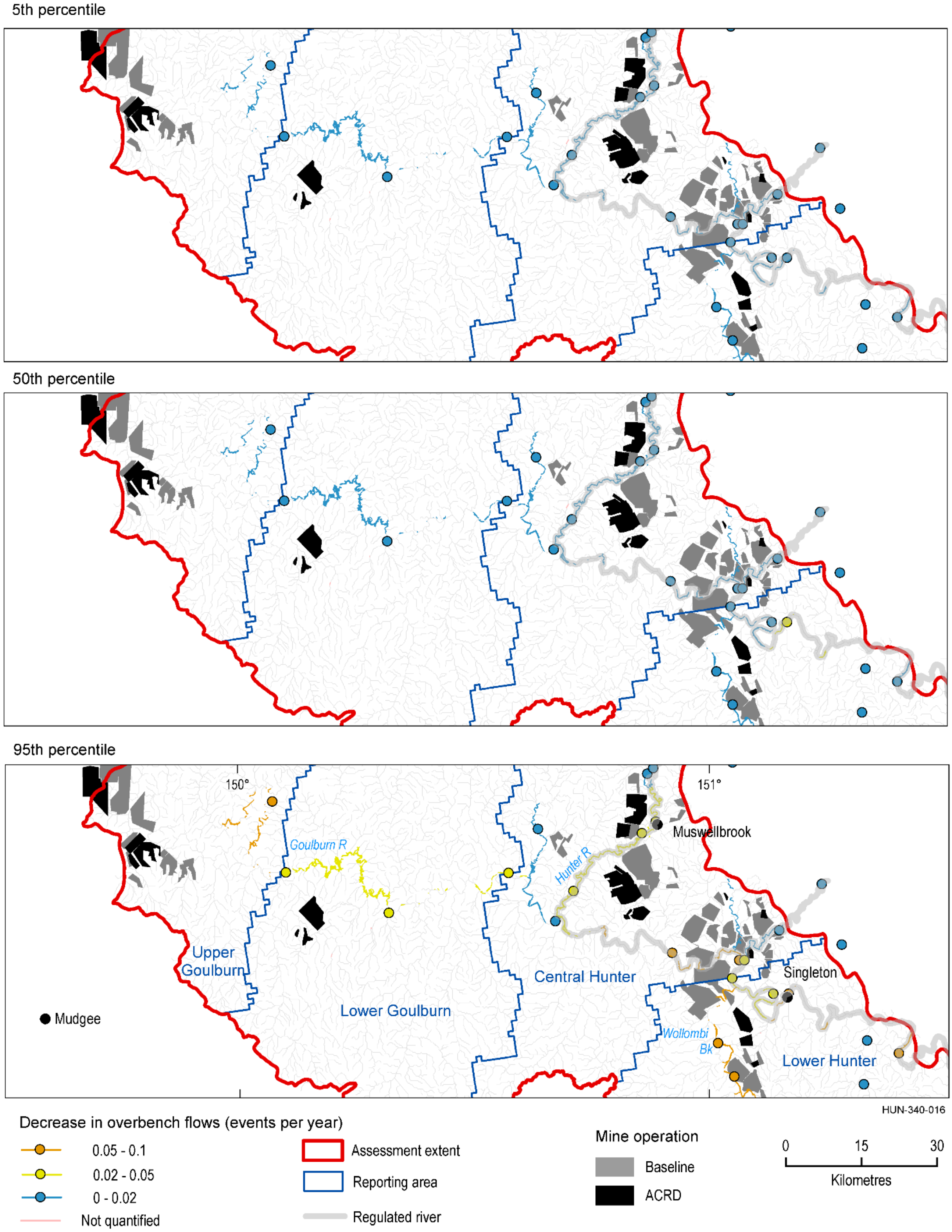

Figure 53 Modelled change in overbench flow in forested wetlands in 2102 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The Hunter Regulated River is greyed out because the receptor impact model was explicitly developed for riverine forests on unregulated rivers in the Hunter river basin.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 4, Dataset 5)

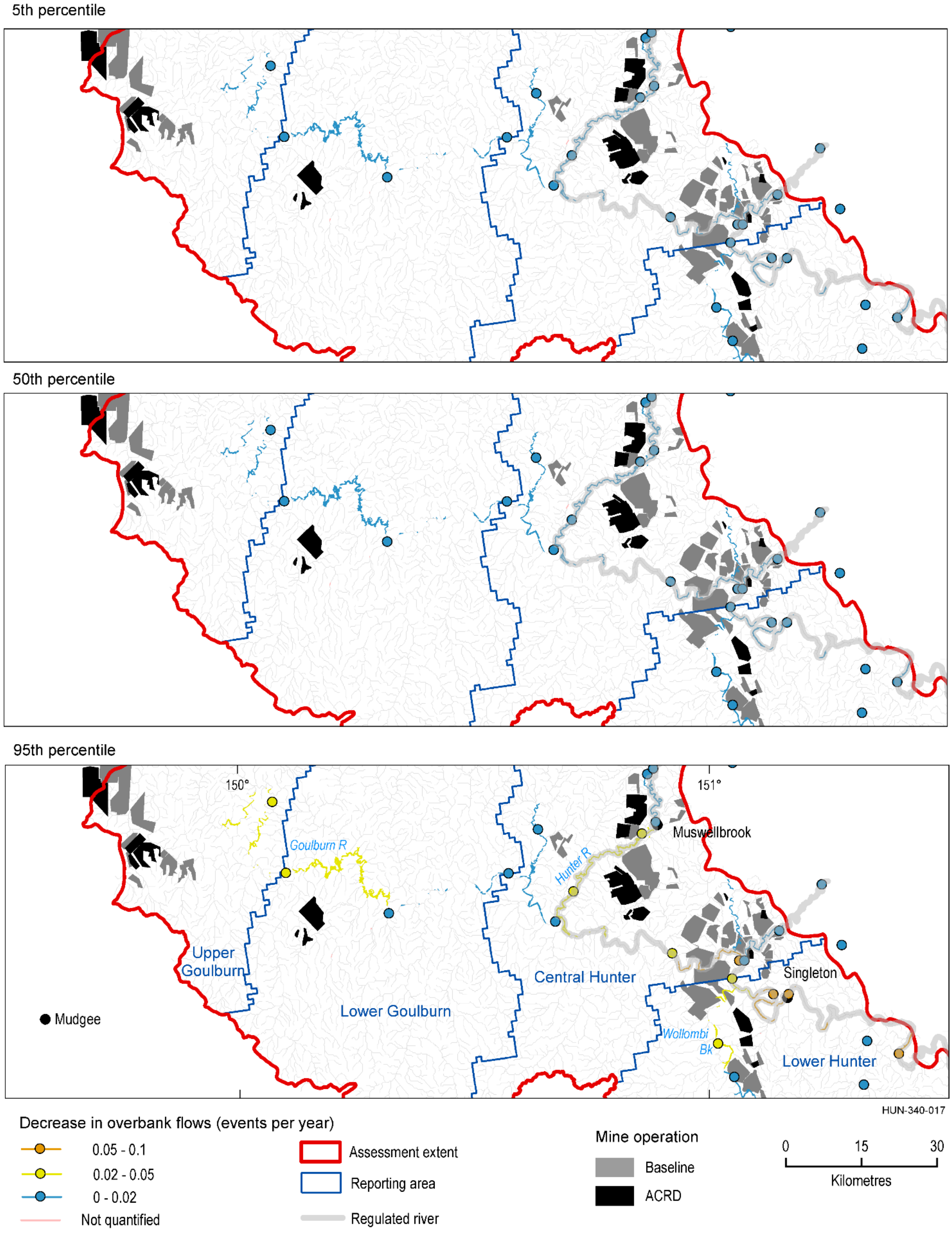

Figure 54 Modelled change in overbank flow in forested wetlands landscape class in 2042 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The Hunter Regulated River is greyed out because the receptor impact model was explicitly developed for riverine forests on unregulated rivers in the Hunter river basin.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 4, Dataset 5)

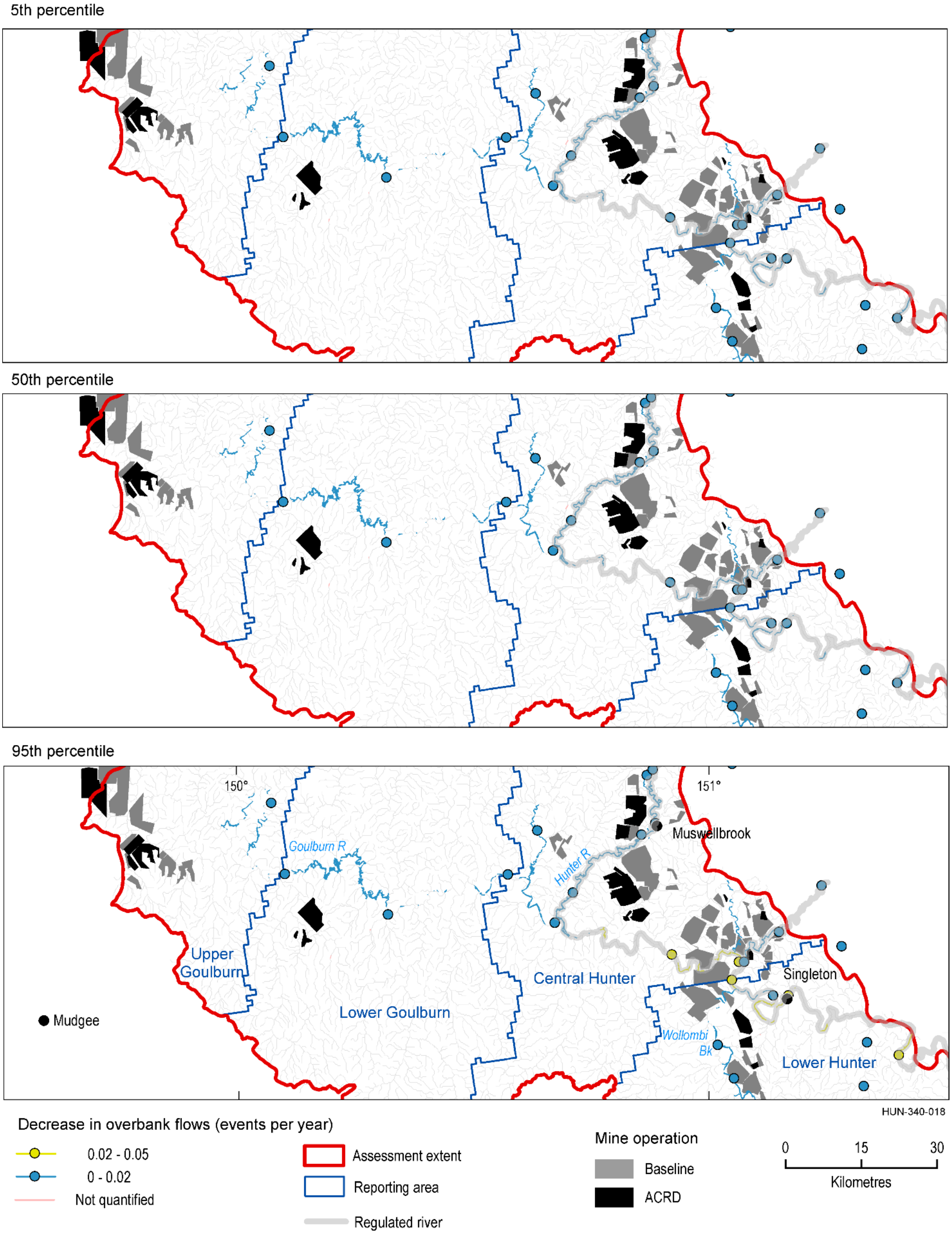

Figure 55 Modelled change in overbank flow in forested wetlands in 2102 in the zone of potential hydrological change (5th, 50th and 95th percentiles)

The Hunter Regulated River is greyed out because the receptor impact model was explicitly developed for riverine forests on unregulated rivers in the Hunter river basin.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 4, Dataset 5)

Table 24 Cumulative area (km²) of forested wetlands potentially exposed to changes in recurrence of overbench flows (EventsR0.3) due to additional coal resource development in the years 2042 and 2102

Year	Landscape class	Area where change not quantified (km²)[a]	Area with no significant change (km²)[a]	Area with >0.05 decrease of EventsR0.3 (km²)			Area with ≥0.1 decrease of EventsR0.3 (km²)			Area with ≥0.2 decrease of EventsR0.3 (km²)		
				5th	50th	95th	5th	50th	95th	5th	50th	95th
2042	Forested wetland – riverine forest	35.0	13.2	0.3	1.2	8.5	0.3	0.3	3.3	0.2	0.3	0.3
2102	Forested wetland – riverine forest	35.0	13.3	0.2	0.2	3.7	0.2	0.2	0.3	0.2	0.2	0.2

[a]Areas include coastal forested wetlands, but receptor impact model only applies to riverine forests along unregulated rivers in the Hunter river basin.
EventsR0.3 is the mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 0.3 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbench flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development. Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 5)

Table 25 Cumulative area (km²) of forested wetlands potentially exposed to changes in recurrence of overbank flows (EventsR3.0) due to additional coal resource development in the years 2042 and 2102

Year	Landscape class	Area where change not quantified (km²)[a]	Area with no significant change (km²)[a]	Area with >0.05 decrease of EventsR3.0 (km²)			Area with ≥0.1 decrease of EventsR3.0 (km²)			Area with ≥0.2 decrease of EventsR3.0 (km²)		
				5th	50th	95th	5th	50th	95th	5th	50th	95th
2042	Forested wetland – riverine forest	35.0	13.3	0.2	0.2	2.1	0.2	0.2	0.3	0.0	0.0	0.2
2102	Forested wetland – riverine forest	35.0	13.4	0	0.2	0.2	0	0.2	0.2	0.0	0.0	0.2

[a]Areas include coastal forested wetlands, but receptor impact model only applies to riverine forests along unregulated rivers in the Hunter river basin.
EventsR3.0 is the mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 3.0 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbank flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development. Some totals do not add up due to rounding.
Data: Bioregional Assessment Programme (Dataset 5)

3.4.4.3 Potential ecosystem impacts

As described in Section 3.4.2, the ‘Spring’, ‘Semi-arid woodland’, ‘Heathland’ and ‘Grassy woodland’ landscape classes within the ‘GDE’ landscape group are *very unlikely* to be impacted. ‘Rainforest’ is also *very unlikely* to be impacted although there are knowledge gaps with respect to ‘Rainforest’ mapped over alluvium. Impacts on the ‘Freshwater wetland’ landscape class are a knowledge gap. In this section the potential ecosystem impacts on ‘Wet sclerophyll forest’, ‘Dry sclerophyll forest’ and ‘Forested wetland’ landscape classes are discussed.

3.4.4.3.1 Wet and dry sclerophyll forests

The receptor impact model for wet and dry sclerophyll forests identified relationships between the hydrological response variables described in Section 3.4.4.2 and projected foliage cover (m^2/m^2).

Median estimates of the projected foliage cover under the baseline and CRDP futures ranged from 0.25 to 0.35 (Figure 56). There was great uncertainty surrounding absolute values of projected foliage cover; there was a 90% probability that projected foliage cover in wet sclerophyll forests and dry sclerophyll forests in the zone could be in the range of less than 0.1 to more than 0.7 in both periods.

The median estimate from modelled changes in projected foliage cover in the 30-year periods preceding both 2042 and 2102 was that there would be no change compared to the baseline period (Figure 56). This is consistent with the small modelled changes in drawdown described in Section 3.4.4.2. Of the 18.8 km^2 of wet sclerophyll forests and dry sclerophyll forests in the zone, it is predicted less than 2 km^2 might experience an increase in projected foliage cover more than 0.03 (95th percentile difference) and that less than 5 km^2 might experience a decrease in projected foliage cover more than 0.03 (5th percentile difference). A change in projected foliage cover of 0.03 represents 10% for the median estimate of projected foliage cover of 0.3. Hence, these changes are small in terms of foliage but would have flow-on effects to flower production, nectar production and nectar-feeding animals.

Overall, the modelled results suggest little detectable impact on the condition of wet sclerophyll forests and dry sclerophyll forests in the Hunter subregion due to additional coal resource development but that there is very high uncertainty surrounding estimates of absolute values. There is a 5% chance that 10 to 15 km^2 of mainly dry sclerophyll forests in the Macquarie-Tuggerah lakes basin will be subjected to an adverse ecological impact, although the risk is much reduced when the groundwater modelling results are constrained by local hydrogeological information (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018); Section 3.3.2). Based on the qualitative model (see Section 2.7.4.3 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) decreases in projected foliage cover will result in declines in shade, habitat structure, nectar production, nectar consumers, predators, sap- and leaf-eating insects, gliders and koalas. The qualitative model also predicted that insects would increase as a consequence of a release from predation pressure.

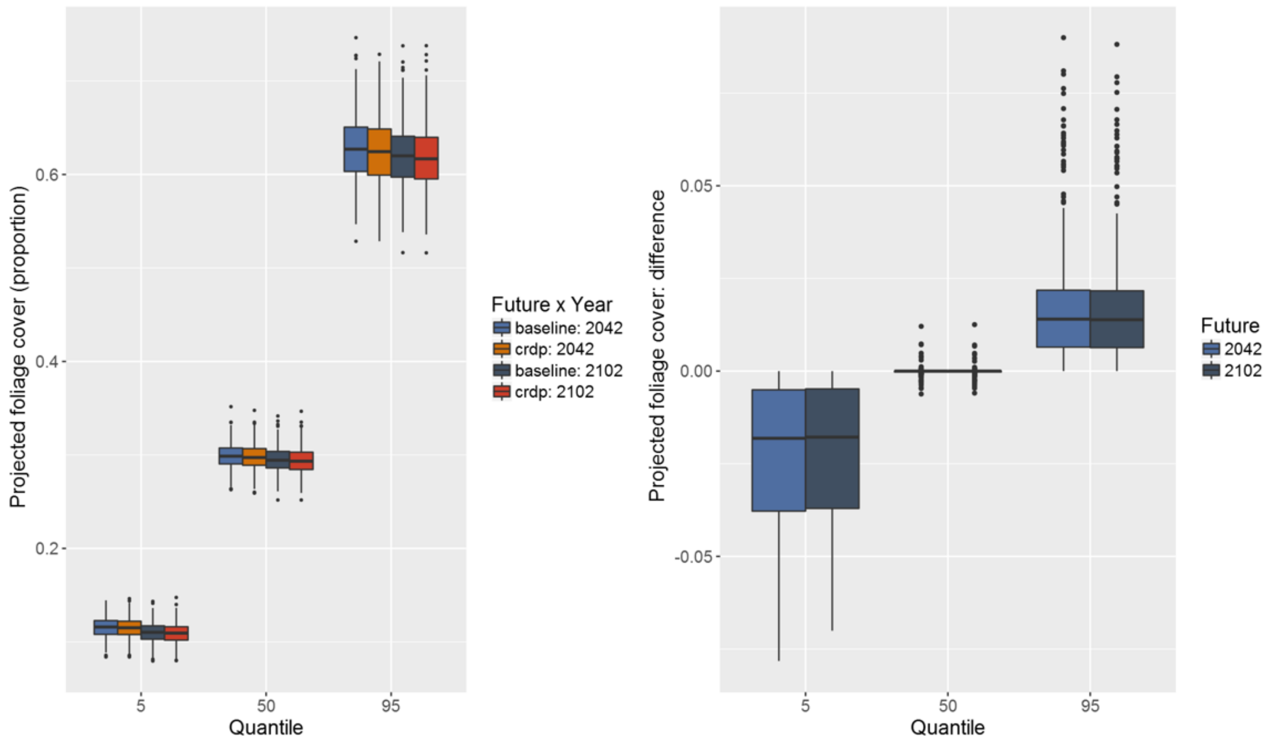

Figure 56 (Left) Modelled projected foliage cover in 2042 and 2102 for wet sclerophyll forests and dry sclerophyll forests under both baseline and coal resource development pathway (CRDP). (Right) Predicted change of projected foliage cover due to additional coal resource development

Data: Bioregional Assessment Programme (Dataset 6)

3.4.4.3.2 Forested wetlands – riverine forests

The receptor impact model for 'Forested wetland – riverine forest' establishes relationships between the hydrological response variables described in Section 3.4.4.2 and projected foliage cover for riverine forests in the zone, excluding the coastal forests. Only about 16 km^2 of riverine forests were able to be modelled because some areas of riverine forests are on stream reaches where hydrological changes at surface water model nodes were not able to be interpolated. Median estimates of the projected foliage cover under the baseline and CRDP futures range from 0.10 to 0.15 (Figure 57), but there is considerable variability around local factors that influence the condition of the canopy of riverine forested wetlands. Experts considered that projected foliage cover could vary between 0.05 to more than 0.60 in both periods, with marginally more projected foliage cover under the baseline than under the CRDP.

The median estimates from modelled changes in projected foliage cover in the 30-year periods preceding both 2042 and 2102 indicate virtually no change compared to the baseline period. This is consistent with the small modelled changes in drawdown, overbench flow and overbank flow described in Section 3.4.4.2. Of the 16 km^2 of 'Forested wetland' in the zone that were modelled, less than 2 km^2 are predicted to experience an increase in projected foliage cover of more than 0.02 (95th percentile difference) and less than 7 km^2 are predicted to experience a decrease in projected foliage cover of more than 0.05 (5th percentile difference).

Overall, the modelled results suggest little impact on the condition of riverine forest in the Hunter subregion due to additional coal resource development. Areas of riverine forest associated with larger decreases in the frequency of overbank and overbench flows, such as along parts of the Goulburn River, are 'more at risk of ecological and hydrological changes'. Based on the qualitative model (see Section 2.7.4.2 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) any decreases in projected foliage cover will reduce shade, habitat structure, bank stability, and orchids and fungi. The predicted decline in tree cover could benefit shrubs and herbaceous vegetation, with flow-on benefits to wombats, nectar production and nectar consumers. The magnitude of the impact and implications for the persistence of riverine forests in these more at risk areas will depend on local factors, influencing their current condition.

The receptor impact model was not developed for coastal 'Forested wetland' within the Macquarie-Tuggerah region, which comprise mainly the Keith (2004) vegetation class 'Coastal Swamp Forests' with some 'Coastal Floodplain Wetlands'. The qualitative model, which applies to all 'Forested wetland' (see Section 2.7.4.2 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a)) indicates that where 'Coastal Swamp Forests' and 'Coastal Floodplain Wetlands' are subject to large drawdown or significant alterations to surface flow, similar changes could be expected as for riverine 'Forested wetland', including a decline in tree cover that might benefit shrubs and herbaceous vegetation, with flow-on benefits to nectar production and nectar consumers. Nectar-bearing flowers of the dominant trees are an important food source for flying-foxes, arboreal marsupials and birds (OEH, 2017). Groundwater modelling predicted that up to 17.6 km^2 of 'Coastal Swamp Forests' might be subject to drawdown greater than 0.2 m and as much as 5.4 km^2 might be subject to drawdown greater than 2 m (Table 21) due to additional coal resource development.

Figure 58 summarises the receptor impact modelling in terms of a relative risk map for 'Forested wetland – riverine forests'. Forested wetlands along the Goulburn River are identified as 'at some risk of ecological and hydrological changes' from additional coal resource development, with those forested wetlands in the vicinity of the proposed Bylong mine predicted to be 'more at risk of ecological and hydrological changes' than upstream and downstream reaches. Forested wetlands along Wollombi Brook are also 'at some risk of ecological and hydrological changes'. There are some 'Forested wetland – riverine forests' in the Central Hunter and Lower Hunter where hydrological changes were not quantified that are close to mines, which could also be at risk. The regulated Hunter River and coastal forested wetlands are greyed out to reflect that the receptor impact model was not intended to predict changes in projected foliage cover in these areas.

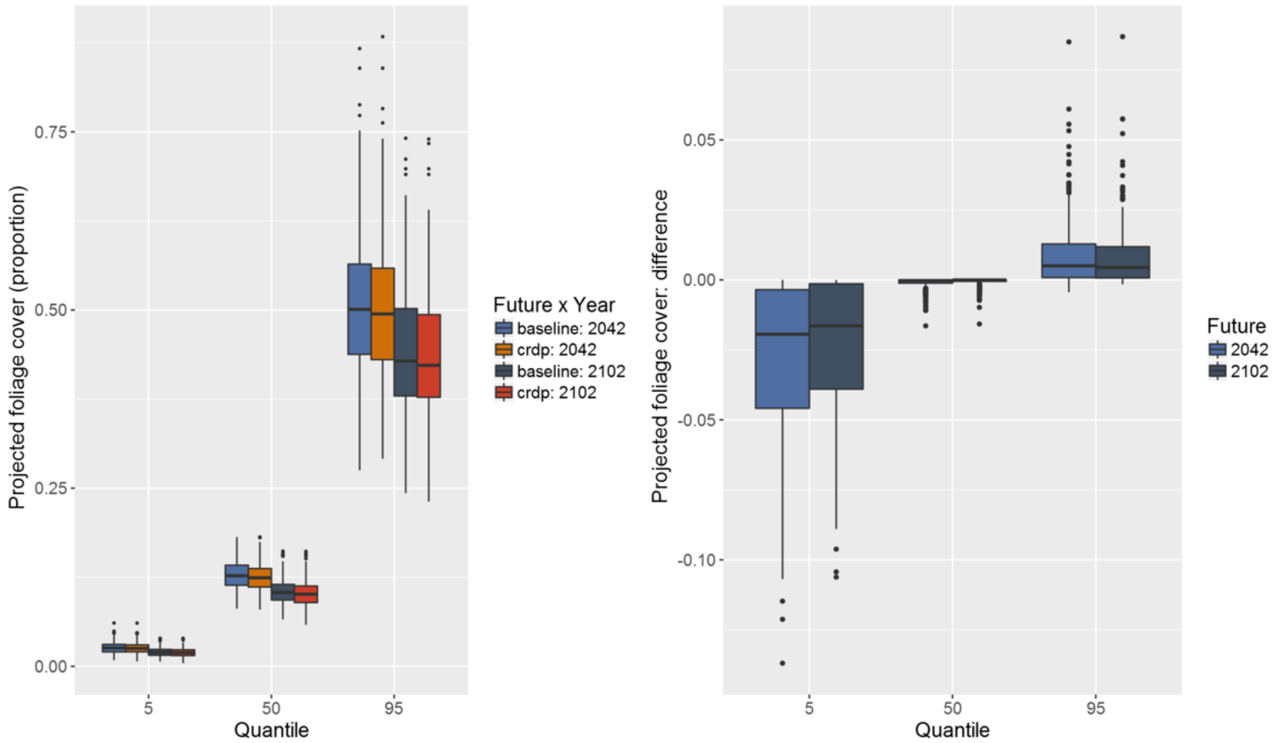

Figure 57 (Left) Modelled projected foliage cover in 2042 and 2102 in forested wetlands under both baseline and coal resource development pathway (CRDP) futures. (Right) Predicted change of projected foliage cover due to additional coal resource development

Data: Bioregional Assessment Programme (Dataset 6)

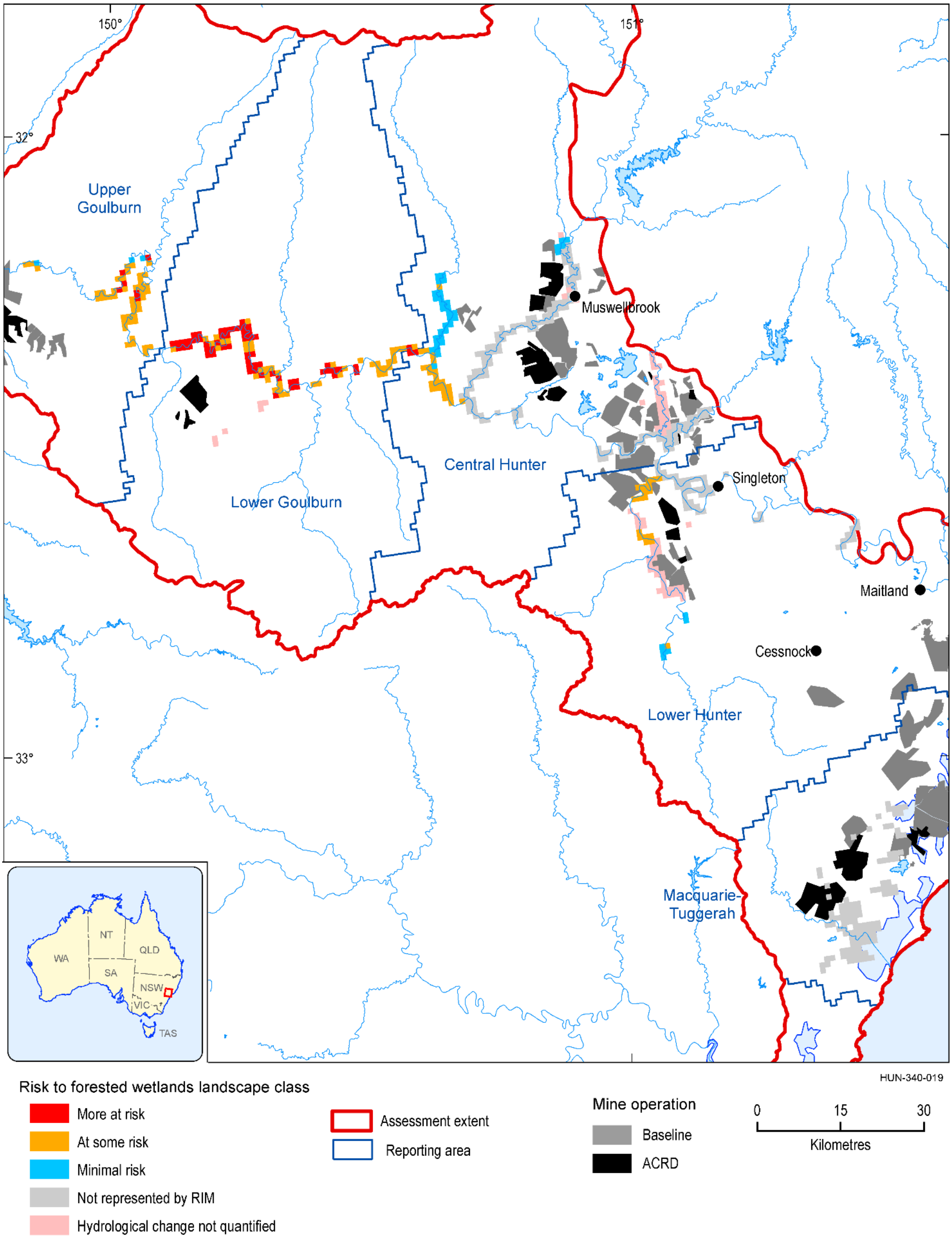

Figure 58 Relative risk to Forested wetlands – Riverine forests from additional coal resource development

'More at risk' refers to 'more at risk of ecological and hydrological changes'; 'At some risk' refers to 'at some risk of ecological and hydrological changes'; 'Minimal risk' refers to 'at minimal risk of ecological and hydrological changes'.
Data: Bioregional Assessment Programme (Dataset 9)

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3.5 Impacts on and risks to water-dependent assets

Summary

Ecological water-dependent assets

Of 1652 ecological assets in the register of water-dependent assets, 731 are in the zone of potential hydrological change and 603 are associated with the following potentially impacted landscape classes: forested wetlands, wet or dry sclerophyll forests, permanent or perennial streams, or lowly to highly intermittent streams. The 921 assets outside the zone, which are *very unlikely* (less than 5% chance) to be impacted, include 2 Ramsar-listed wetlands, 13 Directory of Important Wetlands Australia (DIWA) wetlands, 12 Commonwealth- or state-listed vegetation communities, 2 Important Bird Areas, 48 nationally listed (Collaborative Australian Protected Area Database (CAPAD)) parks and reserves, and potential habitats for 14 Commonwealth- or state-listed species.

Of the 731 assets in the zone that are associated with potentially impacted landscape classes, 210 meet criteria for potential hydrological impact that identifies them as 'more at risk of hydrological changes' from additional coal resource development than other assets within the zone. 'More at risk' assets are deemed to be those where there is at least a 50% chance of the modelled hydrological change exceeding certain defined thresholds for the hydrological response variables relevant to the landscape class with which the asset is associated. An asset was deemed to be associated with a landscape class if it shares an assessment unit with that landscape class, except for species and vegetation communities, whose association with landscape classes were based on knowledge of the ecology of the species or community.

No DIWA wetlands nor threatened ecological communities were identified as 'more at risk of hydrological changes'.

One state-listed vegetation community, 3 Important Bird Areas, 5 nationally listed (CAPAD) parks and reserves, and potential habitats for 23 Commonwealth- or state-listed species were amongst assets identified as 'more at risk of hydrological changes' due to additional coal resource development. These included the Hinterland Spotted Gum Endangered Ecological Community, Lake Macquarie Important Bird Area, Goulburn River National Park, Wollemi National Park and the potential habitats of two iconic species: the koala and the malleefowl. However, owing to the large size of most assets and the relatively small areas potentially impacted, the potential impact on any individual asset is likely to be small.

Based on receptor impact modelling, the potential impacts on ecological assets associated with riverine landscape classes are only likely in small stream reaches associated with large hydrological changes. There is potential for impacts on ecological assets associated with

groundwater-dependent ecosystem (GDE) landscape classes in locations where there is significant groundwater drawdown.

Economic water-dependent assets

There are 5 groundwater sources potentially impacted by hydrological changes due to additional coal resource development. Twenty-four surface water sources intersect the zone, however, the intersection of 5 of these 24 surface water sources is an artefact of the analysis technique and is associated with just eight extraction points. Therefore, only 19 of these surface water sources are potentially impacted by hydrological changes due to additional coal resource development. Fifteen surface water sources and four groundwater sources are *very unlikely* to be impacted due to additional coal resource development. Note that these economic assets do not correspond with those in the asset register as they were based on the old water sharing plans, whereas the analysis in this product uses the current water sharing plans.

There are 3911 groundwater bores and surface water extraction points in the zone that are potentially impacted due to additional coal resource development. Just over half are associated with the Hunter Regulated River water source, 32% with unregulated and alluvial water sources and 15% with non-alluvial groundwater.

The change in water availability (indicated by the change in mean annual flow) is *very likely* (greater than 95% chance) to exceed 5 GL/year in the Hunter Regulated River at Greta, but *very unlikely* to exceed 12 GL/year (1.6% of baseline mean annual flow). In unregulated and alluvial water sources, there is the possibility (at least 5% chance) of reductions in water availability of 3 to 6 GL/year in the Singleton, Muswellbrook, Jerrys and Wyong River water sources.

Potentially significant changes in reliability of supply (as indicated by change in number of cease-to-pump days) are possible for some creeks in the Singleton, Jerrys and Muswellbrook water sources, and in the Wyong River. In the Wyong River, the median change over the three 30-year periods is modelled to be between 6 and 8 days, with a 5% chance of 145 days per year in 2043 to 2072.

Of the 1450 bores in the zone, there is a 5% chance that 170 have drawdowns exceeding 2 m, the minimal impact consideration threshold for water supply works under the *NSW Aquifer Interference Policy, at which point* 'make good' provisions should apply. Of these, 159 are on mining and exploration leases where the predicted drawdowns are considered less likely to lead to an economic impact. The requirement to 'make good' on potential economic impacts to licence holders is considered more likely for the remaining 11 bores, which provide access to water in the Sydney Basin – North Coast groundwater source (7) and Jilliby Jilliby Creek (2), Tuggerah Lakes and South Macquarie Lake water sources.

Sociocultural water-dependent assets

Of 307 water-dependent assets in the water-dependent asset register for the Hunter subregion, 5 assets within the 'Social' subgroup and 62 assets within the 'Cultural' subgroup intersect with the zone of potential hydrological change. Thus it is *very unlikely* that hydrological changes associated with coal resource development affect the remaining 240 sociocultural assets. Of the sociocultural assets that intersect with the zone, 45 are built infrastructure and were not assessed. The remaining 22 sociocultural assets are reserves or national parks composed of a range of water-dependent landscape classes.

There are three National Heritage-listed areas within the zone of potential hydrological change in the Hunter subregion as well as the Greater Blue Mountains World Heritage Area. Any impact on these assets is predicted to be minor.

3.5.1 Overview

This section describes the potential impacts on, and risks to, ecological, economic and sociocultural water-dependent assets from potential hydrological changes due to additional coal resource development. These were assessed using:

- **overlay analysis**, whereby asset polygons (or lines or points) are intersected with a nominated zone of potential hydrological change to identify whether the asset is potentially subject to that hydrological change
- **qualitative mathematical models** derived from expert elicitation
- **quantitative mathematical models** (receptor impact models) derived from expert elicitation and based on the qualitative mathematical models.

As described in companion product 2.7 for the Hunter subregion (Hosack et al., 2018), receptor impact models were developed for two landscape classes in the 'Riverine' landscape group: permanent or perennial streams and lowly to highly intermittent streams, and for three landscape classes in the 'GDE' landscape group. Note that wet sclerophyll forests and dry sclerophyll forests have the same receptor impact model. Qualitative models were developed for other GDE landscape classes and for landscape classes in the 'Coastal lakes and wetlands' landscape group.

Overlay analysis was used to identify assets that are *very unlikely* to be impacted by surface water or groundwater changes due to additional coal resource development, based on lack of intersection of the asset with the zone of potential hydrological change. The zone of potential hydrological change is defined in Section 3.3. The impact and risk analysis uses different probabilities of hydrological change (5th, 50th (median) and 95th percentiles) to indicate the likelihood of hydrological changes to different types of water-dependent assets present in the zone. The 5th percentile identifies the magnitude of hydrological change that is *very likely* (greater than 95% chance); the 95th percentile defines the magnitude of hydrological change (though not necessarily ecological impact) that is *very unlikely* (less than 5% chance).

In this analysis of impacts and risks to water-dependent assets, ecological, economic and sociocultural assets are dealt with separately. Each subgroup of the ecological assets group is also described separately – 'Surface water feature', 'Groundwater feature (subsurface)' and 'Vegetation'. To improve clarity, assets in the 'Vegetation' subgroup are further divided into two classes: 'Groundwater-dependent ecosystems' and 'Habitat (potential species distribution)'. Economic assets are separated into two classes: 'Groundwater management zone or area (surface area)' and 'Surface water management zone or area (surface area)'. Potential hydrological changes to all non-petroleum and gas bores in the zone of potential hydrological change are also considered. The intersection of sociocultural assets with the zone of potential hydrological change is then described, and the potential for impact assessed.

The spatial extent and number of water-dependent assets means that not all assets are mapped and assessed in this section. Instead the focus is on a subset of the assets, which are deemed to be 'more at risk of hydrological changes' (i.e. those assets associated with higher probabilities of larger hydrological changes). Detailed potential impacts on individual assets can be visually explored on the BA Explorer, available at www.bioregionalassessments.gov.au/explorer/HUN/assets.

The impact and risk analysis uses a combination of summary tables, maps of modelled hydrological change within assets, plots of cumulative asset extent and degree of modelled hydrological change and narrative. This section considers only the potential impacts on and risks to assets due to those mines in the coal resource development pathway (CRDP) that were modelled. Section 3.6 provides commentary on the potential impacts due to the CRDP mines that were not modelled.

3.5.2 Ecological assets

3.5.2.1 Description

Of the 1652 water-dependent ecological assets in the Hunter subregion (Bioregional Assessment Programme, Dataset 1), a total of 731 are in the zone of potential hydrological change (Table 26), including 72 assets in the 'Surface water feature' subgroup, 12 assets in the 'Groundwater feature (subsurface)' subgroup, and 647 assets in the 'Vegetation' subgroup. Note that often assets from different data sources may represent essentially the same biophysical entity; for example, Lake Macquarie appears in 11 different data sources, reflecting a range of different values for this asset.

Table 26 Ecological assets in the assessment extent and zone of potential hydrological change

Group	Subgroup	Asset class	Water-dependent assets	Water-dependent assets in the zone
Ecological	Surface water feature	Floodplain	9	2
		Lake, reservoir, lagoon or estuary	100	33
		River or stream reach, tributary, anabranch or bend	66	29
		Wetland, wetland complex or swamp	30	8
Ecological	Groundwater feature (subsurface)	Aquifer, geological feature, alluvium or stratum	24	12
Ecological	Vegetation	Groundwater-dependent ecosystems	587	270
		Habitat (potential species distribution)	836	377
Total			**1652**	**731**

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

There are 921 water-dependent assets outside the zone, which are therefore *very unlikely* to be impacted.

Of the 'Surface water feature' subgroup assets outside the zone, 2 are Ramsar-listed wetlands (Australian Government Department of the Environment, Dataset 3), 13 are wetlands in *A directory of important wetlands in Australia* (Australian Government Department of the Environment, Dataset 4), 65 are from the NSW Wetlands 2006 data source (NSW Department of Environment Climate Change and Water, Dataset 5) and 53 are from the WAIT (Water Asset Information Tool) database (Australian Government Department of the Environment, Dataset 6), which includes the Ramsar-listed Hunter Wetland Centre (referred to as Shortland Wetlands in the asset register) and Kooragang Nature Reserve (Figure 59), as well as the Hunter River Estuary, Hexham Swamp and Brisbane Waters.

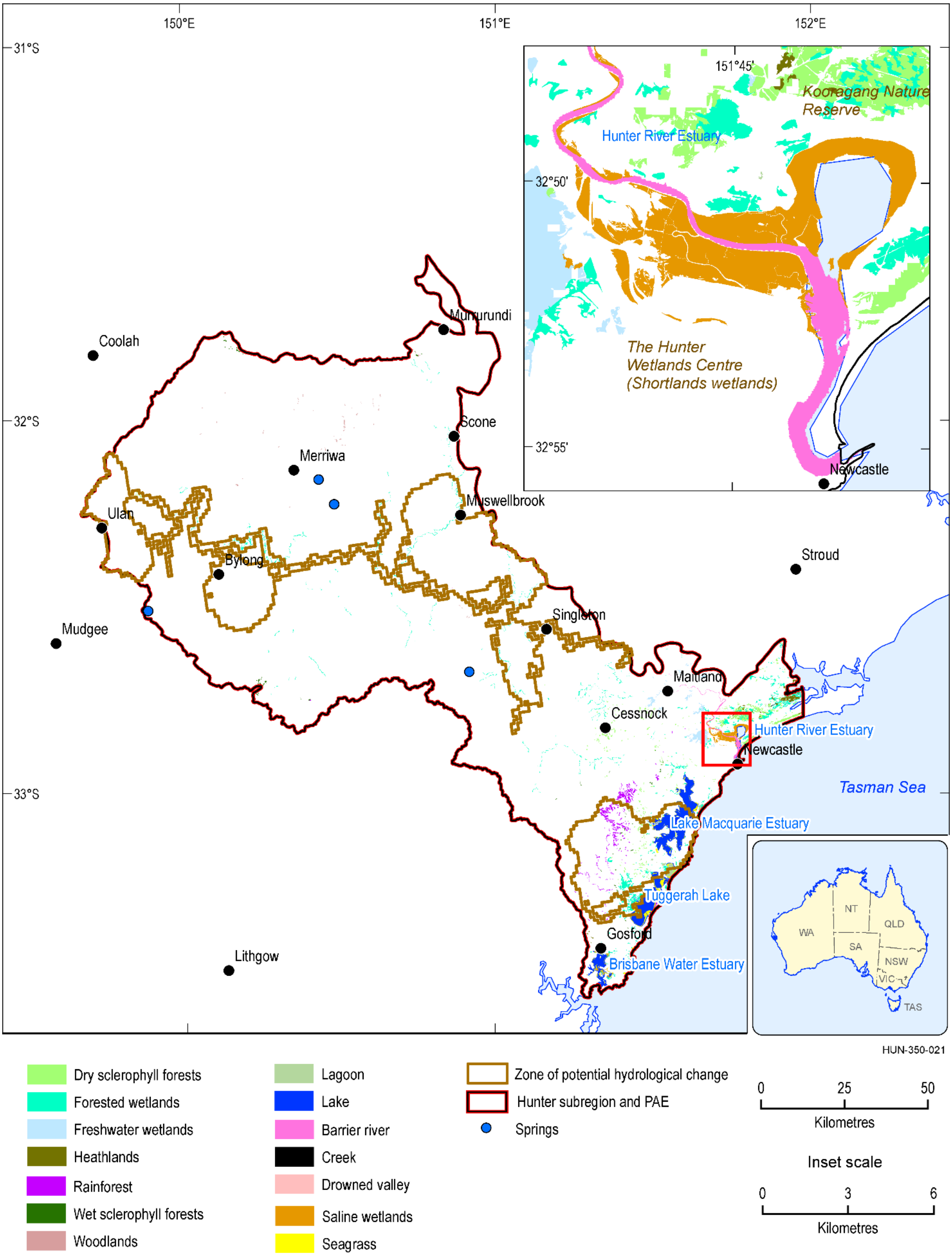

Figure 59 Distribution of springs and assets from Ramsar within the assessment extent

ACRD = additional coal resource development; PAE = preliminay assessment extent
Data: Australian Government Department of Environment (Dataset 3), Bioregional Assessment Programme (Dataset 7, Dataset 8, Dataset 9)

Of the 12 'Groundwater feature' subgroup assets outside the zone, 4 are springs. There are no other springs in the water-dependent asset register.

Of the 776 'Vegetation' subgroup water-dependent assets outside the zone, 317 are in the 'Groundwater-dependent ecosystems' asset class and 459 are in the 'Habitat (potential species distribution)' asset class. Assets in the 'Habitat (potential species distribution)' asset class that are outside the zone include several endangered ecological communities (EECs) and threatened ecological communities:

- endangered ecological communities:
  - Camerons Gorge Grassy White Box Community (EEC)
  - Gosford LGA Umina Woodlands Community (EEC)
  - Hinterland Red Ironbark (110a)(EEC Lower Hunter)
  - Hinterland Red Ironbark (110b)(EEC Lower Hunter)
  - Hunter Red Ironbark (18h)(EEC Lower Hunter)
  - Lower Hunter Beyer's Ironbark Low Forest (17c)(EEC Lower Hunter)
  - Lower Hunter Grey Box Grassy Forest (17i)(EEC Lower Hunter)
  - Lower Hunter Narrow-leaved Ironbark Forest (17m)(EEC Lower Hunter)
  - Red Ironbark (110a)(EEC Lower Hunter)
- threatened ecological communities:
  - Littoral Rainforest and Coastal Vine Thickets of Eastern Australia Threatened Ecological Community
  - Lowland Subtropical Rainforest on Basalt Alluvium in NE NSW and SE Qld Threatened Ecological Community
  - Natural Grasslands on Basalt and Fine-Textured Alluvial Plains of Northern New South Wales and Southern Queensland.

Also *very unlikely* to be impacted are two Important Bird Areas (Birds Australia, Dataset 10), which are entirely outside the zone:

- Brisbane Water Important Bird Area
- Hunter Estuary Important Bird Area.

Forty-eight parks and reserves (CAPAD; Australian Government Department of the Environment, Dataset 11) are *very unlikely* to be impacted, including, amongst others:

- Brisbane Water National Park (CAPAD)
- Camerons Gorge Nature Reserve (CAPAD)
- Hexham Swamp NRS Addition - Gazettal in Progress (CAPAD)
- Hunter Wetlands National Park (CAPAD)
- Karuah National Park.

Potential habitats of 14 species listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) (Australian Government Department of the Environment, Dataset 12) and two additional species provided from the WAIT data source (Australian Government Department of the Environment, Dataset 6) are *very unlikely* to be impacted. These include 11 plant species, three birds, the Booroolong frog (*Litoria booroolongensis*) and the beady pipefish (*Hippichthys penicillus*).

In the following sections, assets that intersect the zone of potential hydrological change and are potentially at risk of impact due to additional coal resource development are identified. For the purposes of the bioregional assessment (BA), the magnitude of risk to an asset is broadly equated to the magnitude of the potential hydrological changes in potentially impacted landscape classes with which the asset is associated. Note that many hazards that lay outside the scope of the BA may pose a risk to assets (see Section 2.3.5.2 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018)) but are not dealt with in this analysis.

For most assets, an asset was deemed to be associated with a landscape class if it shares an assessment unit with that landscape class. The exceptions to this were species and vegetation communities, whose association with landscape classes were assigned based on knowledge of the ecology of the species or community. The latter include:

- GDE vegetation types
- species listed under NSW's *Threatened Species Conservation Act 1995* (TSC) and the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)
- NSW endangered ecological communities
- vegetation listed under the Commonwealth's EPBC Act.

The assets deemed to be 'more at risk of hydrological changes' are those where there is at least a 50% chance of the modelled hydrological change exceeding a defined threshold for the hydrological response variables relevant to the landscape class with which it is associated (i.e. the hydrological response variables in the receptor impact models; see Section 3.4). The thresholds chosen to identify the 'more at risk' assets are:

- wet and dry sclerophyll forests: drawdown due to additional coal resource development exceeding 2 m in an assessment unit shared by the asset
- forested wetlands: drawdown due to additional coal resource development exceeding 2 m; change in the return period of overbank flow greater than 0.5 events per year in the 30 years preceding 2042; or change in the return period of overbench flow of greater than 0.05 events per year in the 30 years preceding 2042 in an assessment unit shared by the asset
- landscape classes in the 'Riverine' landscape group (i.e. permanent or perennial streams and lowly to highly intermittent streams): increase in zero-flow days of more than 20 per year.

The numbers of assets within the zone that are identified as 'more at risk of hydrological changes' due to additional coal resource development are summarised in Table 27, together with the potentially impacted landscape classes with which they are associated. Twenty-three assets in the 'Surface water feature' asset class and 187 in the 'Vegetation' asset class were identified as 'more at risk of hydrological changes'. Since many assets are associated with multiple potentially impacted landscape classes, the numbers in Table 27 for the 'Vegetation' assets do not sum to 187 and likewise, the numbers for the 'Surface water feature' assets do not sum to 23. Assets that are 'more at risk of hydrological changes' are described in more detail in the following sections, with particular emphasis on nationally listed assets.

Note that many assets have very large areas relative to the areas or lengths of impacted landscape classes (see Section 3.4); hence, even assets that are identified as 'more at risk of hydrological changes' generally only have a small fraction of their area potentially impacted.

Table 27 Ecological assets in the zone of potential hydrological change that are identified as 'more at risk of hydrological changes' due to additional coal resource development based on their association with potentially impacted landscape classes and exposure to hydrological change

Group	Subgroup	Asset class	Wet and dry sclerophyll forests	Forested wetlands	Landscape classes in 'Riverine' landscape group
Ecological	Surface water feature	Floodplain	0	0	0
		Lake, reservoir, lagoon or estuary	10	10	0
		River or stream reach, tributary, anabranch or bend	5	13	3
		Wetland, wetland complex or swamp	0	0	0
Ecological	Groundwater feature (subsurface)	Aquifer, geological feature, alluvium or stratum	0	0	4
Ecological	Vegetation	Groundwater-dependent ecosystems	60	40	3
		Habitat (potential species distribution)	61	77	18
Total			**136**	**140**	**30**

Data: Bioregional Assessment Programme (Dataset 2)

3.5.2.2 'Surface water feature' subgroup

Of the 72 'Surface water feature' subgroup assets identified in the zone of potential hydrological change in the Hunter subregion (Table 26), 67 were associated with potentially impacted landscape classes (Table 28). Of these, 23 have a 50% chance of experiencing hydrological change above the thresholds specified in the previous section. All 23 are associated with forested wetlands; 15 are also associated with wet or dry sclerophyll forests; and 3 are associated with landscape classes in the 'Riverine' landscape group. These assets are from the NSW Wetlands 2006 (Dataset 5) and WAIT (Australian Government Department of the Environment, Dataset 6) data sources.

Four assets are derived from DIWA: Colongra Swamp important wetland, Lake Macquarie important wetland, Tuggerah Lake important wetland, and Wyong Racecourse Swamp important wetland (Figure 60). These are either not associated with potentially impacted landscape classes (see Section 3.4.2) or the probability of there being a hydrological change above the defined threshold is less than 50%.

Given the limited extrapolation of surface water modelling results from model nodes to the wider stream network, it is possible that there are other assets that are 'more at risk of hydrological changes' associated with potentially impacted streams that have not been identified.

Table 28 Ecological assets in the 'Surface water feature' subgroup that are in the zone of potential hydrological change and associated with potentially impacted landscape classes

Asset class	Source	Water-dependent assets in the zone	Water-dependent assets associated with potentially impacted landscape classes
Floodplain	NSW Wetlands 2006 (Dataset 5)	2	2
Lake, reservoir, lagoon or estuary	NSW Wetlands 2006 (Dataset 5)	31	27
	WAIT Hunter-Central Rivers (Australian Government Department of the Environment, Dataset 6)	2	2
River or stream reach, tributary, anabranch or bend	WAIT Hunter-Central Rivers (Australian Government Department of the Environment, Dataset 6)	29	28
Wetland, wetland complex or swamp	DIWA (Australian Government Department of the Environment, Dataset 4)	4	4
	WAIT Hunter-Central Rivers (Australian Government Department of the Environment, Dataset 6)	4	4
Total		**72**	**67**

Data: Bioregional Assessment Programme (Dataset 2)

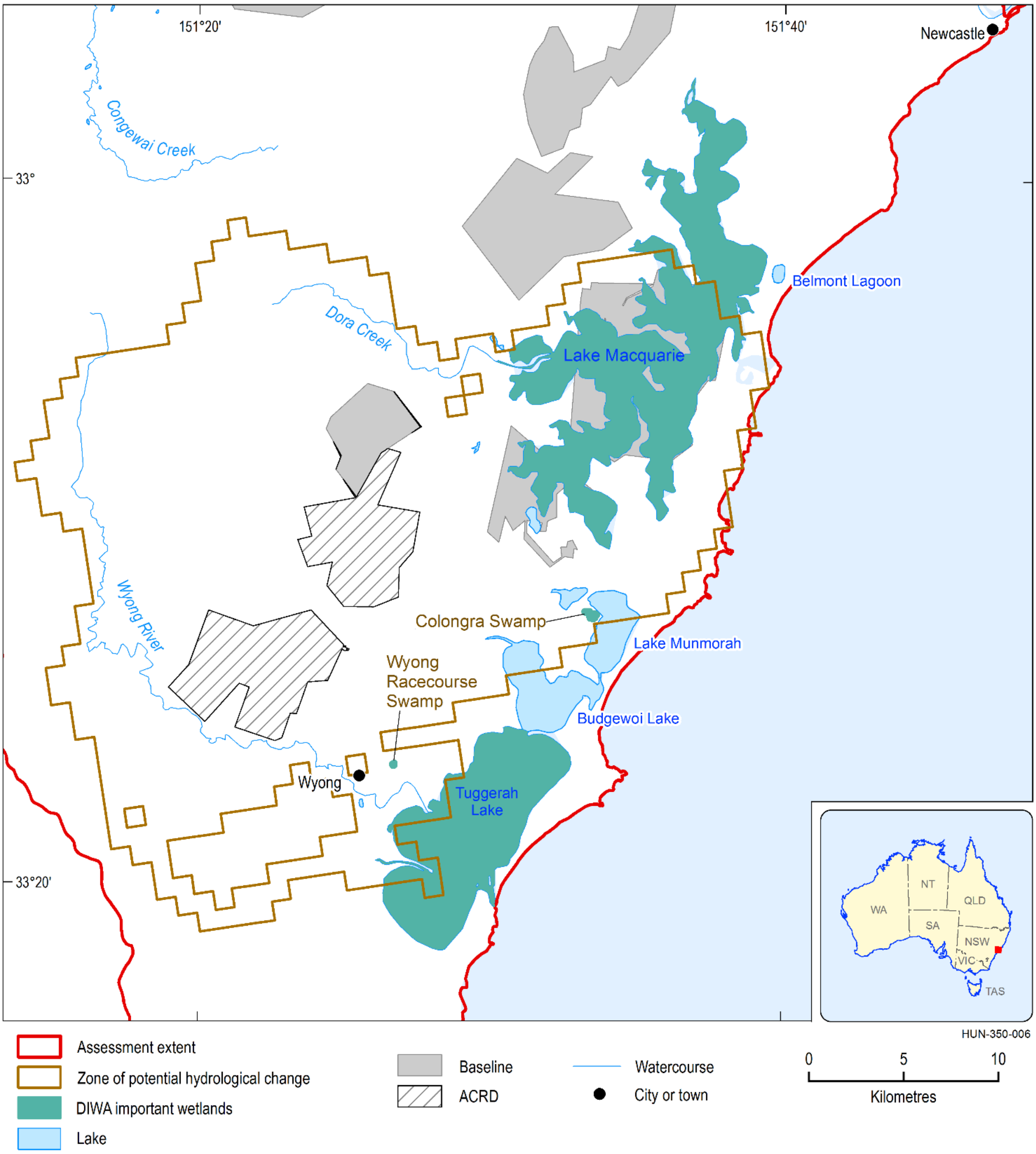

Figure 60 Distribution of assets from *A directory of important wetlands in Australia* (DIWA) in the 'Wetland, wetland complex or swamp' asset class

ACRD = additional coal resource development
Data: Bioregional Assessment Programme (Dataset 4, Dataset 8)

3.5.2.3 'Groundwater feature (subsurface)' subgroup

Assets within this subgroup are the New England Fold Belt and the following assets nominated by natural resource management (NRM) agencies:

- NRM-nominated Goulburn River Alluvium
- NRM-nominated Gunnedah Basin

- NRM-nominated Hunter River Alluvium
- NRM-nominated Kingdon Ponds and Tributaries Alluvium
- NRM-nominated Lachlan Fold Belt
- NRM-nominated Liverpool Ranges Basalt
- NRM-nominated Oxley Basin
- NRM-nominated Sydney Basin – Mangrove Mountain Sandstone
- NRM-nominated Sydney Sandstone Central Coast
- NRM-nominated Tuggerah-Gosford Coastal Sands
- NRM-nominated Wollombi Brook Alluvium.

No ecological landscape classes or models were developed to represent these assets. However, the extent to which these assets also correspond to economic assets (Section 3.5.3) provides some assessment of potential impact.

3.5.2.4 'Vegetation' subgroup

The majority of potentially impacted ecological assets is in the 'Vegetation' subgroup. Of the 653 'Vegetation' subgroup assets in the zone of potential hydrological change (Table 26), 536 are associated with potentially impacted landscape classes (Table 29), of which 187 are deemed 'more at risk of hydrological changes'. The 'Vegetation' subgroup includes two asset classes: 'Groundwater-dependent ecosystems' and 'Habitat (potential species distribution)' (Table 29).

Eighty-eight assets in the 'Groundwater-dependent ecosystems' asset class are identified as 'more at risk of hydrological changes'. Sixty are associated with wet and dry sclerophyll forests; 40 with forested wetlands; and 3 with landscape classes in the 'Riverine' landscape group. These assets are from the *National atlas of groundwater dependent ecosystems* (GDE Atlas) (19; Bureau of Meteorology, Dataset 13) and the NSW GDE mapping (69; NSW Department of Primary Industries, Dataset 14).

Table 29 Ecological assets in the 'Vegetation' subgroup that are in the zone of potential hydrological change and associated with potentially impacted landscape classes

Asset class	Source	Water-dependent assets in the zone	Water-dependent assets associated with potentially impacted landscape classes
Groundwater-dependent ecosystems	*National atlas of groundwater dependent ecosystems* including: •subsurface presence of groundwater data	34	27
	National atlas of groundwater dependent ecosystems including: •surface expression of groundwater	38	37
	New South Wales High Probability Groundwater Dependent Vegetation with High Ecological Value	204	168

Asset class	Source	Water-dependent assets in the zone	Water-dependent assets associated with potentially impacted landscape classes
Habitat (potential species distribution)	*Collaborative Australian Protected Areas Database* (CAPAD)	18	15
	Climate Change Corridors Coastal - North East NSW	3	3
	Climate Change Corridors Dry - North East NSW	21	20
	Climate Change Corridors Moist - North East NSW	5	3
	Fauna Corridors North East NSW	54	52
	Lower Hunter Spotted Gum Forest Endangered Ecological Community EEC 2319	1	1
	Birdlife Australia Important Bird Areas	5	5
	Threatened species listed under the EPBC Act	92	33
	NSW Estuarine Macrophytes	14	14
	NSW_ Darling Hardyhead	1	1
	NSW Native Vegetation Management (NVM)	4	4
	Threatened species listed under the TESC Act	3	3
	NSW Travelling Stock Reserve Conservation Values	26	22
	Threatened ecological communities listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)	3	3
	Water Asset Information Tool database	127	125
Total		**653**	**536**

Data: Bioregional Assessment Programme (Dataset 2)

Eighty-nine assets from the 'Habitat (potential species distribution)' asset class are identified as 'more at risk of hydrological changes'. Sixty-one assets are associated with wet and dry sclerophyll forests; 77 assets with forested wetlands; and 18 with landscape classes in the 'Riverine' landscape group. These assets are from:

- National EPBC Act Species List (23)
- NSW TSC Species List (3)
- Important Bird Areas (3)
- CAPAD (5)

- Hunter Lower EEC 2010 E2319 (1)
- NSW DPI Fisheries (1)
- Climate change or fauna corridors (25)
- NSW NVM Management Benefits (4)
- WAIT (24).

Given the limited interpolation from surface water modelling results to the wider stream network, it is possible that there are other assets that are 'more at risk of hydrological changes' associated with potentially impacted streams that have not been identified.

Nationally significant assets are described in further detail below, along with the three TSC-listed species and the Hinterland Spotted Gum EEC.

EPBC Act-listed species that are 'more at risk of hydrological changes' and associated potentially impacted landscape classes are listed in Table 30 and selected assets are shown in Figure 61, Figure 62 and Figure 63. The malleefowl (*Leipoa ocellata*) is the only identified species associated with a single landscape class, namely dry sclerophyll forests. The malleefowl is one of two NSW iconic species, along with the koala (*Phascolarctos cinereus*), identified as 'more at risk of hydrological changes'. However, Section 3.5.5 indicates that a more detailed analysis of potential impacts to the maleefowl indicate that it may not in fact be at risk. Such an analysis for every asset is however not possible within the current project.

The asset associated with the iconic Wollemi pine (*Wollemia nobilis*) occurs in the zone but is associated with the 'Rainforest' landscape class, which is not predicted to be impacted within the Wollemi National Park.

In addition to being associated with landscape classes in the 'GDE' landscape group, the giant barred frog (*Mixophyes iteratus*) and stuttering frog (*Mixophyes balbus*) are also associated with permanent or perennial streams and lowly to highly intermittent streams in the 'Riverine' landscape group. The giant burrowing frog (*Helieoporus australiacus*) is also associated with lowly to highly intermittent streams. The potential distribution of the green and golden bell frog (*Litoria aurea*) is not identified as 'more at risk of hydrological changes'. The distributions of EPBC Act-listed frog species are shown in Figure 64.

Table 30 Groundwater-dependent ecosystem (GDE) landscape classes that overlap with ecological assets that are 'more at risk of hydrological changes' in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change

Asset name[a]	Area within zone (km^2)	Wet and dry sclerophyll forests	Forested wetlands
Leafless Tongue-orchid (*Cryptostylis hunteriana*)	824	yes	yes
Philotheca ericifolia	598	yes	no
Australian Painted Snipe (*Rostratula australis*)	34.0	no	yes
Biconvex Paperbark (*Melaleuca biconvexa*)	350	yes	yes
Black-faced Monarch (*Monarcha melanopsis*)	2682	yes	no
Cattle Egret (*Ardea ibis*)	2794	yes	yes
Charmhaven Apple (*Angophora inopina*)	240	yes	yes
Eastern Bristlebird (*Dasyornis brachypterus*)	681	yes	yes
Fork-tailed Swift (*Apus pacificus*)	3233	yes	yes
Giant Barred Frog (*Mixophyes iteratus*)	48.4	yes	yes
Giant Burrowing Frog (*Heleioporus australiacus*)	684	yes	yes
Great Egret, White Egret (*Ardea alba*)	3233	no	yes
Grey-headed Flying-fox (*Pteropus poliocephalus*)	1843	yes	yes
Heath Wrinklewort (*Rutidosis heterogama*)	89.3	yes	no
Koala (*Phascolarctos cinereus*)	2010	yes	yes
Malleefowl (*Leipoa ocellata*)	296	yes	no
Red Goshawk (*Erythrotriorchis radiatus*)	526	yes	yes
Regent Honeyeater (*Anthochaera phrygia*)	2959	yes	yes
Satin Flycatcher (*Myiagra cyanoleuca*)	3229	yes	yes
Small-flower Grevillea (*Grevillea parviflora* subsp. *parviflora*)	372	yes	yes
Spot-tailed Quoll (*Dasyurus maculatus* subsp. *maculatus*)	2319	yes	yes
Stuttering Frog (*Mixophyes balbus*)	403	yes	no
Swift Parrot (*Lathamus discolor*)	1637	yes	yes

[a]Punctuation and typography appear as used in the asset database.
These species are listed nationally under the Commonwealth's *Environment Protection and Biodiversity Act 1999*.
Data: Bioregional Assessment Programme (Dataset 2)

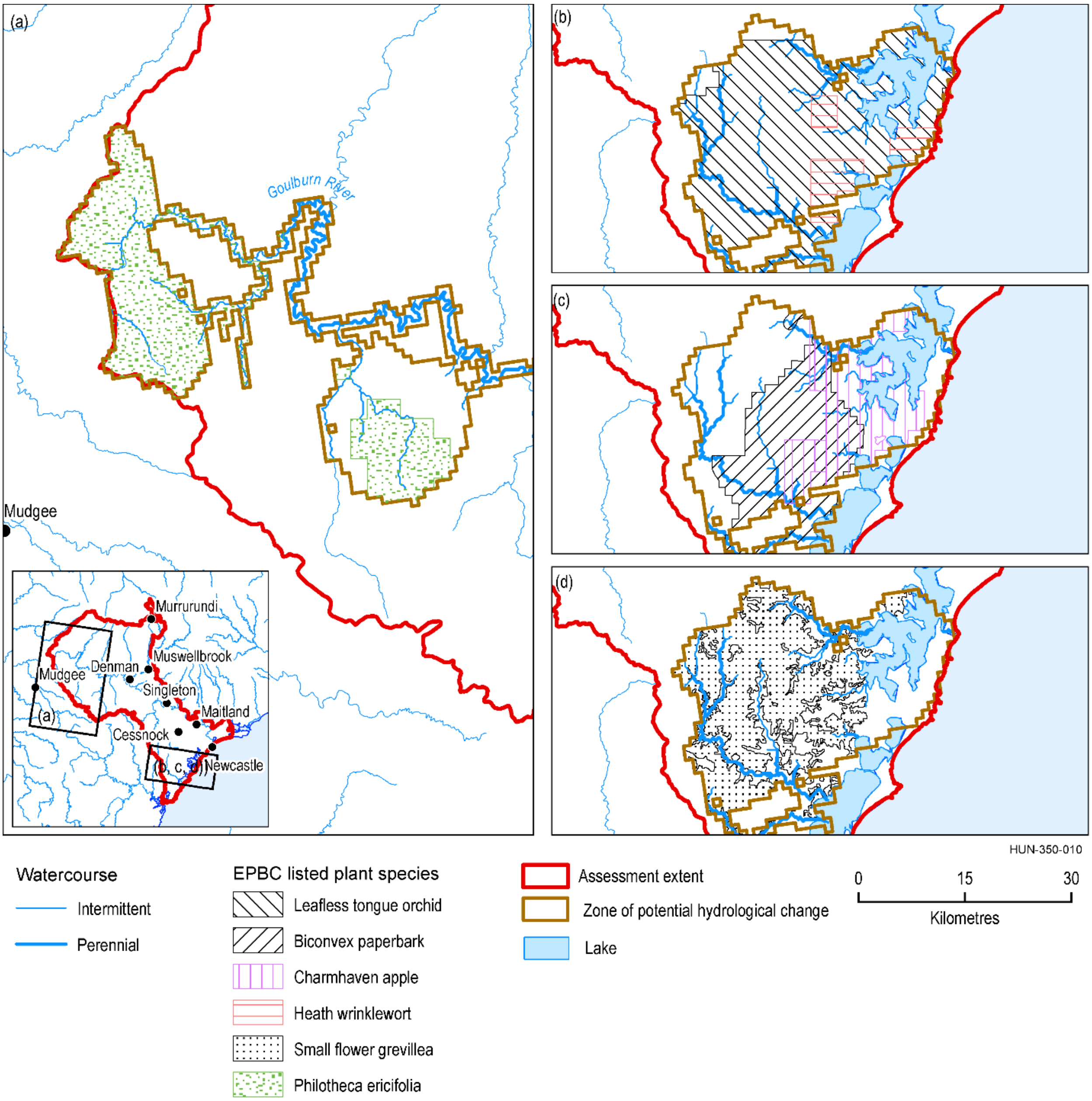

Figure 61 Distribution of selected plants in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change

These species are listed nationally under the Commonwealth's *Environment Protection and Biodiversity Act 1999*.
ACRD = additional coal resource development
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8), Australian Government Department of Environment (Dataset 12),

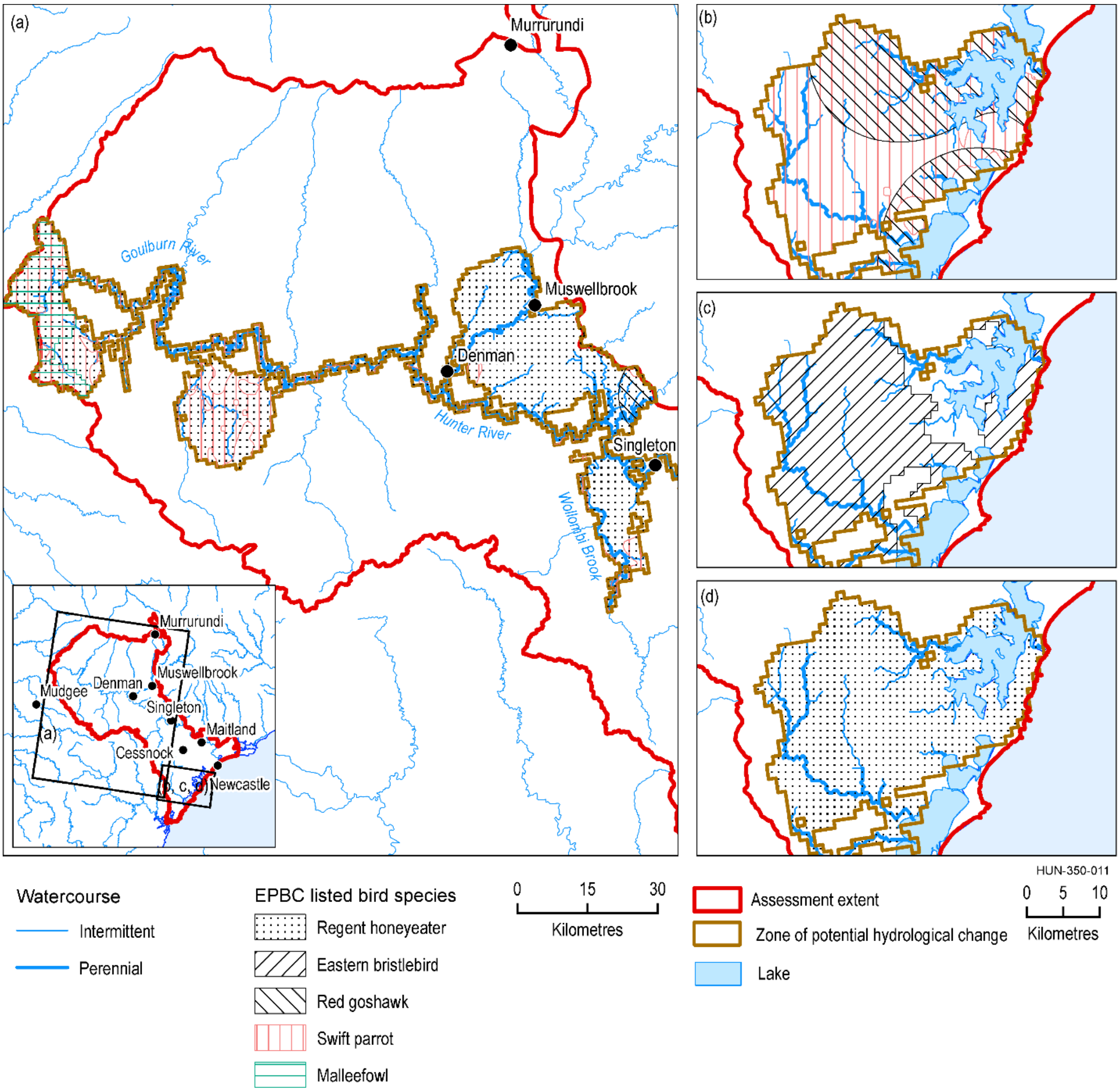

Figure 62 Distribution of selected birds in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change

These species are listed nationally under the Commonwealth's *Environment Protection and Biodiversity Act 1999*.
ACRD = additional coal resource development
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8), Australian Government Department of Environment (Dataset 12)

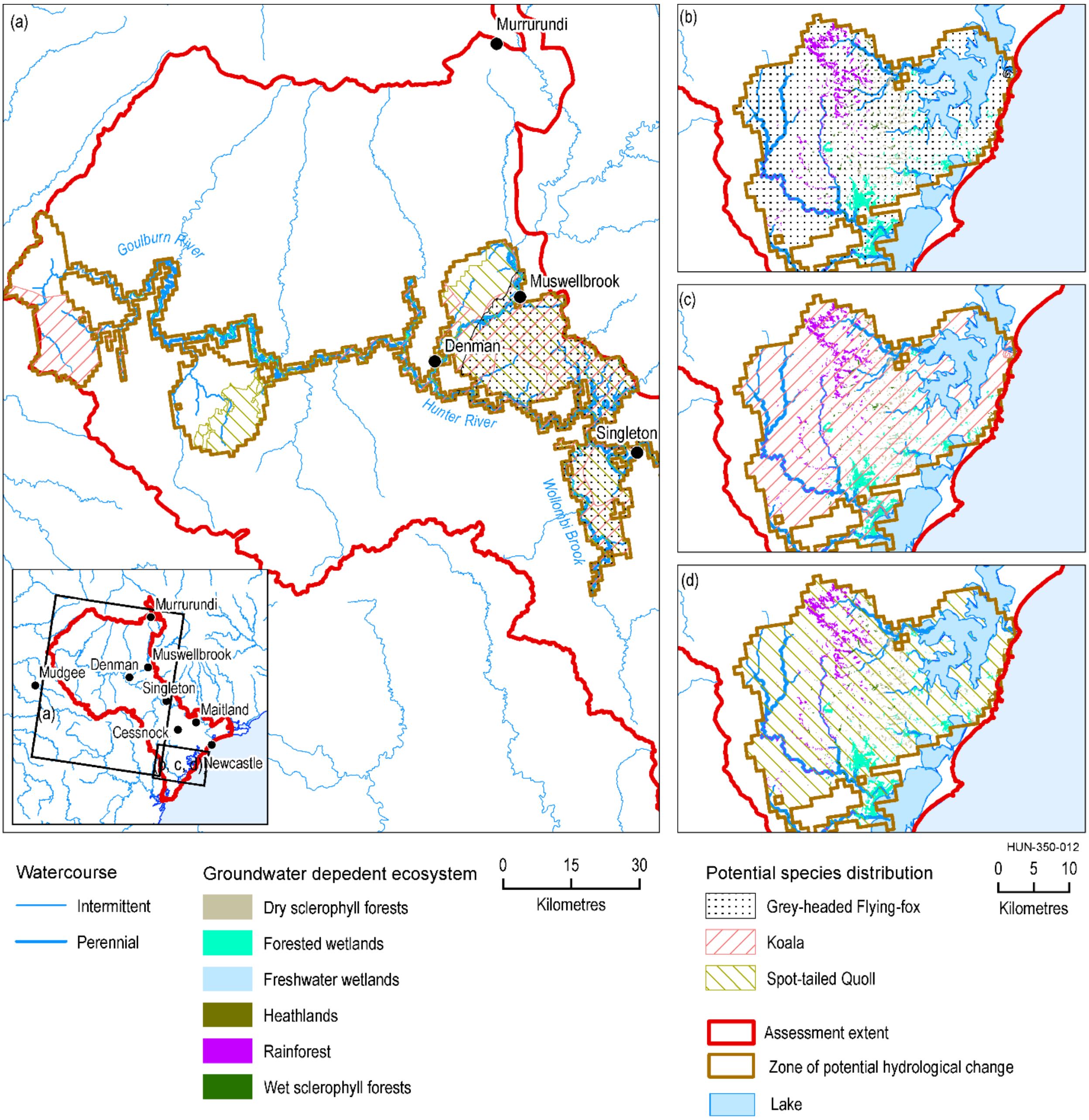

Figure 63 Distribution of selected mammals in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change, overlaid with groundwater-dependent ecosystem (GDE) landscape classes

These species are listed nationally under the Commonwealth's *Environment Protection and Biodiversity Act 1999*.
ACRD = additional coal resource development
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8), Australian Government Department of Environment (Dataset 12)

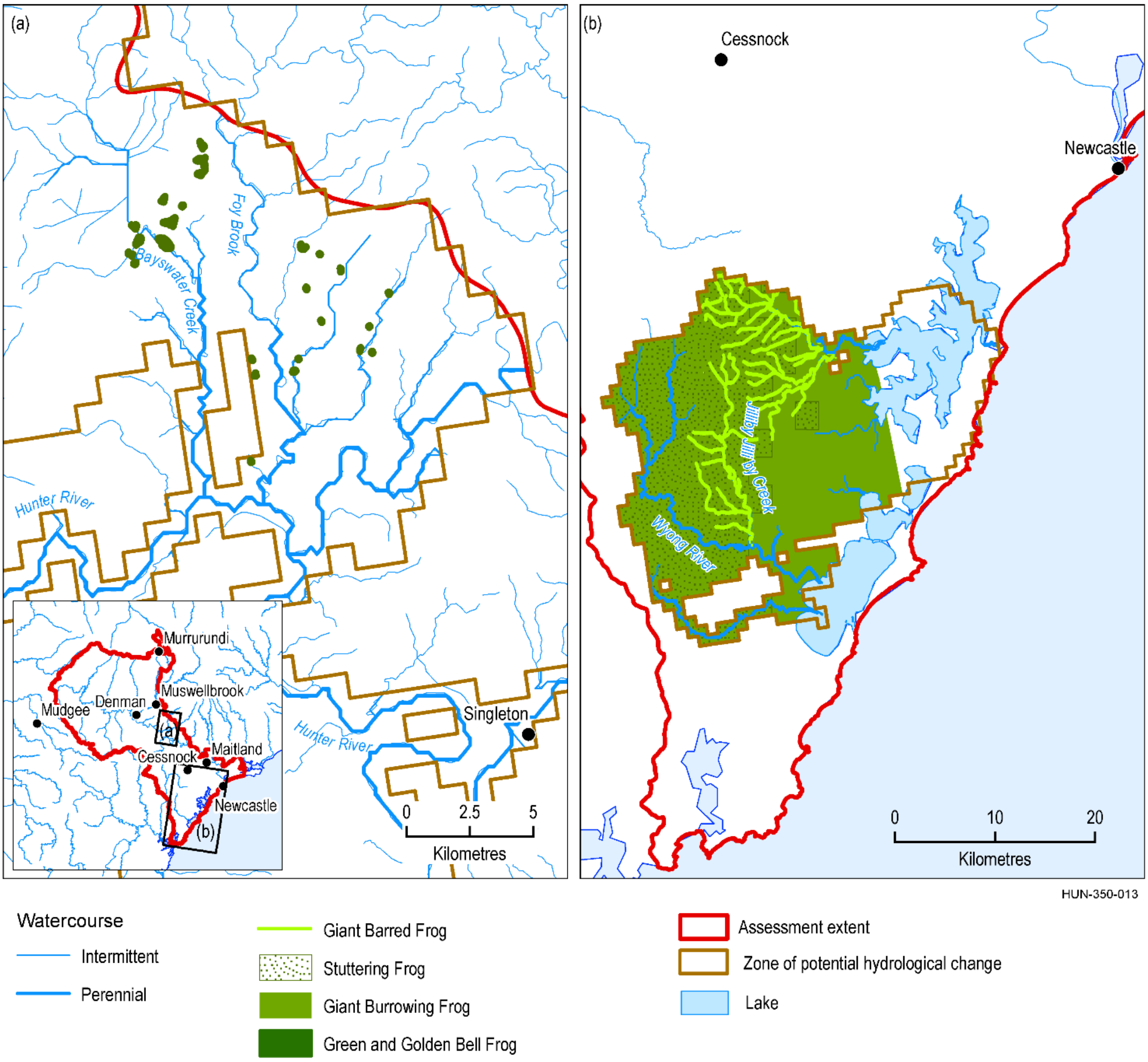

Figure 64 Distribution of selected frogs in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change

These species are listed nationally under the Commonwealth's *Environment Protection and Biodiversity Act 1999*.
ACRD = additional coal resource development
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8), Australian Government Department of Environment (Dataset 12)

There are three frog species listed under NSW's *Threatened Species Conservation Act 1995*: green-thighed frog, red-crowned toadlet and wallum froglet. These all have extensive potential distributions across the zone (2150 to 3170 km^2) and are associated with both potentially impacted GDE landscape classes. These assets represent the potential distribution of three species of frog, all associated with wet or dry sclerophyll forests. The green-thighed frog and wallum froglet are also associated with forested wetlands. The red-crowned toadlet is also associated with ephemeral streams (OEH, 2017a).

Of the asset 'Darling Hardyhead (*Craterocephalus amniculus*) Habitat' from the NSW_DPI_Fisheries_DarlingHardyhead data source, 2 km^2 overlaps the zone of potential hydrological change. Darling hardyhead are associated with permanent or perennial streams and lowly to highly intermittent streams. These small fish are usually found in slow-flowing, clear, shallow waters or in aquatic vegetation at the edge of such waters. The species has also been recorded from the edge of fast-flowing habitats such as the runs at the head of pools (OEH, 2017b). Given the relatively small areas of modelled impacts on riverine landscape classes it is unlikely that this species will be significantly impacted.

There are three Important Bird Areas within the zone that are associated with potentially impacted GDE landscape classes: of the 134 km^2 of the Greater Blue Mountains Important Bird Area in the zone, 1.5 km^2 is associated with forested wetlands; of the 112 km^2 of the Lake Macquarie Important Bird Area in the zone, 5 km^2 is associated with wet and dry sclerophyll forests and 3.8 km^2 with forested wetlands; of 395 km^2 of the Mudgee-Wollar Important Bird Area in the zone, 1 km^2 is associated with wet and dry sclerophyll forests and about 10 km^2 with forested wetlands (Figure 65). These are not associated with potentially impacted riverine landscape classes.

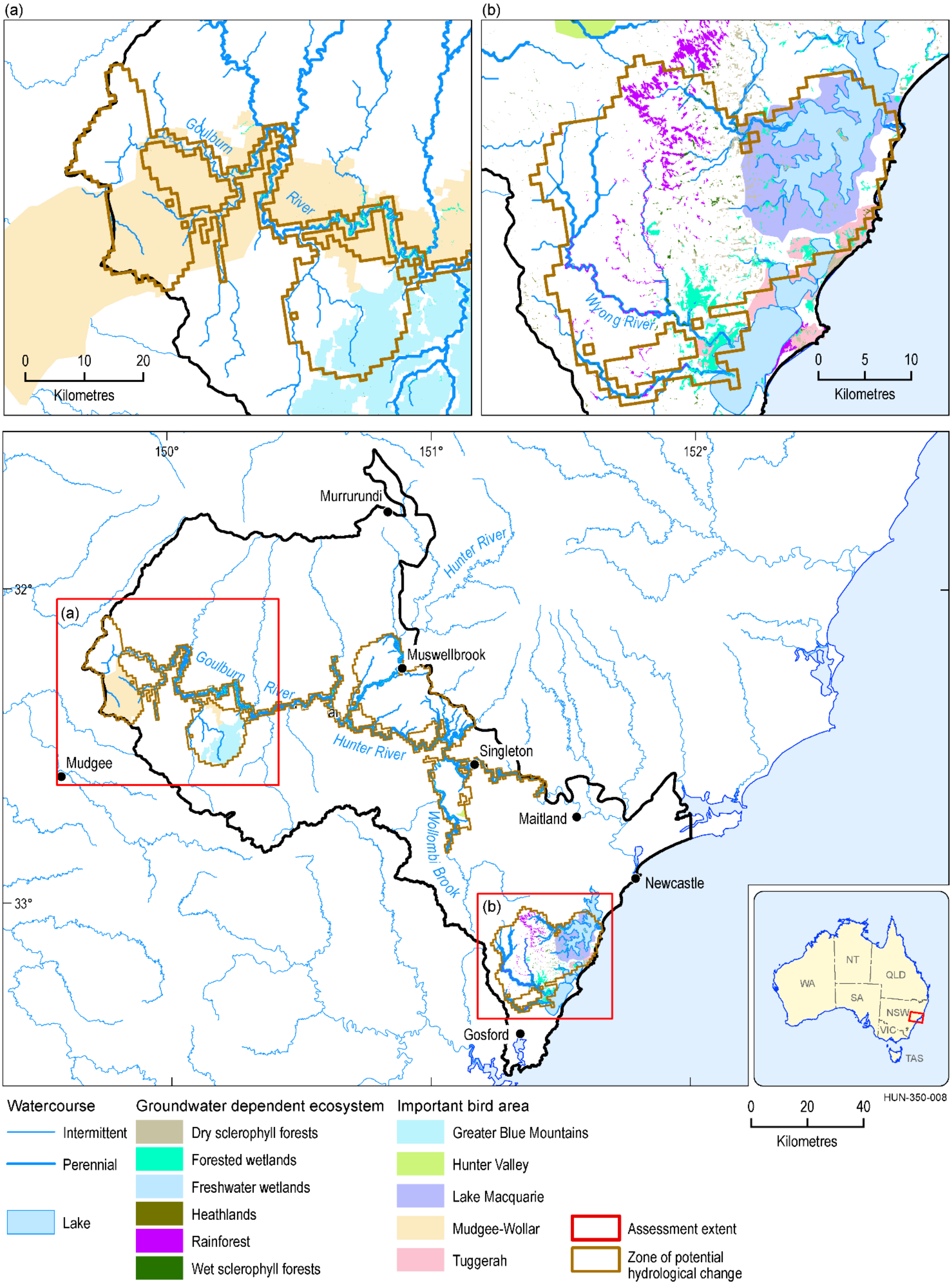

Figure 65 Distribution of Important Bird Areas in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change, overlaid with groundwater-dependent ecosystem (GDE) landscape classes

ACRD = additional coal resource development

Data: Bioregional Assessment Programme (Dataset 7, Dataset 8), Birds Australia (Dataset 10), Australian Government Department of the Environment (Dataset 12)

Five assets from the Collaborative Australian Protected Area Database (CAPAD) are associated with potentially impacted GDE landscape classes (Figure 67 and Table 31). These are not associated with potentially impacted riverine landscape classes. Since 2015, and post-commencement of this bioregional assessment (BA), the Goulburn River National Park has incorporated 'The Drip Gorge' (Figure 66) between Ulan and Mudgee (DPI NSW, 2014). This iconic landscape feature has not been assessed as part of the BA, but was identified at Hunter workshops as a locally important feature. The Wollemi National Park is associated with 1.5 km^2 of potentially impacted forested wetland.

Figure 66 The Drip Gorge in the western Goulburn River catchment

Source: Martin Krogh (2017)

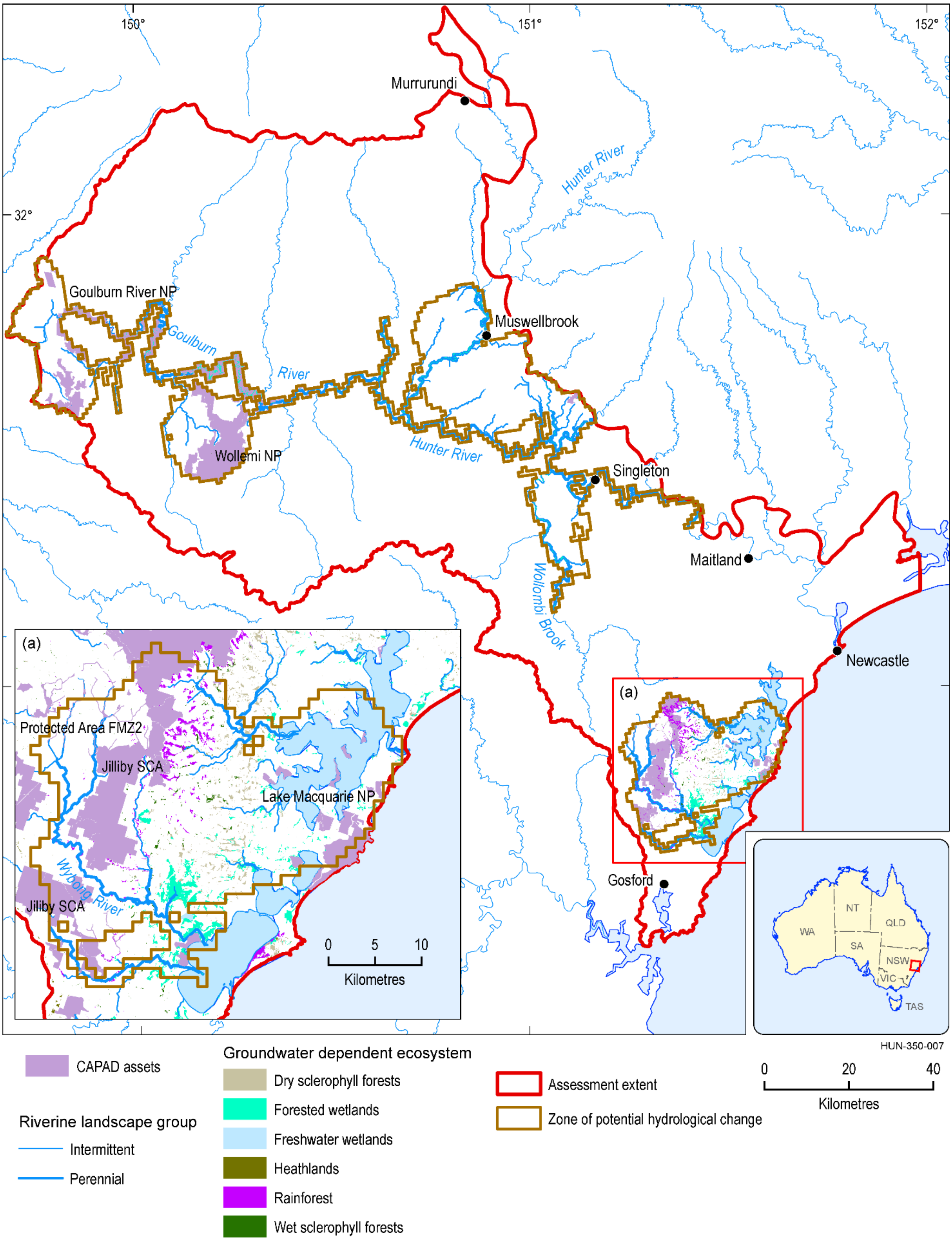

Figure 67 Distribution of Collaborative Australian Protected Area Database (CAPAD) assets in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change, overlaid with groundwater-dependent ecosystem (GDE) landscape classes

ACRD = additional coal resource development, FMZ = forest management zone, NP = national park, SCA = state conservation area
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8), Australian Government Department of Environment (Dataset 11)

Table 31 Groundwater-dependent ecosystem (GDE) landscape classes that overlap with assessment units that are 'more at risk of hydrological changes' Collaborative Australian Protected Area Database (CAPAD) assets in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change

Asset name	Area within zone (km^2)	Wet and dry sclerophyll forests	Forested wetlands
Goulburn River National Park	161	yes	yes
Jilliby State Conservation Area	89.0	yes	no
Lake Macquarie State Conservation Area	5.2	yes	yes
Unnamed Forest Management Zone 2 Grouped by the NSW Forests Management Area of MORISSET and is a Protected area	8.1	yes	yes
Wollemi National Park	137	no	yes

Data: Bioregional Assessment Programme (Dataset 2)

Three assets in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change are threatened ecological communities (Figure 68):

- Grey Box (*Eucalyptus microcarpa*) Grassy Woodlands and Derived Native Grasslands of South-eastern Australia Threatened Ecological Community
- Weeping Myall - Coobah - Scrub Wilga Shrubland of the Hunter Valley Threatened Ecological Community
- White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community.

None of these is identified as 'more at risk of hydrological changes' due to additional coal resource development. One endangered ecological community (EEC) is identified as 'more at risk of hydrological changes': 3.6 km^2 of the Hinterland Spotted Gum EEC (Hunter Lower EEC 2010 E2319 data source) is in the zone, of which 1.3 km^2 is associated with wet and dry sclerophyll forests. Given its association with wet and dry sclerophyll forests and its location near regions of potentially larger hydrological change, this asset may be at risk due to additional coal resource development.

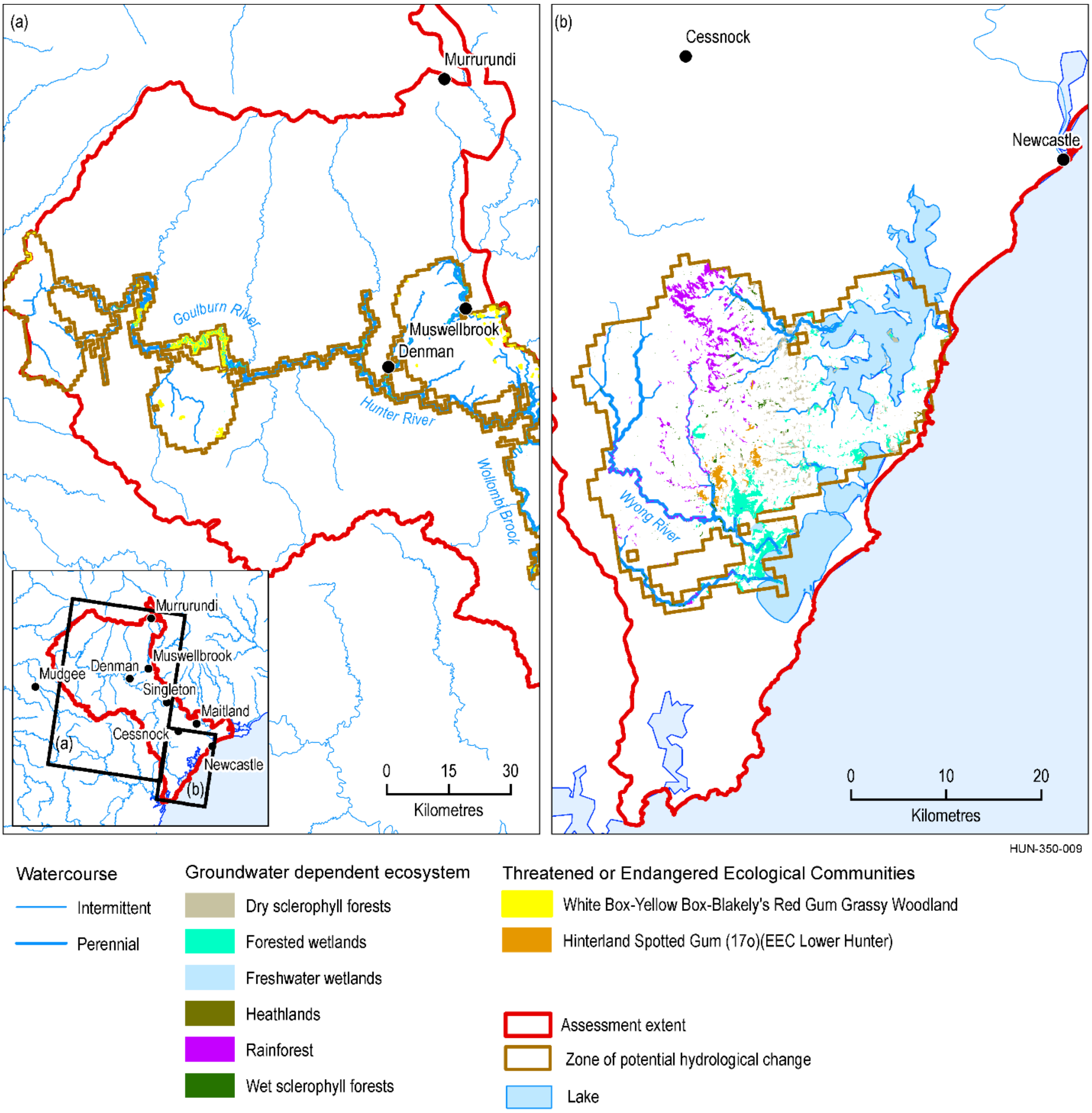

Figure 68 Distribution of threatened ecological communities in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change, overlaid with groundwater-dependent ecosystem (GDE) landscape classes

Data: NSW Department of Environment Climate Change and Water (Dataset 5), Bioregional Assessment Programme (Dataset 7, Dataset 8)

Two assets in the 'Habitat (potential species distribution)' asset class in the zone of potential hydrological change are platypus habitat from the WAIT_ALA_ERIN data source:

- Platypus (*Ornithorhynchus anatinus* (Shaw, 1799))(WAIT)
- Platypus (*Ornithorhynchus anatinus*)(WAIT).

The platypus asset is assumed to be associated with the 'Permanent or perennial' landscape class based on its known habitat and ecology (Grant, 1995). Given the relatively small area of modelled impacts on landscape classes in the 'Riverine' landscape group it is unlikely that this species would be impacted.

3.5.3 Economic assets

In NSW, water resources in river and groundwater systems are managed through water sharing plans. These are subordinate legislation under the NSW *Water Management Act 2000*. Table 32 lists the water sharing plans relevant to the Hunter subregion at the time that the asset register was compiled in 2015. In July 2016, NSW Department of Primary Industries Water replaced, merged and commenced a number of plans, details of which are provided in the second column of Table 32. Thus where previously there were 11 relevant water sharing plans in the Hunter subregion, since July 2016 there are 8, 2 of which are new plans. These changes have generally not resulted in the re-definition of existing water source areas, which form the basis for asset groupings in the Hunter water-dependent asset register. However, where there are differences, the names and spatial extents of the water sources named in the 2016 plans are used in the following assessment of impacts on economic assets. Each water sharing plan specifies the water sources to which it applies.

Impacts on economic assets due to additional coal resource development can arise where changes in groundwater and surface water hydrology increase the cost of water supply and access. The assessment of potential impact does not involve estimates of costs in monetary terms, instead economic assets within the zone of potential hydrological change are identified and the likelihood of changes to water access are assessed. Economic assets include the water resources themselves and the water supply works, which enable users to access water under a water access licence or a basic water right.

Table 32 Water sharing plans in 2015 and since July 2016 in the Hunter subregion

Water sharing plans in 2015	Change since 1 July 2016
Hunter Regulated River Water Source 2003	Replaced in 2016
Hunter Unregulated and Alluvial Water Sources 2009	Unchanged
Wybong Creek Water Source 2003	Merged into Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources 2009
Central Coast Unregulated Water Sources 2009	Unchanged
Jilliby Jilliby Creek Water Source 2003	Merged into Water Sharing Plan for the Central Coast Unregulated Water Sources 2009
Ourimbah Creek Water Source 2003	Merged into Water Sharing Plan for the Central Coast Unregulated Water Sources 2009
Kulnura Mangrove Mountain Groundwater Sources 2003	Merged into the new Water Sharing Plan for the North Coast Fractured and Porous Rock Groundwater Sources 2016
Tomago Tomaree Stockton Groundwater Sources 2003	Merged into the new Water Sharing Plan for the North Coast Coastal Sands Groundwater Sources 2016
Karuah Unregulated and Alluvial Water Sources 2013	Merged into Water Sharing Plan for the Lower North Coast Unregulated and Alluvial Water Sources 2009
NSW Murray Darling Basin Porous Rock Groundwater Sources 2011	Unchanged
NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011	Unchanged

3.5.3.1 Assets in the zone of potential hydrological change

The water-dependent asset register for the Hunter subregion (companion product 1.3 (Macfarlane et al., 2016)) has 249 economic water-dependent assets, comprising 10,327 elements. Within the Hunter zone of potential hydrological change, there are 123 economic assets, comprising 3950 elements (Table 33). Eighty-two surface water assets and 43 groundwater assets can be ruled out as *very unlikely* to be impacted due to additional coal resource development. The final column in Table 33 enumerates the groundwater and surface water elements in the mine pit exclusion zone. While the 129 bores and 133 surface water extraction points are clearly within the zone of potential hydrological change and hence potentially impacted due to additional coal resource development, the modelled estimates of drawdown in the vicinity of open-cut pits are highly uncertain.

Table 33 Economic assets and elements in the Hunter assessment extent, zone of potential hydrological change and mine pit exclusion zone

Numbers are reported against the old water sharing plans (see Table 32) and these numbers are consistent with the water-dependent asset register for the Hunter subregion. However, where there are differences with the 2016 plans, the names and spatial extents of the water sources named in the 2016 plans are used in the following assessment of impacts on economic assets.

Asset subgroup	Asset class	Number in assessment extent		Number in zone of potential hydrological change		Number in mine pit exclusion zone
		Assets	Elements	Assets	Elements	Elements
Groundwater management zone or area (surface area)	A groundwater feature used for water supply	10	10	5	6	0
	Water supply and monitoring infrastructure	0	0	0	0	0
	Water access right	86	4,965	42	1335	114
	Basic water right (stock and domestic)	45	488	11	115	15
	Subtotal	**141**	**5,463**	**58**	**1456**	**129**
Surface water management zone or area (surface area)	A surface water feature used for water supply	44	44	33	33	0
	Water supply and monitoring infrastructure	2	2	0	0	0
	Water access right	39	4,463	21	2288	26
	Basic water right (stock and domestic)	23	355	11	173	107
	Subtotal	**108**	**4,864**	**65**	**2494**	**133**
Total		**249**	**10,327**	**123**	**3950**	**262**

Data: Bioregional Assessment Programme (Dataset 15)

Figure 69 and Figure 70 identify the groundwater sources and bores and surface water sources and extraction points, respectively, that intersect the zone of potential hydrological change, and hence are potentially impacted due to additional coal resource development. Table 34 lists the potentially impacted groundwater and surface water sources and the number of water rights holders (both access licence and basic rights) within the zone of potential hydrological change. The following clarifications and conclusions can be made about water sources:

- There are 5 groundwater and 24 surface water sources (including alluvial) that intersect the zone of potential hydrological change and are potentially impacted due to additional coal resource development. The intersection of 5 of these 24 surface water sources is an artefact of the analysis technique and associated with just eight extraction points. Therefore, only 19 of these surface water points are potentially impacted due to additional coal resource development.
- Ten unregulated and alluvial water sources that are in the Hunter assessment extent – Pages River, Munmurra River, Bow River, Merriwa River, Martindale Creek, Doyles Creek, Upper Wollombi Brook, Wallis Creek, Patterson/Allyn Rivers and Newcastle – are not within the

zone of potential hydrological change and can be ruled out as *very unlikely* to be impacted due to additional coal resource development.

- Four groundwater sources can be ruled out as *very unlikely* to be impacted due to additional coal resource development. The Liverpool Ranges Basalt Coast groundwater source, covered by the *Water Sharing Plan for the North Coast Fractured and Porous Rock Groundwater Sources 2016*, and the Stockton, Tomaree and Tomago water sources, covered by the *Water Sharing Plan for the North Coast Coastal Sands Groundwater Sources 2016*, do not intersect the zone of potential hydrological change.
- The unregulated and alluvial water sources of Baerami Creek, Black Creek, Halls Creek, Krui River and Widden Brook are identified as potentially impacted because the 1 km assessment units associated with the Goulburn River and Hunter River surface water zone of potential hydrological change cause these water sources to be intersected where they meet these larger rivers. A few extraction points are picked up within these assessment units, but overall, the additional coal resource development is considered unlikely to impact these water sources.
- The Luskintyre and Singleton water sources, which straddle the Hunter Regulated River, are associated with very few extraction points because the majority of extraction points in these water sources is captured within the numbers given for the Hunter Regulated River. Only six water access licences in the Luskintyre water source and three in the Singleton water source that are within the zone relate to unregulated and alluvial water sources and not to the Hunter Regulated River water source.

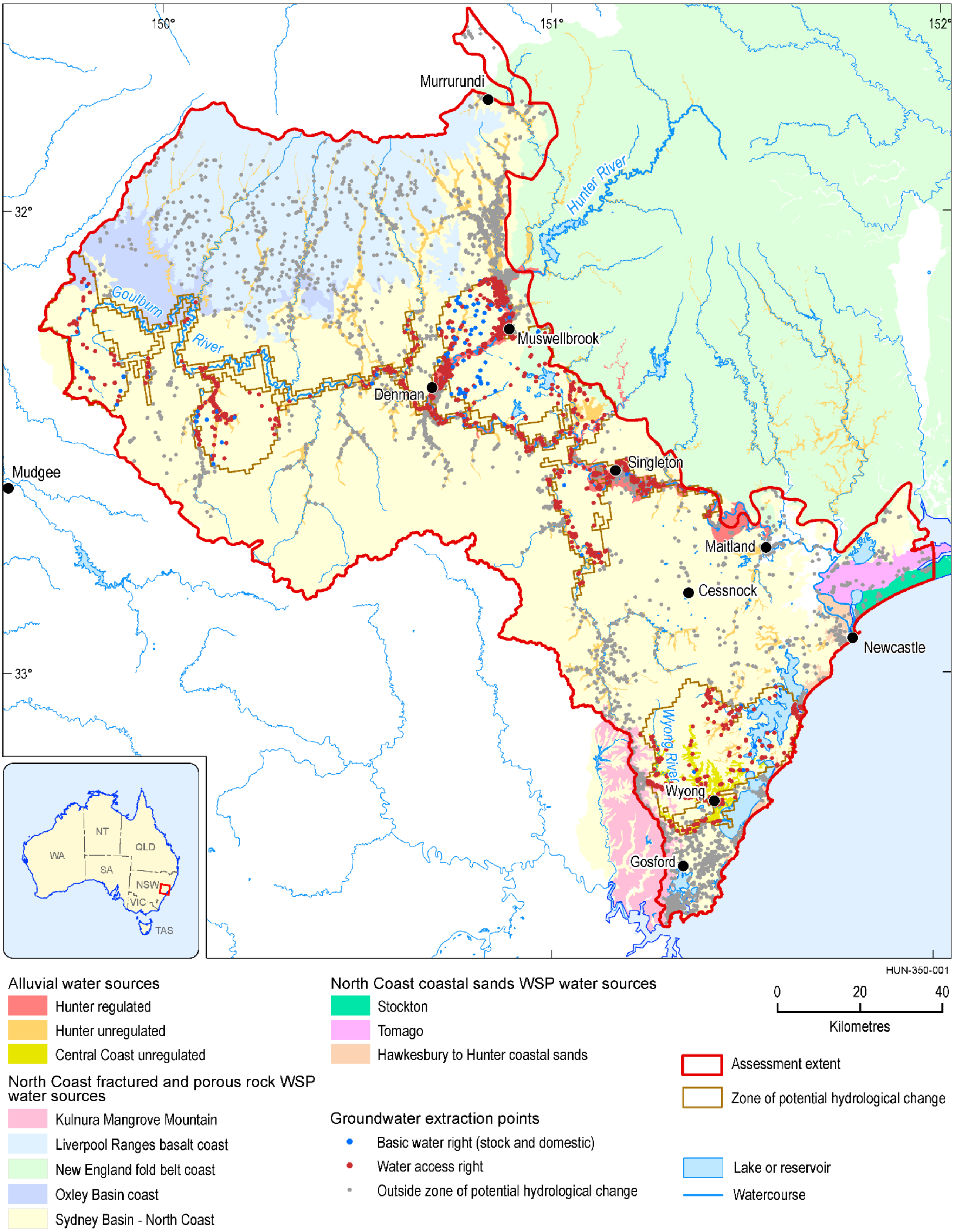

Figure 69 Groundwater source areas and bores in the zone of potential hydrological change

WSP = water sharing plan

Data: Bioregional Assessment Programme (Dataset 8, Dataset 9, Dataset 15, Dataset 16)

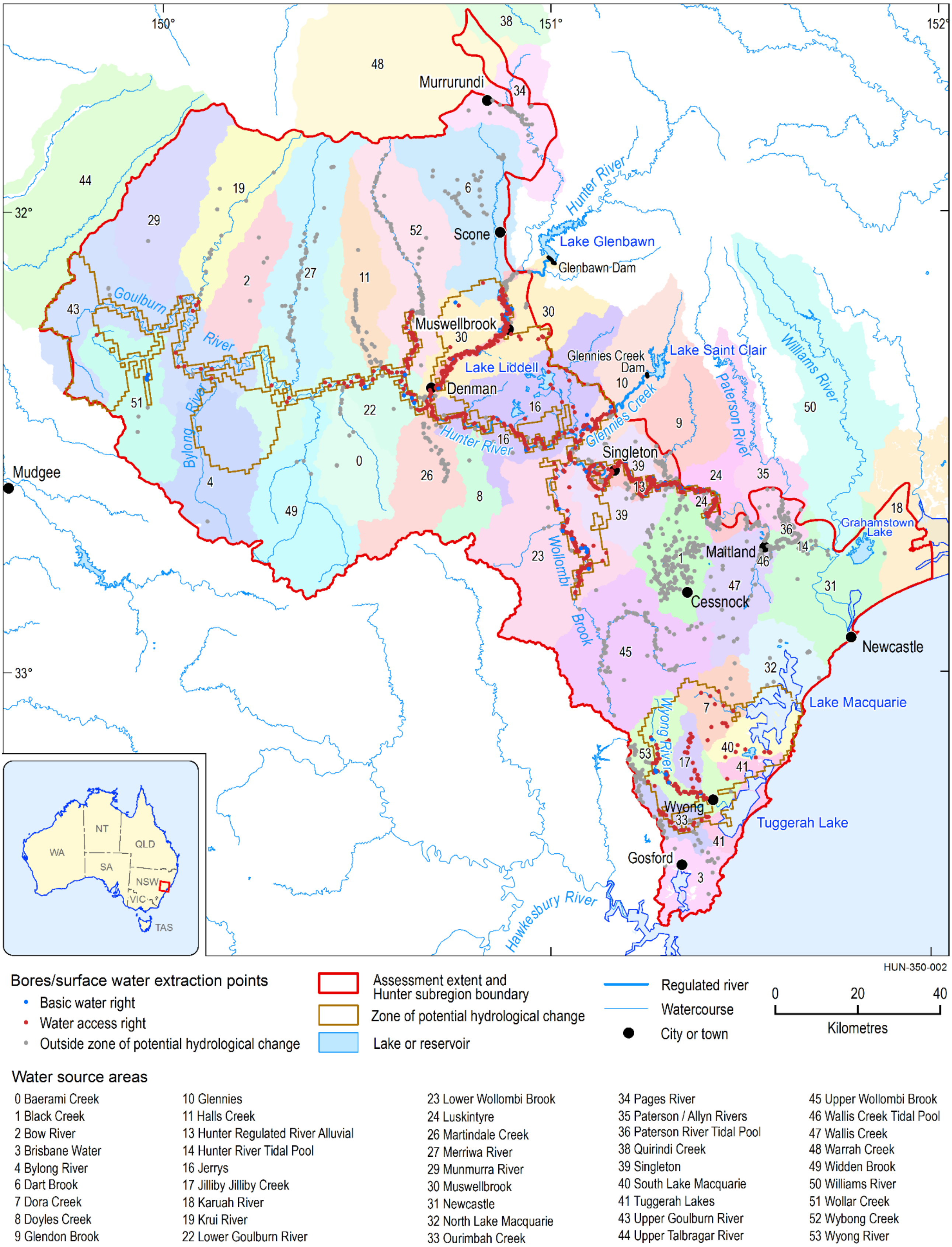

Figure 70 Surface water source areas and extraction points in the zone of potential hydrological change

Data: Bioregional Assessment Programme (Dataset 8, Dataset 9, Dataset 15)

Table 34 Water source areas and extraction points in the zone of potential hydrological change

Water sharing plan	Water source area	In zone	Water access licence	Basic water rights	In mine pit exclusion zone
Central Coast Unregulated Water Sources 2009	Jilliby Jilliby Creek	58	58	0	0
	Ourimbah Creek	54	52	2	0
	Tuggerah Lakes	13	10	3	0
	Wyong River (incl. Lower Floodplain Alluvial)	168	156	12	0
Hunter Regulated River 2004	Hunter Regulated River	2064	1942	122	155
Hunter Unregulated and Alluvial Water Sources 2009	Baerami Creek	1	1	0	0
	Black Creek	2	2	0	0
	Bylong River	92	84	8	13
	Dart Brook	78	76	2	0
	Dora Creek (incl. Lower Floodplain Alluvial)	50	50	0	0
	Glennies	0	0	0	0
	Halls Creek	2	2	0	0
	Jerrys	46	46	0	5
	Krui River	4	4	0	0
	Lower Goulburn River	198	183	15	0
	Lower Wollombi Brook	252	234	18	13
	Luskintyre	6	6	0	0
	Muswellbrook	53	36	17	0
	Singleton	3	3	0	0
	South Lake Macquarie	18	18	0	0
	Upper Goulburn River	20	20	0	0
	Widden Brook	1	1	0	0
	Wollar Creek	15	6	9	0
	Wybong Creek	111	105	6	0
North Coast Coastal Sands Groundwater Sources 2016	Hawkesbury to Hunter Coastal Sands	47	47	0	0
North Coast Fractured and Porous Rock Groundwater Sources 2016	Kulnura Mangrove Mountain	26	26	0	0
	New England Fold Belt	28	22	6	2
	Oxley Basin Coast	7	6	1	0
	Sydney Basin – North Coast	494	427	67	72
Total		**3911**[a]	**3623**	**288**	**260**

[a]Of the 3950 elements in the zone of potential hydrological change (Table 33), 3911 relate to water access licences and basic water rights.
Data: Bioregional Assessment Programme (Dataset 15)

Of the 3950 elements in the zone of potential hydrological change (Table 33), 3911 relate to bores and surface water extraction points. The following clarifications and conclusions can be made about extraction points within potentially impacted water sources:

- Mardi Dam and Grahamstown Dam, the two water infrastructure assets in the Hunter asset register, are outside the zone of potential hydrological change and inflows are unlikely to be impacted. Mardi Dam is an offstream storage and is filled by pumping water from Wyong River and Ourimbah Creek. Changes in streamflow in Wyong River could impact water supply to Mardi Dam.
- Just over half (~53%) of the 3911 extraction points in the zone of potential hydrological change are associated with the Hunter Regulated River water source; almost 32% (1245) relate to unregulated and alluvial water sources; and just over 15% are from water sources in fractured and porous rock aquifers.
- There are 260 bores and surface water extraction points in the mine pit exclusion zone: 90 are within the groundwater zone of potential hydrological change and their modelled drawdowns are considered very uncertain due to their proximity to open-cut mine pits.
- Table 34 suggests there are no extraction points in Glennies water source in the zone of potential hydrological change. Glennies Creek is part of the Hunter Regulated River water source and the bores and surface water extraction points that are within the zone are included in the Hunter Regulated River numbers. Thus the zero values in Table 34 indicate there are no extraction points along unregulated tributaries of Glennies Creek within the zone.

Of the 1450 groundwater bores identified in Table 33 as in the zone of potential hydrological change, 780 bores are within the groundwater zone of potential hydrological change and 670 bores are solely within the surface water zone of potential hydrological change. Of the 670 bores selected due to intersection with the surface water zone of potential hydrological change, only those bores used to extract water from an alluvial aquifer could potentially be impacted. This is because alluvial aquifers tend to be highly connected to the streams that intersect them, such that changes in baseflow due to additional coal resource development could affect water levels at bores within the alluvium, even outside the area of greater than 0.2 m of drawdown. In NSW, these highly connected water sources are managed conjunctively. Analysis of the bore dataset revealed that 62 of these bores are in fractured rock aquifers (Sydney Basin – North Coast) and can be ruled out. Another 415 were clearly identified as in alluvial aquifers and therefore potentially impacted. Of the remaining 193, drill depth data were used to determine likelihood of potential impact, with bores lacking drill depth data being retained as potentially impacted. In the Hunter subregion, depths of alluvium have been reported as ranging from 3 to 17 m (Australian Groundwater Consultants Pty Ltd, 1984) and up to 20 m (Wilford et al., 2015). In companion product 1.5 for the Hunter subregion (Zhang et al., 2016), a depth of 20 m was adopted to distinguish bores that (i) had no screen depth data and (ii) coincided with mapped Hunter River alluvium into alluvial and fractured rock bores. The same threshold is used here to differentiate alluvial bores, which are potentially impacted, from deeper, fractured rock bores that are unlikely to be impacted due to additional coal resource development. Table 35 summarises the breakdown, with 590 of these bores retained as potentially impacted and 80 ruled out as unlikely to be impacted.

Table 35 Drill depths and purpose of potentially impacted bores solely in surface water zone of potential hydrological change

Bores solely in surface water zone	Unlikely to be impacted		Potentially impacted		
	Fractured rock	>20 m	Alluvial	No depth	<20 m
670	62	18	415	85	90

Data: Bioregional Assessment Programme (Dataset 15)

In summary, 19 surface water sources and 5 groundwater sources are potentially impacted by hydrological changes due to additional coal resource development. Figure 71 summarises the steps for deeming bores and surface water extraction points in the zone 'potentially impacted'. Of 3911 bores and surface water extraction points within the zone, 3831 are potentially affected due to additional coal resource development.

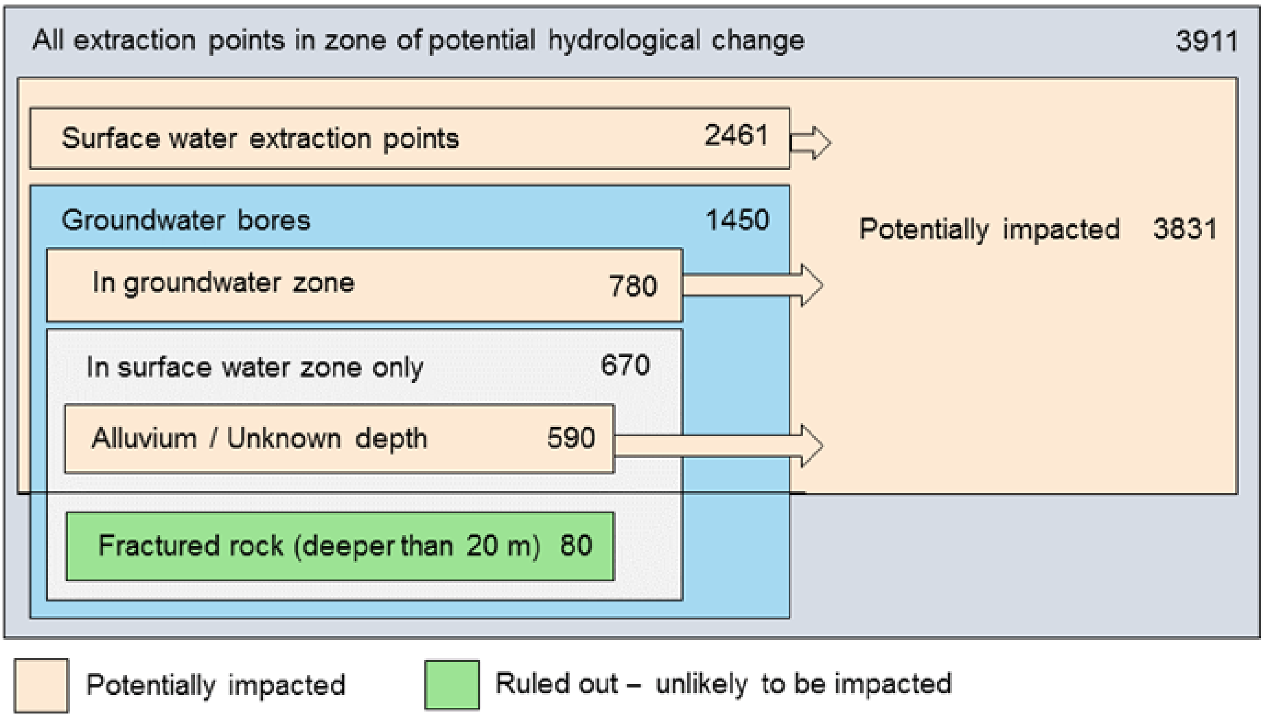

Figure 71 Determining 'potentially impacted' extraction points in the Hunter zone of potential hydrological change

Data: Bioregional Assessment Programme (Dataset 15)

Whether the modelled hydrological changes due to additional coal resource development are likely to impact water rights holders can be assessed through quantifying changes in water availability and reliability of flows in the potentially impacted unregulated and alluvial water source areas and determining whether the modelled drawdowns could interfere with licensed bore water users access to groundwater. These three indicators of impact are considered in the following sections.

3.5.3.2 Impact on water availability (surface water)

The change in average annual flow is used here as an indicator of change in water availability due to additional coal resource development.

Twenty-four water source areas intersect the Hunter zone of potential hydrological change. Five were identified as having minimal intersection with the zone and unlikely to be impacted, with results at model nodes on Baerami Creek and Black Creek confirming no significant hydrological change for two of these water sources. Modelling results at model nodes on Wybong Creek and Dart Brook also indicate no significant change in average annual flows. Surface water modelling was not undertaken for Dora Creek, South Lake Macquarie, Ourimbah Creek, Jilliby Jilliby Creek and Tuggerah Lakes water sources, and changes in average annual flows cannot be quantified. Results of changes in average annual flows are presented for 11 water sources, noting that changes in the Luskintyre water source (not reported) are encapsulated in the changes reported for zone 2B of the Hunter Regulated River.

Table 36 summarises changes in annual flows for the Hunter Regulated River water source by management zone. Management zones along the Hunter River number from 1A immediately below Glenbawn Dam to 2B at the downstream end of the regulated river, a few kilometres north of Maitland; zone 3A corresponds to the regulated reach between Glennies Creek Dam and the junction with the Hunter River. In absolute terms, the biggest reduction in annual flows occurs in zone 2B, and reflects the cumulative impact of all the modelled developments upstream of this point. Between 2013 and 2042, this is modelled to be up to 12 GL/year (95th percentile) or 1.6% of the baseline mean annual flow for the same period. By the 2073 to 2102 period, this impact is modelled to have lessened to 6 GL/year. Reductions in mean annual flows range between 2 and 5 GL/year along zones 1B and 2A, the length of river between the Goulburn and Hunter rivers junction and the Wollombi Brook and Hunter River junction.

Table 36 Change in water availability due to the additional coal resource development for management zones within the Hunter Regulated River water source. The average annual baseline flow for the short-term period (2013–2042, 95th percentile) is provided as context

Zone	Node	Baseline	Reduction due to additional coal resource development (GL/year)								
		Short-term period (2013–2042)	Short-term period (2013–2042)			Medium-term period (2043–2072)			Long-term period (2073–2102)		
		95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
1A	51	386	1.2	2.1	3.3	0.6	1.1	2.0	0.4	0.7	1.3
1B	25	293	1.9	3.1	4.5	0.7	1.1	1.8	0.5	0.8	1.4
2A	20	378	2.1	3.3	4.8	0.7	1.2	1.9	0.5	0.9	1.4
2B	1	758	5.3	8.5	12.2	3.7	5.8	8.2	2.7	4.3	6.1
3A	21	89.1	<0.1	0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Data: Bioregional Assessment Programme (Dataset 17)

Table 37 summarises changes in annual flows for Hunter unregulated and alluvial water sources. Generally, the most downstream node for the water source has been used to assess the change in water availability, however for the Singleton, Jerrys and Muswellbrook water sources, which overlap the Hunter Regulated River water source, the sum of changes in annual flows at nodes on small tributary streams within the water source area has been used to give an indication of the change in water availability for these water sources. They are likely to underestimate the change due to additional coal resource development because the effect of baseflow reductions downstream of these nodes is not captured in the reported numbers at this scale. However, the changes in the management zones along the Hunter Regulated River water source (Table 36) include those baseflow reductions: for the Muswellbrook water source, zone 1A is relevant; zone 1B reflects changes in Jerrys water source; and zone 2 captures changes in tributary flows within the Singleton water source.

The biggest reductions in annual flows occur in the Singleton water source (95th percentile of ~6.3 GL/year), followed by Jerrys (~3.5 GL/year) and Muswellbrook (~2.85 GL/year) water sources between 2013 and 2042. In the Wyong River, decreases in the mean annual flow are modelled to peak between 2043 and 2072 (95th percentile of ~5.7 GL/year), with the effect persisting through the 2073 to 2102 period. Changes to water availability in the Goulburn River water sources – Lower Goulburn River, Upper Goulburn River, and Bylong and Wollar Creek – are comparatively small, with the largest decrease in mean annual flow of 0.9 GL/year (95th percentile) occurring in the Wollar Creek water source between 2013 and 2042, and increasing reductions in the Bylong water source from 0.24 to 0.4 to 0.48 GL/year over the three 30-year periods.

Table 37 Change in water availability due to the additional coal resource development for Hunter unregulated and alluvial water sources in the zone of potential hydrological change. The average annual baseline flow for the short-term period (2013–2042, 95th percentile) is provided as context

Water source	Node	Baseline	Reduction due to additional coal resource development (GL/year)								
		Short-term period (2013–2042)	Short-term period (2013–2042)			Medium-term period (2043–2072)			Long-term period (2073–2102)		
		95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
Singleton[a]	7, 11	18.5	2.9	4.5	6.3	2.5	4.1	5.8	1.8	3.1	4.7
Lower Wollombi Brook	12	142	0.6	1.1	1.6	0.4	0.7	1.0	0.2	0.3	0.5
Glennies	21	See Hunter Regulated River – Zone 3A (Table 36)									
Jerrys[a]	26–30, 35	61.0	1.4	2.3	3.5	0.4	0.7	1.2	0.4	0.6	1.1
Muswellbrook[a]	52, 55	6.4	0.7	1.4	2.9	0.3	0.8	1.7	0.2	0.5	1.1
Lower Goulburn River	36	77.9	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Upper Goulburn River	41	73.0	0.2	0.3	0.6	0.1	0.1	0.4	0.06	0.1	0.3
Bylong	42	57.3	<0.1	<0.1	0.2	<0.1	<0.1	0.4	<0.1	<0.1	0.5
Wollar Creek	46	22.3	0.4	0.6	0.9	0.2	0.4	0.6	0.1	0.2	0.3
Wyong River	64	116	0.2	0.7	4.2	0.6	1.3	5.7	0.6	1.2	5.6

[a]Water sources with no suitable downstream node – values represent the sum of changes at multiple nodes within the water source area.
Data: Bioregional Assessment Programme (Dataset 17)

3.5.3.3 Impact on reliability (surface water)

3.5.3.3.1 Regulated river

The Hunter Regulated River – between Glenbawn Dam and Glennies Creek Dam and the tidal limit of the Hunter River – has a prescribed long-term average annual extraction limit and is a fully allocated water source. No new water access licences are available from the state, so access to water is permitted only through an existing licence or purchase of an entitlement or an allocation through the water market. Licensed entitlement holders in regulated rivers are able to place orders for water from Glenbawn and Glennies Creek dams to meet their water needs. How much they are permitted to extract in any given year depends on water availability in these storages. Available water determinations (AWDs) are made at the commencement of the water year based on the volume of stored water and the assumption that inflows to the dams in the ensuing year will be the lowest on record. In years when the starting AWD is less than 100% of entitlement, the AWD can be updated throughout the water year in response to changing conditions.

The environment is also a recognised 'user' of water in the regulated river. The *Water Sharing Plan for the Hunter Regulated River Water Source* makes provision for environmental water through not only setting a limit on long-term annual extractions of 217,000 ML/year, which ensures about 80% of the long-term annual flow is left in the river, but also through specifying environmental water requirements (EWRs) at the Liddell and Greta gauging stations (nodes 31 and 1, respectively). EWRs are managed through imposing limits on extractions when the dam spills or when high flows from unregulated tributaries enter the system to ensure sufficient volumes for flooding of wetland areas; imposing limits on extractions when inflows from the unregulated tributaries to the regulated river are low to ensure sufficient water is retained in the river; and through releases of water from Glenbawn and Glennies Creek dams.

A potential economic impact of coal resource development is upon security of supply to consumptive users. If reductions in baseflow and catchment runoff lead to a greater frequency of flow rates below the minimum EWR at Liddell and Greta, then water in the Glenbawn and Glennies Creek storages that might otherwise have been part of the consumptive pool may be needed to meet the EWR. This could potentially reduce the security of supply to users of the consumptive pool, reflected in a decrease in the percentage of years that they can expect to receive an AWD of 100% at the start of the water year. This potential impact has not been modelled as part of the BA for the Hunter subregion, but is identified as a risk. The NSW Department of Primary Industries Water IQQM of the Hunter Regulated River is the appropriate modelling platform for exploring the implications of potential flow reductions on environmental water and the consumptive pool.

3.5.3.3.2 Unregulated river and alluvial water sources

One way flows in unregulated rivers can be protected is through controls on extraction. Cease-to-pump rules in water sharing plans specify the river level below which extractions are not permitted. Some plans specify how much water is permitted to be extracted for different flow ranges. Cease-to-pump rules are developed for each water source based on all current water licence entitlements accessing either surface water or groundwater (in highly connected alluvial aquifers) – that is, rules assume full development rather than actual take. For water sources covered by the *Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources* that have cease-to-pump rules, the general requirement is for pumping from the river to cease when there is no visible flow in the water source at the location where water is proposed to be taken or, where water is taken from a pool, there is no visible flow into or out of the pool. Some water sources are split into a number of management zones (e.g. Dart Brook has five; Jerrys has two), some of which may have a groundwater trigger, rather than a streamflow trigger, to define when extractions are and are not permitted. Not all water sources in the Hunter subregion have had the groundwater trigger, reference point and cease-to-pump rules specified for them. Table 38 lists the water sources within the zone of potential hydrological change that surface water modelling found to have an above-threshold change in the number of zero-flow days (ZFD) or low-flow days (LFD) due to additional coal resource development, details the cease-to-pump rules for each water source and specifies the flow threshold used to quantify the impact on cease-to-pump days due to additional coal resource development. Where cease to pump is triggered by 'no visible flow', the change in the average number of zero-flow days in each 30-year period has been used to quantify the change. Where cease to pump is based on the flow rate falling below a specified flow rate at a reference location, then the change is assessed using the specified threshold. Where the cease-to-pump trigger has not been specified for a water source, the assessment has been based on the change in the average number of zero-flow days.

Table 38 Cease-to-pump rules for water sources in the surface water zone of potential hydrological change that surface water modelling found to have a change in zero-flow or low-flow days due to additional coal resource development greater than the defined thresholds

Water source	Cease to pump when…	Flow threshold
Black Creek	no visible inflow to, or outflow from, the pumping pool	Zero flow
Dart Brook	no visible inflow to, or outflow from, the pumping pool; for alluvial management zones, a groundwater level trigger is yet to be defined	Zero flow for non-alluvial areas; not defined for alluvial areas, use zero flow
Glennies	(a) no visible flow immediately downstream of the pump site or into and out of the pumping pool, and (b) no visible flow at the reference point: Causeway, 230 m downstream of boundary between DP 752462, Lot 23 and Lot 24	Zero flow
Jerrys	no visible inflow to, or outflow from, the pumping pool	Zero flow
Lower Goulburn River	a groundwater level trigger is yet to be defined	Not defined, use zero flow
Lower Wollombi Brook	a groundwater level trigger is yet to be defined	Not defined, use zero flow
Muswellbrook	no visible inflow to, or outflow from, the pumping pool	Zero flow
Singleton	no visible inflow to, or outflow from, the pumping pool	Zero flow
Wyong River	combined flows at Wyong River at Gracemere gauge and Jilliby Jilliby Creek at upstream of Wyong River (Durren Lane) gauge are <4 ML/day (Pump A Class); <13.5 ML/day (Pump B Class); <26 ML/day (Pump C Class)	<4 ML/day <13.5 ML/day <26 ML/day

Source: *Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources 2009*; *Water Sharing Plan for the Central Coast Unregulated Water Sources 2009*

Table 39 summarises the increase in the number of cease-to-pump days from the additional coal resource development at model nodes where there was at least a 5% chance of an increase in ZFD or LFD of at least 3 days/year. Baseline cease-to-pump days for 2013 to 2042 are provided for context. Under the baseline, cease-to-pump days are relatively unlikely in Black Creek, Wollombi Brook, Glennies Creek and Foy Brook, whereas in Doctors Creek, Redbank Creek and an unnamed creek in Jerrys water source (node 29), reliability of flow is low as reflected in the high number of cease-to-pump (zero-flow) days even at the 5th percentile. In Doctors Creek, additional coal resource development is predicted to increase the number of cease-to-pump days by a median 34 days, but with some simulations estimating as many as 102 more cease-to-pump days. Redbank Creek, Wollombi Brook, Glennies Creek, Foy Brook, Bayswater Creek, Saltwater Creek, Goulburn River and Dart Brook are unlikely to experience significant change in the reliability of flows due to additional coal resource development.

Potentially significant changes in reliability of flow due to the additional coal resource development are possible for a number of creeks in the Singleton water source, in Saddlers Creek in Jerrys water source, in Dry Creek and an unnamed creek in the Muswellbrook water source, and in the Wyong River. In the Wyong River, the median change over the three 30-year periods is modelled to be between 6 and 8 days, but could be as much as 140 days (95th percentile, 2043 to 2072), noting that these predictions do not take into account the results of modelling using local-scale data from the Wallarah 2 Environmental Imapct Statement.

Table 39 Increase in cease-to-pump days due to additional coal resource development (ACRD)

Node	Watercourse	Water source	Baseline cease-to-pump days			Increase in cease-to-pump days due to ACRD								
			Short-term period (2013–2042)			Short-term period (2013–2042)			Medium-term period (2043–2072)			Long-term period (2073–2102)		
			5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
4	Black Creek	Black Creek	0	0	290	0	0	2	0	0	4	0	0	1
7	Loders Creek	Singleton	0	3	209	0	7	77	0	3	46	0	1	32
8	Doctors Creek	Singleton	58	240	317	7	34	102	4	18	68	0	0	15
9	Loders Creek	Singleton	0	34	277	0	6	58	0	4	62	0	4	53
11	Unnamed Creek	Singleton	0	128	290	1	5	100	0	2	40	0	0	0
13	Redbank Creek	Lower Wollombi Brook	49	166	324	0	0	0	0	0	0	0	0	0
16	Wollombi Brook	Lower Wollombi Brook	0	0	93	0	0	4	0	0	4	0	0	4
17	Wollombi Brook	Lower Wollombi Brook	0	0	40	0	0	1	0	0	2	0	0	1
21	Glennies Creek	Glennies	0	0	15	0	0	1	0	0	0	0	0	0
26	Betty's Creek	Jerrys	0	19	317	0	0	10	0	0	3	0	0	1
27	Swamp Creek	Jerrys	0	0	148	0	0	5	0	0	0	0	0	0
28	Foy Brook	Jerrys	0	0	11	0	0	1	0	0	1	0	0	0
29	Unnamed Creek	Jerrys	97	282	340	2	4	18	0	1	5	0	0	4
30	Bayswater Creek	Jerrys	0	0	299	0	0	5	0	0	2	0	0	2
32	Saltwater Creek	Jerrys	0	0	167	0	0	0	0	0	1	0	0	0
35	Saddlers Creek	Jerrys	0	138	310	0	22	131	0	5	54	0	2	44
38	Goulburn River	Lower Goulburn River	0	0	195	0	0	0	0	0	0	0	0	0
52	Dry Creek	Muswellbrook	0	74	298	0	23	158	0	8	45	0	2	34
55	Unnamed Creek	Muswellbrook	0	82	239	16	59	177	10	31	74	0	13	38
56	Dart Brook	Dart Brook	0	0	161	0	0	2	0	0	3	0	0	1
64	Wyong River	Wyong River	0	63	242	0	7	114	0	8	139	0	6	134
65	Wyong River	Wyong River	0	68	256	0	7	117	0	8	145	0	6	140

Note that the baseline and additional coal resource development values are not additive.
Data: Bioregional Assessment Programme (Dataset 17)

3.5.3.4 Bores where 'make good' provisions might apply (groundwater)

Environmental provisions relating to extractions from aquifers are intended to protect the long-term storage component of the aquifer. Extractions are based on reserving a proportion of recharge for the environment. Cease-to-pump rules are used to restrict pumping when levels drop below some specified level or water quality is deteriorating. The *NSW Aquifer Interference Policy* (DPI Water, 2012), which was introduced in September 2012, is intended to protect groundwater resources from activities that potentially interfere with them. It requires that all water extracted from an aquifer must be accounted for, that the activity must address minimal impact considerations and planning must make provision for situations where actual impacts are greater than predicted.

Minimal impact thresholds are specified for highly productive and less productive groundwater sources and different aquifer types (alluvial, coastal sands, porous rock and fractured rock), but can generally be defined as less than 10% cumulative variation in watertable level, 40 m from any high-priority GDE or culturally significant site, with a maximum decline of 2 m at any water supply work. Where an activity is likely to result in the minimal impact threshold being exceeded, 'make good' provisions should apply, unless it can be demonstrated to the Minister's satisfaction that the variation will not prevent the long-term viability of the GDE or culturally significant site. Here the 'maximum decline of 2 m at any water supply work' threshold is used as the basis for identifying bores where a potential economic impact may result due to the additional coal resource development. It is possible that 'make good' provisions could be required at bores where drawdowns are predicted to be less than the minimal impact threshold, but there is no basis for identifying these in a regional-scale assessment.

Table 40 lists the water sources that have bores within the zone of potential hydrological change with at least a 5% chance of drawdowns exceeding 2 m due to additional coal resource development. Of the 1450 bores in the zone, 170 bores have at least a 5% chance of drawdowns exceeding 2 m due to additional coal resource development; 50 of these are in the mine pit exclusion zone and might be, or have been, removed in the process of mine pit excavation. Using the 50% percentile to define the bores that are 'more at risk of hydrological changes', 51 bores outside the mine pit exclusion zone are considered to be more at risk. Of these, 44 are on exploration or mining leases and are likely to be held by mining companies, and 2 are on exploration leases held by the Secretary of the Department of Planning and Environment. There is at least a 5% chance that the drawdown due to the additional coal resource developments will exceed the minimal impact threshold at 11 bores that are not on mining or exploration leases, of which 5 are considered 'more at risk of hydrological changes'. A summary graphic of potentially impacted bore numbers is provided in Figure 72. The 11 bores that are not on mining or exploration leases relate to extractions permitted under a water access licence, with 7 in the Sydney Basin – North Coast groundwater source, and the others in the unregulated and alluvial water sources of Jilliby Jilliby Creek (2), Tuggerah Lakes (1) and South Lake Macquarie (1). Bores that are 'more at risk of hydrological changes' are the three in the Jilliby Jilliby Creek and south Lake Macquarie water sources, and two in the Sydney Basin – North Coast groundwater source. The location of the 120 bores (95th percentile) are shown in Figure 73.

Table 40 Number of bores where additional drawdown is greater than 2 m for 5th, 50th and 95th percentiles

Water source	In mine pit exclusion zone	Number of bores with additional drawdown >2 m					
		Water access licence			Basic water right		
		5th	50th	95th	5th	50th	95th
Jilliby Jilliby Creek	0	0	8	8	0	0	0
Wyong River	0	0	0	3	0	0	0
Bylong River	13	4	8	21	0	3	4
Dora Creek	0	0	2	2	0	0	0
Hunter Regulated River	1	0	0	0	0	0	0
Jerrys	2	0	0	3	0	0	0
Muswellbrook	0	0	0	2	0	0	0
South Lake Macquarie	0	0	1	1	0	0	0
New England Fold Belt Coast Groundwater Source	1	0	0	0	0	0	0
Oxley Basin Coast Groundwater Source	0	0	0	1	0	0	0
Sydney Basin – North Coast Groundwater Source	33	3	18	60	3	11	15
Total	**50**	**7**	**37**	**101**	**3**	**14**	**19**

Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 15)

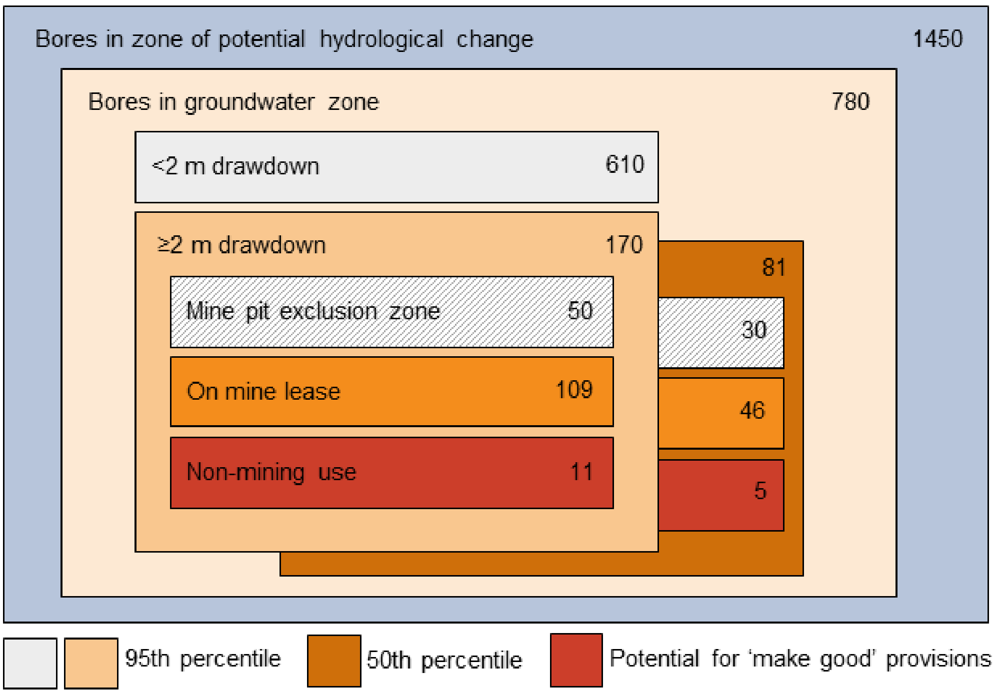

Figure 72 Summary of number of bores in the zone of potential hydrological change (95th percentile), and those with at least 5% and 50% chances that 'make good' provisions due to additional coal resource development could apply

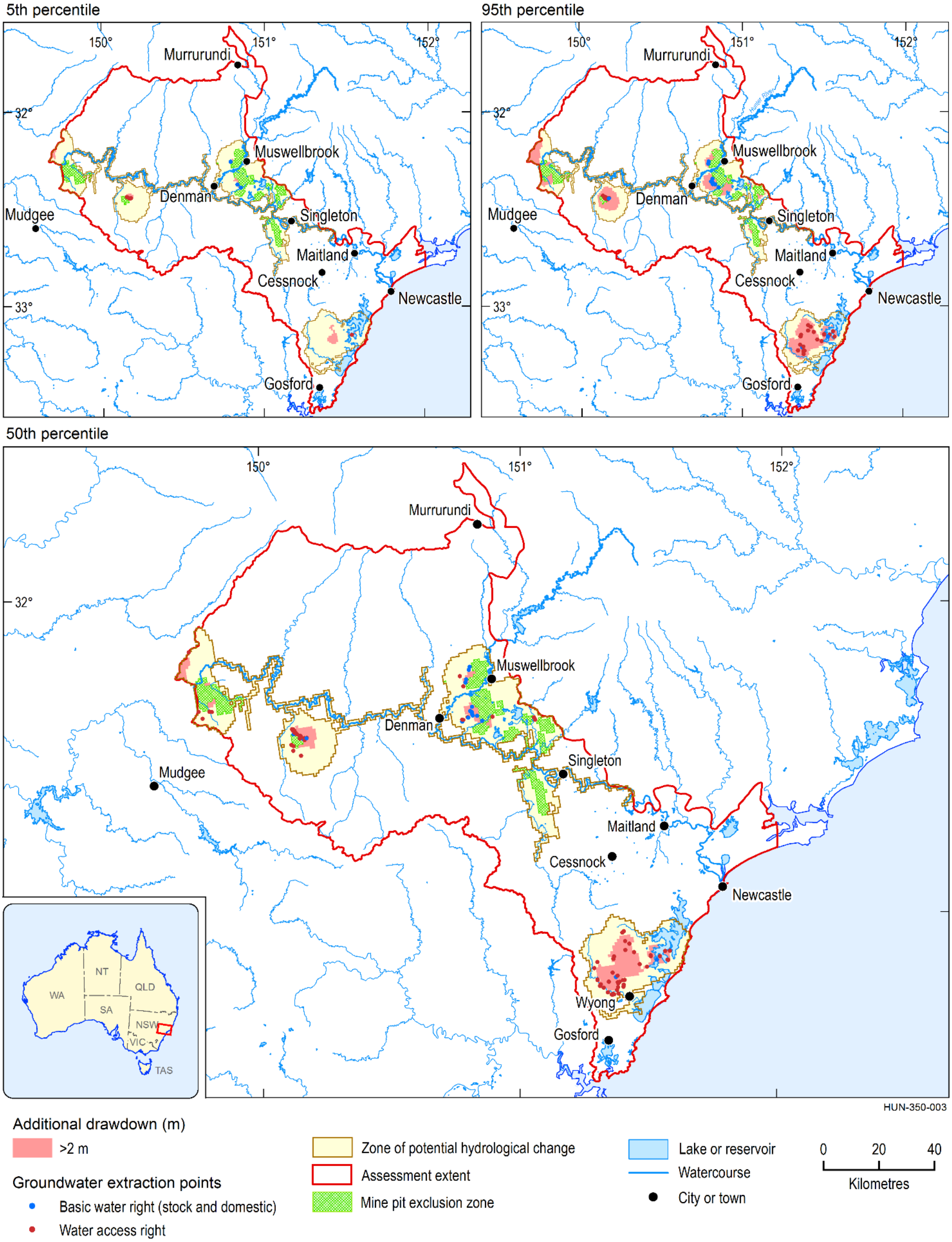

Figure 73 Location of bores with at least a 5% chance of drawdown exceeding 2 m due to additional coal resource development (5th, 50th and 95th percentiles)

Data: Bioregional Assessment Programme (Dataset 8, Dataset 9, Dataset 18)

3.5.4 Sociocultural assets

The water-dependent asset register for the Hunter subregion (companion product 1.3 (Macfarlane et al., 2016); Bioregional Assessment Programme, 2017) contains 307 sociocultural assets that have been deemed to be water dependent. Of these, 5 assets in the 'Social' subgroup and 62 assets in the 'Cultural' subgroup intersect with the zone of potential hydrological change. Thus it is *very unlikely* that hydrological changes associated with coal resource development will affect the remaining 240 sociocultural assets.

The nature of the water dependency for sociocultural assets is vaguely defined, thus it is difficult to comment on the impact of any potential hydrological changes on these assets. Assets were deemed to be water dependent by association with water-dependent landscapes. For example, a heritage-listed building was deemed to be water dependent if it was within 500 m of a water body, for example a river or stream (companion product 1.3 for the Hunter subregion (Macfarlane et al., 2016)). Within the 'Cultural' subgroup of the sociocultural assets that occur within the zone of potential hydrological change, 45 assets listed in the Register of the National Estate are built infrastructure, including four bridges. The Bioregional Assessment Programme does not have the expertise to comment on potential impacts of changes in hydrological regimes on built infrastructure.

The remaining 22 sociocultural assets (17 in the 'Cultural' subgroup and 5 in the 'Social' subgroup) are reserves or national parks. These are composed of a range of water-dependent landscape classes. A breakdown by area or length of each of the landscape groups is given in Table 41. A breakdown of each subgroup by landscape class is provided for the GDE landscape classes in Table 42, for the riverine landscape classes in Table 43 and the coastal lakes and estuaries landscape classes in Table 44.

There are three National Heritage-listed areas within the zone of potential hydrological change in the Hunter subregion as well as one World Heritage Area:

- National Heritage-listed Catherine Hill Bay Heritage Conservation Area
- National Heritage-listed Greater Blue Mountains Area
- National Heritage-listed Rathmines Park
- Greater Blue Mountains Area World Heritage Area.

Owing to the coastal environment of Catherine Hill Bay Heritage Conservation Area and Rathmines Park, it is unlikely that these National Heritage-listed sites will be impacted due to additional coal resource development.

There are 137 km^2 of the Greater Blue Mountains Area World Heritage Area within the zone of potential hydrological change in the Hunter subregion (Figure 74). Of the potentially impacted landscape classes, it is associated with forested wetlands, permanent or perennial streams, and lowly to highly intermittent streams.

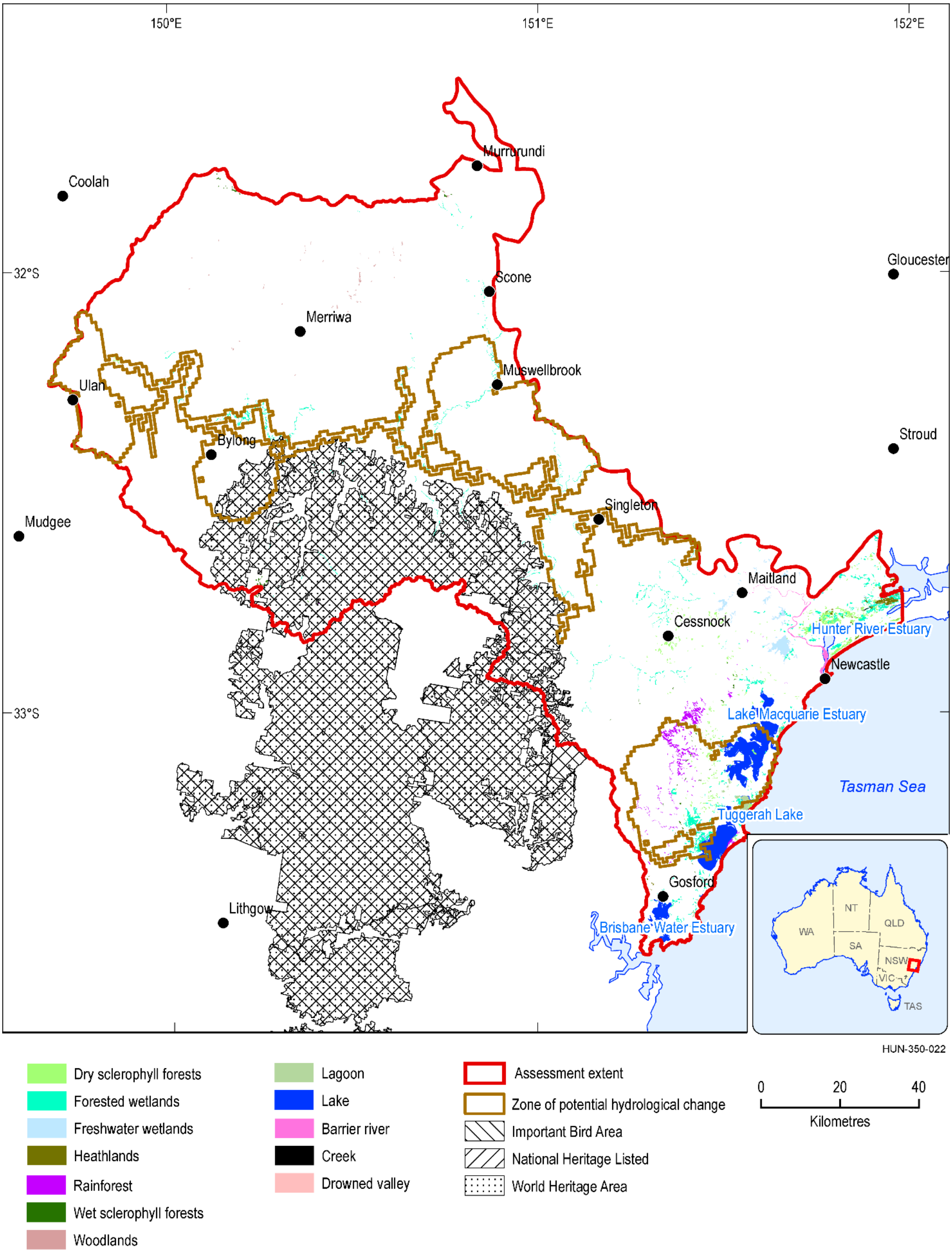

Figure 74 Distribution of selected National Heritage-listed, World Heritage-listed and the Important Bird Area assets associated with the Greater Blue Mountains Area in the zone of potential hydrological change, overlaid with groundwater-dependent ecosystem (GDE) and coastal lakes and estuaries landscape classes

Data: Bioregional Assessment Programme (Dataset 4, Dataset 6, Dataset 7, Dataset 8, Dataset 9)

There are two Indigenous sites within the zone of potential hydrological change in the Hunter subregion:

- Register of National Estate-listed Swansea Heads Area – Lambton Parade, Swansea Heads
- Register of National Estate-listed Bobadeen Area (Hands on the Rock Shelter) – Cassilis Rd, Ulan.

Owing to the coastal environment of Swansea Heads, it is unlikely that this Indigenous site will be impacted due to additional coal resource development. The Bobadeen Area (Hands on the Rock Shelter) is a painted rock shelter containing a frieze of red hand-stencils about 100 m long located near Queens Creek (Moore, 1970). The site has been interfered with, both by humans and by water. The site is located near lowly to highly intermittent streams. An assessment of the potential impact of changed stream hydrology on the site would require a site-specific study.

Table 41 Sociocultural assets in the zone of potential hydrological change: area or length in water-dependent landscape groups

Subgroup	Number of assets	Area in 'GDE' landscape group (km^2)	Stream length in 'Riverine' landscape group (km)	Area in 'Coastal lakes and estuaries' landscape group (km^2)
Cultural	17	2.5	271	0.32
Social	5	10.8	411	0.02
Total	**22**	**13.3**	**682**	**0.34**

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

Table 42 Sociocultural assets in the zone of potential hydrological change: area in landscape classes in the 'GDE' landscape group

Subgroup	Dry sclerophyll forests (km^2)	Forested wetlands (km^2)	Grassy woodlands (km^2)	Wet sclerophyll forests (km^2)	Heathlands (km^2)	Rainforests (km^2)
Cultural	0.06	1.85	0.02	0.04	0.2	0
Social	1.67	8.97	0.14	0.04	0	<0.01
Total	**1.73**	**10.82**	**0.16**	**0.08**	**0.2**	**<0.01**

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

Table 43 Sociocultural assets in the zone of potential hydrological change: length in landscape classes in the 'Riverine' landscape group

Subgroup	Highly intermittent or ephemeral streams (km)	Lowly to moderately intermittent streams (km)	Moderately to highly intermittent streams (km)	Permanent or perennial streams (km)
Cultural	228	18	<1	26
Social	295	56	2	58
Total	**523**	**74**	**2**	**84**

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

Table 44 Sociocultural assets in the zone of potential hydrological change: area in landscape classes in the 'Coastal lakes and estuaries' landscape group

Subgroup	Lakes (km^2)	Saline wetlands (km^2)	Seagrass (km^2)
Cultural	0.03	0.11	0.17
Social	0.02	0	<0.01
Total	**0.05**	**0.11**	**0.17**

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

3.5.5 Potential impacts on an individual asset

It is not possible to report potential impacts on each of the hundreds of individual assets within the zone of potential hydrological change. Instead, an example is provided using multiple lines of evidence to assess potential impacts on an individual asset – the 'potential distribution of Malleefowl (*Leipoa ocellata*)' (asset number 60766). Malleefowl is the only species in the genus *Leipoa* and is listed as vulnerable nationally under the EPBC Act. It is also one of only two iconic species (OEH, n.d.) occurring in the Hunter subregion. The asset was assessed as 'more at risk of hydrological changes' based on the overlap of the asset with assessment units that are potentially subjected to substantial change in a hydrological response variable that is relevant to the receptor impact model for one or more landscape classes that are associated with the asset.

The malleefowl (Figure 75) is a large (1.5 to 2.5 kg) ground-dwelling bird. It differs from other Australian megapodes (i.e. mound-building birds that do not brood) in that it inhabits semi-arid and arid habitats rather than damp forests. Dry regions are not conducive to the methods typically employed for incubating eggs by other megapodes (Frith, 1956); hence, the malleefowl incubates its eggs by building nests in which moist litter is buried beneath a mound of soil. Nests can be up to 1 m high and 3 to 5 m in diameter. Microbial decomposition of the moist litter is an important source of heat for incubation early in the breeding season but later stages of incubation also rely on heating by the sun. In contrast, other species of megapode use large heaps of rotting litter as nests.

Figure 75 Malleefowl

Source: Wikimedia Commons contributors (2017). By butupa (IMGP7721.JPGUploaded by snowmanradio). This figure is covered by a Creative Commons Attribution 2.0 Generic Licence [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons.

The malleefowl once covered much of the southern half of the continent but in southern Australia its distribution has contracted by over 20% since 1981, and the species may now be extinct in the NT (Benshemesh, 2007). It is principally found in shrublands and woodlands dominated by mallee, and associated habitats, but is also found in some *Acacia* shrublands, mulga and eucalypt woodlands. At the eastern limit of its known distribution, to the west of the Hunter subregion, it is associated with red ironbark (*E. sideroxylon*) woodland (Korn, 1989). Clearing of the mallee for wheat and sheep production has been the major factor in the decline of malleefowl in southern Australia, although new threats to remaining areas of habitat are emerging, including mining and other land uses (Benshemesh, 2007). Other threats to the malleefowl include predation by foxes, cats and raptors, large fires, disease, inbreeding, chemical exposure and habitat alteration as a result of climate change (Benshemesh, 2007).

The ‘potential distribution of Malleefowl (*Leipoa ocellata*)’ (asset number 60766) extends beyond the known range of the malleefowl and intersects the westernmost parts of the Hunter subregion, primarily in the Upper Goulburn. The potential geographic extent of this and other species-related assets is based on maximum entropy (MAXENT) modelling that relies largely on physical parameters and past observations of the presence and absence of the species (Elith et al., 2011). There are 296 km^2 of ‘potential distribution of Malleefowl (*Leipoa ocellata*)’ within the zone of potential hydrological change (Table 30). Of this, 267 km^2 were classified as non-GDE vegetation that would not be affected by hydrological changes, while 0.74 km^2 was classified as wet or dry sclerophyll forest and 0.02 km^2 was classified as forested wetland that could be sensitive to hydrological change. The remainder were economic land use landscape classes including ‘Dryland agriculture’, ‘Irrigated agriculture’ and ‘Plantation or production forestry’.

Based on the known habitat preferences of the malleefowl, which include some types of dry sclerophyll forest, the 'potential distribution of Malleefowl (*Leipoa ocellata*)' asset was judged to be associated with wet and dry sclerophyll forests but not forested wetlands or any economic land use landscape classes. Hence, possible impacts on the asset are assessed based on the possible impacts on wet and dry sclerophyll forests, where they are coincident with the asset. The receptor impact model for wet and dry sclerophyll forests, described in Section 3.4.4.2, identified relationships between the hydrological response variable, maximum groundwater drawdown and the receptor impact variable projected foliage cover (see Section 2.7.4.3 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018)). A severe reduction in pfc could indicate a complete change of vegetation state, equivalent to land clearing and complete loss of habitat, while a smaller reduction in pfc could indicate a reduction in primary productivity and litterfall, which could limit the availability of nesting materials or reduce cover needed to avoid predators, thus resulting in reduced suitability of habitat.

As reported in Section 3.4.4.3.1, the receptor impact model predicts little detectable impact on the condition of dry sclerophyll forests in the Hunter subregion due to additional coal resource development; however, there is very high uncertainty surrounding estimates of absolute values. Negative impacts of development on dry sclerophyll forest are most likely in the Macquarie-Tuggerah lakes basin. The area of dry sclerophyll forest within the zone that is also coincident with the 'potential distribution of Malleefowl (*Leipoa ocellata*)' asset, is located in the Goulburn River National Park, along the Goulburn River, 15 to 16 km east-north-east of the town of Ulan, near the northern end of Millers Trail. It intersects eight assessment units in the Upper Goulburn (Figure 76). All of these assessment units lie outside the groundwater zone of potential hydrological change; hence, none of these assessment units is potentially subject to additional drawdown of greater than 0.2 m as a result of additional coal resource development. Therefore, there is little chance of any dry sclerophyll forest that is potential habitat for malleefowl experiencing a hydrological change that is relevant to this landscape class, and little chance of any impact on the suitability of this forest for malleefowl habitat. In conclusion, there is little chance of any impact of additional coal resource development on the 'potential distribution of Malleefowl (*Leipoa ocellata*)' asset.

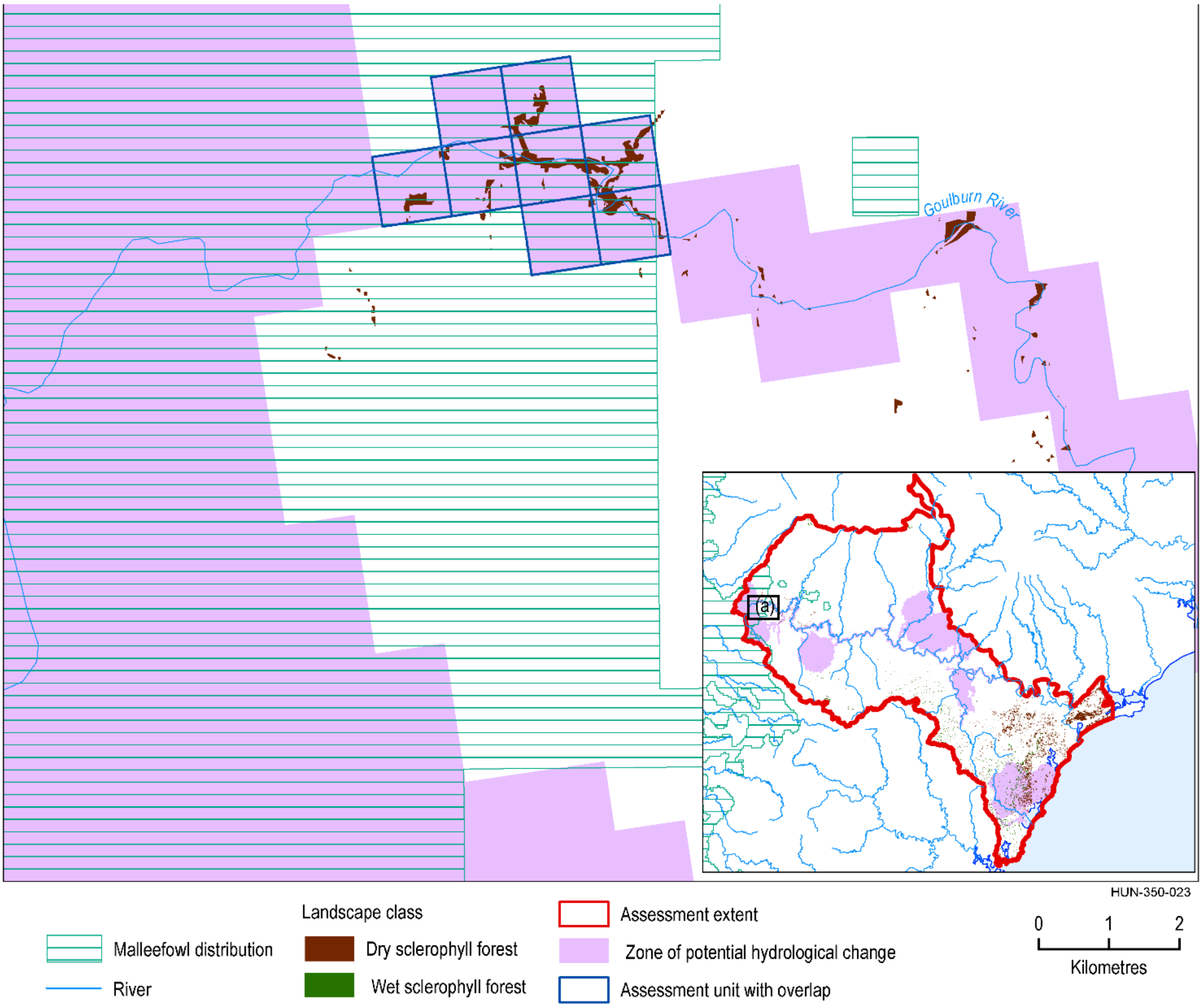

Figure 76 Overlap of the malleefowl distribution with the zone of potential hydrological change and the dry and wet sclerophyll forests landscape classes

Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 7, Dataset 8, Dataset 9)

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3.6 Commentary for coal resource developments that are not modelled

Summary

Seven mining proposals identified as additional coal resource developments as at September 2015 were not included in the surface water and/or groundwater modelling due to the unavailability of data required for the modelling. Based on proposal details, the Austar underground, Chain Valley underground and Mount Arthur open-cut developments were considered unlikely to result in significant hydrological change. The non-modelled Mandalong underground, West Muswellbrook open-cut, Wambo underground and Wilpinjong open-cut additional coal resource developments could increase the regional impact.

Mandalong Southern Extension was not included in surface water modelling. Groundwater modelling results indicate an extensive drawdown zone, which intersects drawdown from Wallarah 2. Modelled changes in the Wyong River flow regime caused by groundwater drawdown and consequent reductions in baseflow from the Mandalong Southern Extension and Wallarah 2 developments suggest that potentially significant changes in the flow regimes of Dora, Mannering, Morans, Stockton, Wallarah and Wyee creeks are likely, with potential impacts on associated forested wetlands and wet and dry sclerophyll communities.

The West Muswellbrook Project is a new proposal for two open-cut pits and site facilities, 12 km north-west of Muswellbrook. Its effect on catchment runoff, groundwater drawdown and baseflow would likely compound changes from the nearby additional coal resource developments at Mount Pleasant and Bengalla and baseline developments at Mangoola and Dartbrook. Based on predictions of drawdown from the modelled additional coal resource development, it is likely the West Muswellbrook mine would expand the groundwater zone of potential hydrological change further into Wybong Creek, increasing the potential for impacts on Wybong Creek flow, and contribute to greater reductions in baseflow to the Hunter River and its tributaries, including Dartbrook.

The Wambo underground additional coal resource development proposal comprised three new longwall panels under existing panels. Increases in mine water extraction are estimated at about 54 ML/year. Modelling of drawdowns from the nearby Mount Thorley–Warkworth mine, which has significantly higher pumping rates, suggests that the impact of the additional coal resource development at Wambo will be fairly contained. Some additional hydrological changes at nearby woodland and forested wetland groundwater-dependent ecosystems (GDEs), which are potentially impacted under the baseline, cannot be ruled out.

At Wilpinjong mine, the additional coal resource development would increase the area of existing open-cut pits by 500 ha and develop an eighth pit of approximately 300 ha. It was not included in the groundwater modelling, and although the change in catchment runoff was modelled, the river modelling does not include changes in baseflow. Having regard to the groundwater modelling and site-scale modelling for the bioregional assessment of the Hunter subregion, it is possible that drawdowns due to additional coal resource development could extend towards, and potentially affect baseflow into, the Goulburn River. Wollar Creek – 2 km to the east – could also be affected, given its proximity and that it is potentially affected under the baseline. The potential for some impact on nearby GDEs, at the very least a prolonging of baseline effects due to the 7-year extension to operations under the additional coal resource development proposal, cannot be ruled out.

3.6.1 Non-modelled and partially modelled additional coal resource developments

A number of mining proposals in the Hunter subregion were identified as additional coal resource developments (as at September 2105) based on the Bioregional Assessment Programme’s definition but not included in the surface water and/or groundwater model simulations. The reasons for not including these developments are discussed in companion product 2.3 for the Hunter subregion (Dawes et al., 2018), and are also provided in Table 45. Figure 77 shows the location of these additional coal resource developments in relation to the zone of potential hydrological change.

Table 45 Reasons for not modelling some mines comprising the additional coal resource development

Mine	Company	In SW model	In GW model	Reasons for not modelling
Austar UG	Yancoal	No	No	The proposed modification entails retractions and/or extensions of four approved longwall panels, resulting in a net increase in footprint area of 5–10% of baseline extent and no change in approved mine pumping rates.
Chain Valley UG	Lake Coal (LDO Group)	No	Yes	Mine footprint is under Lake Macquarie. Surface water models not able to represent hydrological changes.
Mandalong Southern Extension UG	Centennial Coal	No	Yes	No stream network represented in the groundwater model in this area, therefore no modelled baseflows. Changes to streamflow could not be modelled properly without the changes in baseflow.
Mount Arthur OC	BHP Billiton	Yes	No	Small increase in existing open-cut mine footprint. Groundwater model is not sensitive to this scale of change.
Wambo UG	Peabody Energy	No	No	Insufficient data to represent in groundwater models. Additional panels all underlie already approved panels and use existing site facilities, so no additional impact at surface to that under baseline conditions.
West Muswellbrook OC	Muswellbrook Coal Company	No	No	Insufficient data to represent in surface water and groundwater models.
Wilpinjong OC	Peabody Energy	Yes	No	Insufficient data to represent in groundwater models. No environmental impact statement available.

GW = groundwater, OC = open-cut, SW = surface water, UG = underground

Since September 2015, Glencore and Peabody Energy have submitted a joint proposal – United Wambo Open Cut Coal Mine Project (Umwelt, 2016) – which includes a northwest extension to the existing open-cut pit at Wambo and establishment of a new pit between the existing Wambo pit and the Hunter Valley Operations open-cut mine. The potential implications of this development are not considered here.

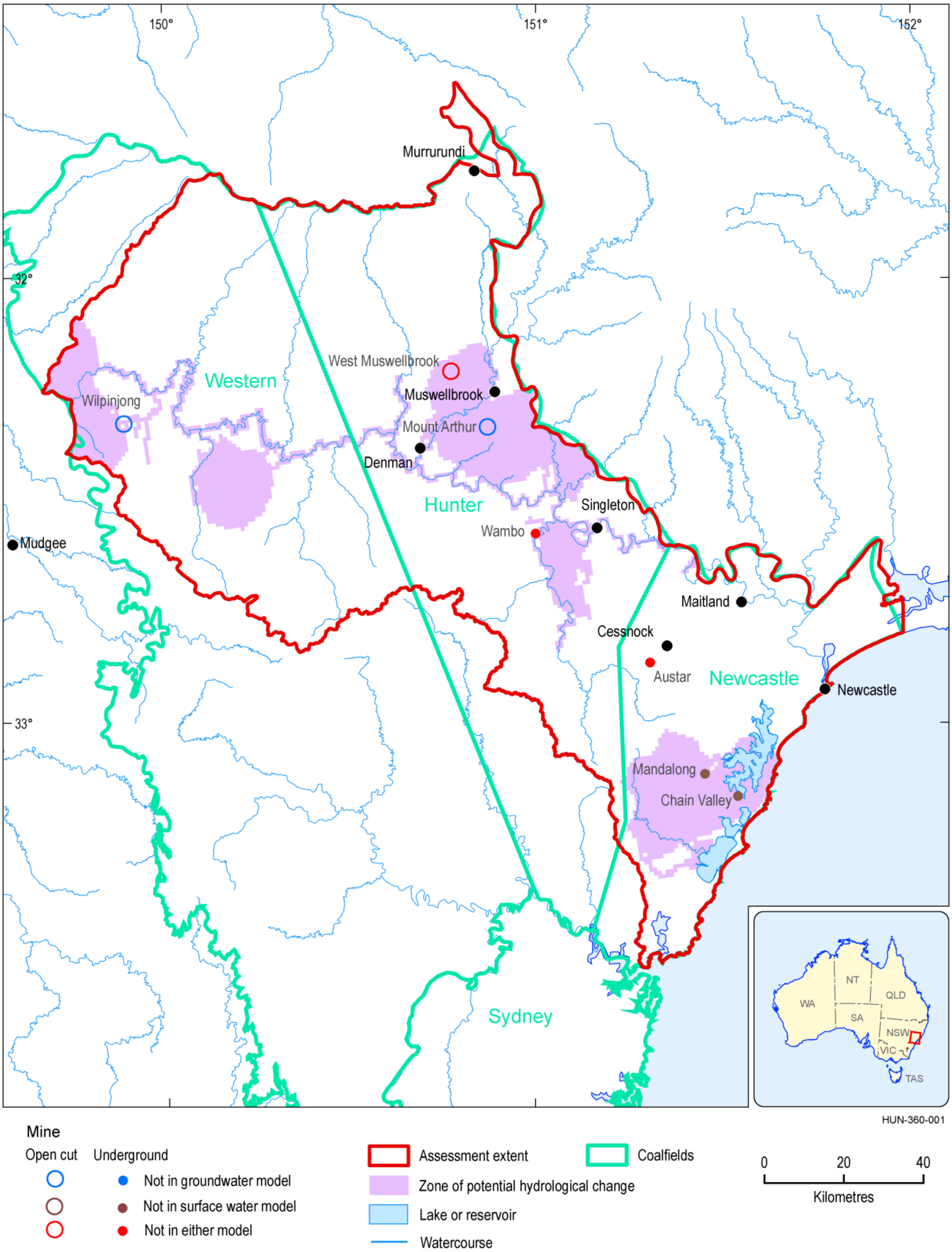

Figure 77 Location of additional coal resource developments that were not included in surface water and/or groundwater modelling

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

Details of the proposals for a number of the non-modelled and partially modelled additional coal resource developments in Table 45 indicate negligible hydrological changes, and therefore the potential for adverse impacts on water-dependent landscape classes and assets is deemed unlikely. These are the Austar underground, Chain Valley underground and Mount Arthur open-cut proposed developments:

- **Austar underground** – The proposed change at Austar underground mine involves minor modifications to longwall panels approved in September 2009 (MOD 3, Project Approval 08_0111), which would give access to an additional 1.05 Mt of run-of-mine (ROM) coal. These modifications entail retraction of starting locations due to structural constraints and/or extension at the other end of four Stage 3 longwall panels (LW A7-A10). The result is a net increase in longwall extent of 5 to 10% or less than 1% of the total baseline footprint, no change in approved mine pumping rates, no change to the rate of extraction, and no change to the life of the approved operations. An assessment of the proposed changes on groundwater indicated no significant changes to predictions for the approved longwall layout (Umwelt, 2013a). The modifications to Project Approval 08_0111 were signed off by the Minister for Planning and Infrastructure on 17 December 2013 (NSW Planning and Infrastructure, 2013).
- **Chain Valley underground** – The proposal involves expansion of the approved underground extraction area, an increase in the maximum rate of production and extension of the approved mining period by 14 years. The area of expansion is entirely under Lake Macquarie, which is connected to the ocean by a small channel. The bioregional assessment (BA) surface water models are not intended for use in lacustrine and tidal environments, but even if they were, the effects of subsidence on surface water hydrology are likely to be negligible given the large area of lake and connection to marine waters. The groundwater effects are modelled, but not mine subsidence. At the expert elicitation workshop for coastal landscape classes, impacts on the lagoons, seagrasses, mangroves and saline wetlands from additional coal resource development were considered unlikely because of existing regulatory requirements for managing subsidence, an unknown dependence of seagrass and lake connection to regional groundwater, and the connection to marine waters. These landscape classes were ruled out as unlikely to be impacted due to additional coal resource development (see companion product 2.7 for the Hunter subregion (Hosack et al., 2018)).
- **Mount Arthur open-cut** – The proposal to expand the area of open-cut was not modelled in the groundwater model because the area of expansion is small (235 ha) and spans a long, narrow belt (i.e. too narrow to represent at the resolution of the model), and the expansion is not predicted to increase mine water inflow rates (AGE, 2013). It was not included in the groundwater modelling of the coal resource development pathway (CRDP) based on the assumption of negligible changes in drawdowns and surface water – groundwater fluxes and, by extension, no additional impacts on landscape classes and assets. The hydrological changes from disruption of surface drainage were captured in the surface water modelling results.

The remaining non-modelled or partially modelled mines in Table 45 could potentially result in hydrological changes off site. The implications on surface water and groundwater hydrology, and in turn landscape classes and assets, from the Mandalong underground, West Muswellbrook open-cut, Wambo underground and Wilpinjong open-cut additional coal resource developments are considered in Section 3.6.2.

3.6.2 Potential impacts of non-modelled additional coal resource developments

3.6.2.1 Mandalong Southern Extension (underground)

The Mandalong Southern Extension (Mandalong SE) Project involves expanding Centennial Coal's existing underground operations into the Exploration Licence 6317 area (the Southern Extension Area), approximately 4470 ha of land south of existing workings (Figure 78). This represents a 50% increase on the 9000 ha of operations under development consent 97/800. The proposed development would extend the life of Mandalong's underground operations by 21 years to 2040. Development consent SSD-5144 was granted by the Planning and Assessment Commission on 12 October 2015.

The surface mine footprint will include parts of Morans Creek (which flows into Stockton and then Dora creeks), Wyee Creek and Mannering Creek catchments, which drain into Lake Macquarie; and Buttonderry Creek catchment, which drains into the Wyong River. The streams overlying the site are typically first- and second-order streams, with some third-order streams, and are ephemeral (Umwelt, 2013b). Subsidence modelling suggests there will be some vertical subsidence, but that connective cracking is unlikely (Ditton Geotechnical Services, 2013). The predicted subsidence was not identified as affecting catchment boundaries or stream alignments (Umwelt, 2013b). There may be an increase in scouring along some creeks, but negligible increase in areas affected by ponding (3.6 ha).

Drawdown from mine dewatering and the consequent effect on fluxes of groundwater to streams are likely to have a larger effect on streamflow hydrology than changes in surface runoff from disruption of natural drainage. Mine dewatering is predicted to increase to 2154 ML/year from the 1825 ML/year approved under Mandalong's current dewatering licence (20BL169424). Drawdowns have been modelled as part of the BA for the Hunter subregion, but model nodes were not specified for any of the draining streams and the change in the groundwater flux to streams was not computed. Results from the Wallarah 2 underground mine in the adjacent Wyong river basin provide some insights into potential effects on streamflow hydrology. A comparison of the groundwater modelling parameters for the two mines, extracted from Table 23 in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a), is provided in Table 46. In summary, Mandalong SE covers a larger area, extraction is on average at a shallower depth, maximum flow rates are almost 2.5 times higher, and the period of extraction (as modelled) is slightly shorter. Thus, maximum drawdown of the regional watertable from mining of Mandalong SE is predicted to be greater than from mining at Wallarah 2 (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b); and Figure 18 of this product). The implications are that streamflow in perennial and intermittent streams that drain the Mandalong SE area will experience potentially significant changes in hydrology, similar to the changes modelled in the

Wyong River (see Section 3.3.3). Potentially affected streams include Dora, Mannering, Morans, Stockton, Wallarah and Wyee creeks (Figure 78). Monitoring of these streams will contribute to understanding the hydrological effects and impacts on instream habitat of the additional coal resource development in this area. Quantification of changes in the number of zero-flow days per year and duration of zero-flow day spells would enable a preliminary assessment of the risk to instream habitat using the Hunter subregion receptor impact models for perennial streams and intermittent streams (see companion product 2.7 for the Hunter subregion (Hosack et al., 2018)), with local information used to better resolve the magnitude of risk.

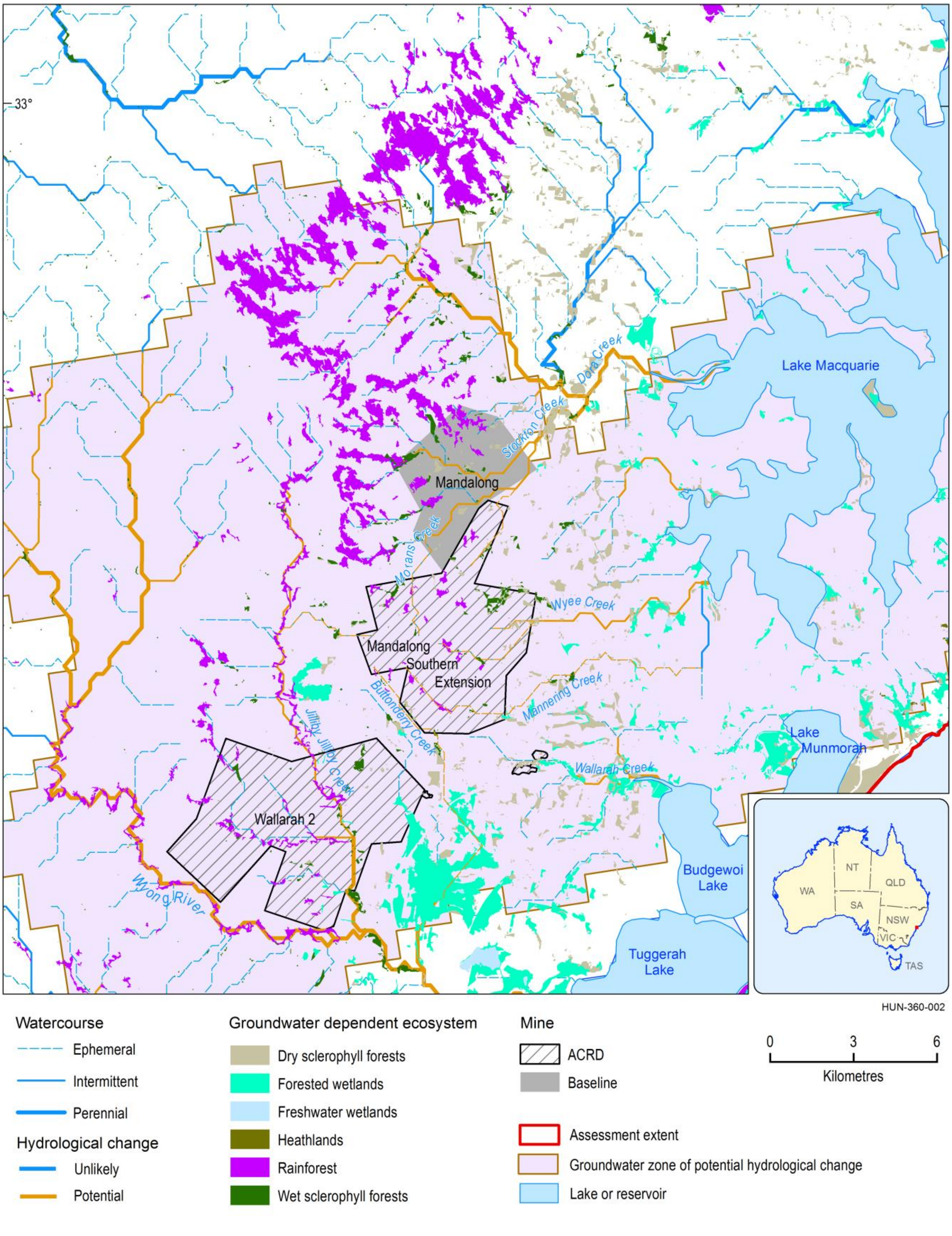

Figure 78 The Mandalong Southern Extension Project area

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 6)

Table 46 Groundwater model input parameters for Mandalong Southern Extension and Wallarah 2 underground mines

Mine	Maximum footprint area (ha)	Minimum extraction depth (m)	Maximum flow rate (ML/y)	Period of mine dewatering
Mandalong Southern Extension	4401	280	2154	2015–2052
Wallarah 2	3750	412	876	2018–2058

Similarly, the forested wetlands and wet and dry sclerophyll forest communities that occupy the riparian lands along some of these creeks could be affected by the additional coal resource development. Better understanding of the groundwater dependency of the wet and dry sclerophyll forest communities and streamflow and alluvial groundwater dependencies of the forested wetlands in this area will assist in assessing the risk to their persistence and condition from coal mining induced groundwater drawdowns and streamflow changes.

3.6.2.2 Wambo underground

The Wambo coal mine is located in the Hunter Coalfield 30 km west of Singleton. Nearby mines include Hunter Valley Operations to the north and Mount Thorley–Warkworth and Bulga mine complexes to the south-east. The Wambo additional coal resource development relates to Modification 15 to Development Consent 305-7-2003 to access coal reserves in the Wambo seam underneath the approved South Bates underground mine (Whybrow seam). The proposal is for three additional longwall panels (14–16) under already approved panels (11–13). From a surface water perspective, the new panels will result in negligible additional disturbance to surface drainage and no change to water demand and supply, and were therefore deemed to not affect catchment runoff. This is consistent with conclusions from the surface water impact assessment (Advisian, 2015) prepared as part of the Environmental Assessment (Resource Strategies, 2015) for South Bates underground mine. The environmental assessment concluded that there could be some additional surface cracking above panels 15 and 16 at the North Wambo Creek diversion end, however changes in drainage due to cracking were not part of the surface water modelling for the subregion.

The groundwater modelling for the subregion did not include the Wambo additional coal resource development, thus the modelled predictions do not take account of the effect of regional watertable drawdown from dewatering the Wambo seam, below the Whybrow seam. In the groundwater assessment (Hydrosimulations, 2015a) undertaken as part of the Environmental Assessment, peak inflow rates were estimated to increase to 179 ML/year from 124 ML/year under the approved layout. Since the location of the new panels is the same as that for panels 11 to 13 (except deeper), and since a multiplier was used in the uncertainty analysis to vary the inflow rates between 0.5 and 1.5 of the specified input rates, baseline results based on the 1.5 multiplier can be interpreted as broadly consistent with inclusion of additional coal resource development. Hydrosimulations (2015a) modelling results suggested no significant change to the regional watertable from dewatering of the Wambo Seam and no discernible change to baseflow.

The groundwater modelling of the likely change in drawdown due to additional coal resource development at the nearby Mount Thorley–Warkworth (about 2 km away at closest points), which has a bigger maximum footprint and peak flow rates of 1560 ML/year, suggests that a 5% chance of >0.2 m drawdowns will not extend west of Wollombi Brook. The drawdown associated with an increase in flow rates of 54 ML/year at Wambo is likely to be comparatively small. The Ashton South East Open Cut additional coal resource development has a similar peak inflow rate (51 ML/year) and results indicate that its contribution to drawdown of the regional watertable is negligible. While the Wambo mine is 2 km from the Mount Thorley–Warkworth development, modelling results for Mount Thorley–Warkworth and Ashton South East Open Cut suggest a low likelihood that drawdown of the regional watertable from the Wambo additional coal resource development will intersect the drawdown cone from Mount Thorley–Warkworth. However, it cannot be ruled out. The generalised 'worst case' estimate of drawdown extent from the Hunter groundwater modelling (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)) suggested that the drawdown extents from mines within 20 km could potentially intersect. More likely, any additional drawdown will be localised and impact very local intermittent streams such as Stony Creek and North Wambo Creek.

Figure 79 includes the greater than 0.2 m drawdown under the baseline. Woodland GDEs to the north-west and forested wetland GDEs to the north and south are potentially impacted due to baseline developments, which include mining at Wambo. It is possible that the drawdown due to additional coal resource development could compound hydrological changes in these GDEs, but the significance of additional drawdown, on top of what is predicted under the baseline, is unknown.

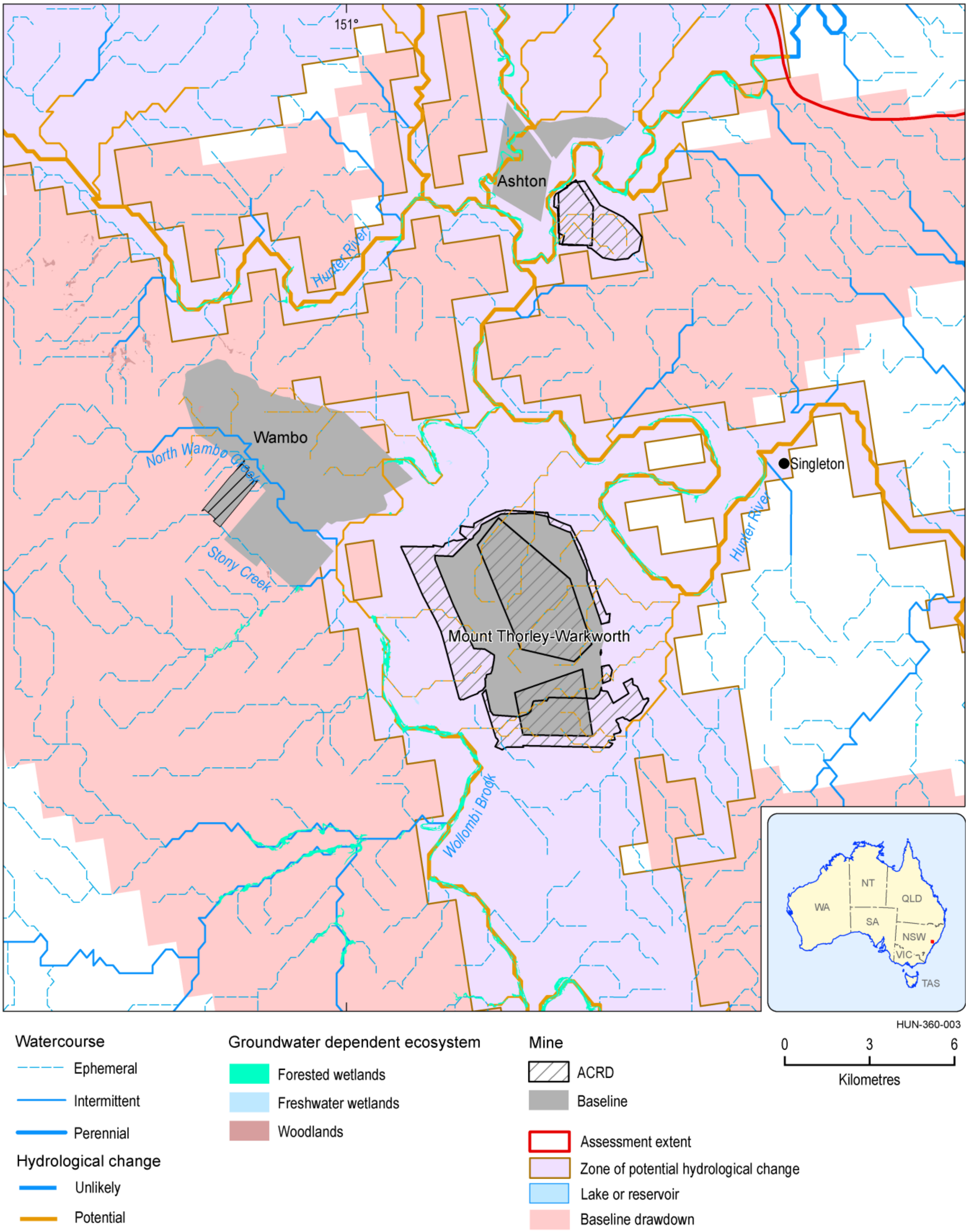

Figure 79 The Wambo baseline mine area

Drawdown under the baseline is shown to identify the area potentially affected by existing operations. The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 6)

3.6.2.3 West Muswellbrook open-cut

The West Muswellbrook Project is a new development proposal in the Hunter Coalfield for two open-cut pits and associated infrastructure in Assessment Lease 19, approximately 12 km north-west of Muswellbrook (Figure 80). The development would operate over 30 years and disturb an area of approximately 5620 ha, including diversion of a creek (IESC, 2015). At the time the CRDP was being defined, this proposal had not progressed beyond a Gateway application and there were insufficient details available to enable modelling as part of the additional coal resource development. As of December 2016, an environmental assessment had not been lodged.

The proposed development is located to the west and north-west of, but in proximity to, Dartbrook, Mount Pleasant and Bengalla mines and to the north-east of Mangoola mine. At its closest points, the mine footprint is about 10 km east of Wybong Creek itself, but less than 3 km from some of its tributaries; and 5 km from Dart Brook. The effects on catchment runoff, groundwater drawdown and changes in groundwater fluxes to streamflow are expected to compound any changes from the additional coal resource developments at Mount Pleasant and Bengalla, and also from the baseline developments at Mangoola mine, which is approved to 2026, and Dartbrook, which has been in care and maintenance since 2007, but looks set to re-open following its acquisition by Australian Pacific Coal Ltd in 2016.

Based on predictions of drawdown from the modelled additional coal resource development, drawdowns of at least 0.2 m are *very likely* within a 5 km radius of the mine footprints with a possibility of extending to about 20 km away (companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)). Thus it is likely that the West Muswellbrook Project would expand the groundwater zone of potential hydrological change further into the Wybong Creek catchment to the west of the development, particularly if the drawdowns from Bengalla, Mount Pleasant and West Muswellbrook compound each other. Under the modelled additional coal resource development, which included Bengalla and Mount Pleasant developments, the hydrological modelling indicated a possibility of increases in the number of low-flow spells in Wybong Creek. With the addition of the West Muswellbrook open-cut mines, it is likely that Wybong Creek will experience changes in flow regime across more of the hydrological response variables than just the low-flow spells. Monitoring of groundwater levels and streamflow in the Wybong Creek catchment would enable the impacts of the West Muswellbrook and neighbouring mines to be determined.

Similarly, to the north and east, it is likely that groundwater drawdowns will extend further into the Dart Brook catchment and potentially enhance drawdowns from the Mount Pleasant and Bengalla mines near the Hunter River. Greater reductions in baseflow in the lower Dart Brook and along parts of the Hunter River cannot be ruled out. Both Sandy Creek North and Sandy Creek South, which flow out of the proposed mine area, are in the zone of potential hydrological change due to the Mount Pleasant and Bengalla developments. It is likely that these streams would experience larger hydrological changes if the West Muswellbrook mine was included in the modelling. Some ephemeral streams in these catchments will be directly impacted by the excavation of the mine pits.

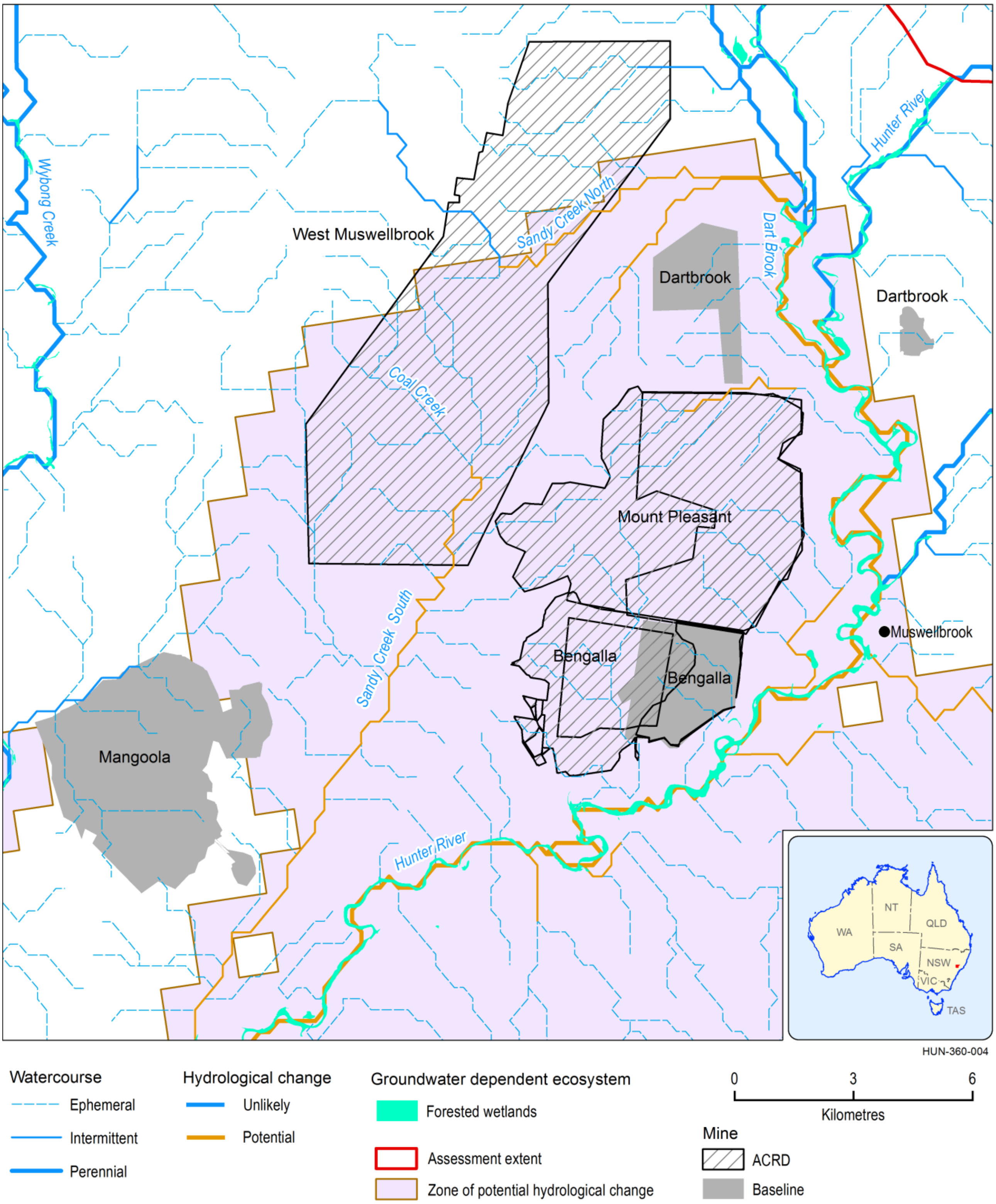

Figure 80 The proposed West Muswellbrook Project area

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 6, Dataset 7)

Since the Hunter River has minimum environmental flow requirements specified in the regulated river, any reductions in tributary inflows could mean additional releases of water from Glenbawn Dam would be needed to ensure the minimum flow condition is met. However, the analysis of changes in environmental water releases presented in Section 3.5.3.3 for the modelled additional coal resource development suggests that additional releases would be relatively small.

In Figure 80, it can be seen that some additional areas of forested wetlands on Wybong Creek to the west and on Dart Brook and Kingdon Ponds to the north-east of the proposed mine could potentially be affected by the West Muswellbrook development.

3.6.2.4 Wilpinjong open-cut

Wilpinjong Mine is located in the Western Coalfield and comprises seven open-cut pits. The additional coal resource development is a proposal to increase the area of existing open-cut pits by incremental additions totalling 500 ha, and develop an eighth pit of approximately 300 ha (Figure 81), which together would necessitate some infrastructure changes and extend the life of the operation by 7 years. The proposal requires no changes to key sources of water supply (i.e. runoff collected on site, dewatering of open-cut pits and groundwater), nor to water disposal as per the existing Environment Protection Licence 12425. The proposed changes on catchment runoff have been modelled as part of this Assessment, but the river modelling does not include changes in baseflow from this development because it was not included in the groundwater modelling (noting that the information summarised below was released in 2015 after the BA groundwater model was set up). Pit inflows have been predicted as part of the groundwater assessment (Table 6-6, Hydrosimulations, 2015b) for the Wilpinjong Extension Project Environmental Assessment. (Peabody Energy, 2015). They are predicted to reach a maximum of 1269 ML/year in 2018 to 2019 across the eight pits, decreasing to 10 ML/year by 2034 when mining ceases. The inflow predictions do not differentiate the baseline and additional coal resource development components, except for the new pit (pit 8), which represents about 30% of the inflow rate in 2018 to 2020, but significantly lower proportions in other years. The extra 7 years of operations are associated with predicted inflow rates of between 263 and 753 ML/year.

The Hydrosimulations (2015b) groundwater assessment found considerable drawdown of the watertable at the pit margins, but overall watertable drawdowns were laterally restricted with only limited areas of drawdown of 1 to 2 m further away from the mine pits. Drawdowns were predicted to induce a flux of water from the Wollar Creek alluvium (up to 170 ML/year during the period of mining) with peak baseflow reductions in Wilpinjong Creek and Cumbo Creek of 0.47 ML/day (cf. 0.48 ML/day from prior modelling of baseline development).

Considering the groundwater modelling of the baseline and additional coal resource development mines, and Hydrosimulations' (2015b) predicted mine inflow rates and results from site-scale modelling, it is probable that the drawdown cone associated with additional coal resource development could extend towards the Goulburn River in the north and potentially affect baseflows in the Goulburn River. At the 95th percentile under the baseline, drawdowns exceeding 0.2 m are predicted under a stretch of the Goulburn River (Figure 20 in Section 3.3). However, it is unclear the extent to which the operations at Wilpinjong are contributing to this, since the Ulan and Moolarben mines are closer to this area and the effects of the mines were not modelled individually.

Wollar Creek, 2 km to the east of the eastern edge of the Wilpinjong operation, could also be affected given its proximity and that it is potentially affected under the baseline (Figure 81). The potential for some impact on nearby streams, at the very least a prolonging of baseline impacts due to the 7-year extension to operations under the additional coal resource development proposal, cannot be ruled out.

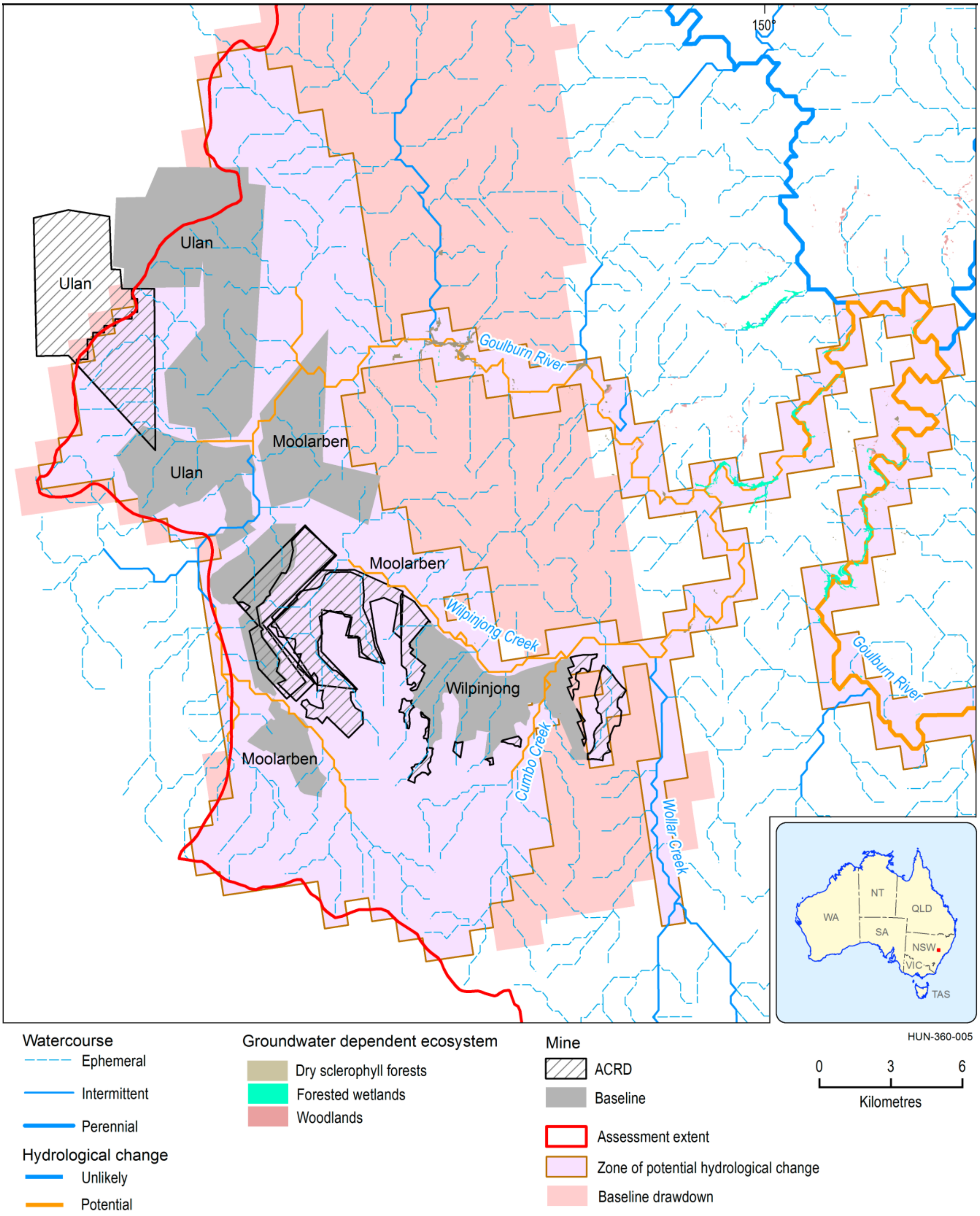

Figure 81 The Wilpinjong mine and associated drawdown extent under the baseline and due to additional coal resource development

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 6)

The GDEs in the vicinity of Wilpinjong mine include forested wetlands, dry sclerophyll forests and woodlands. All of these are in the zone of potential hydrological change for the modelled additional coal resource development. The additional drawdown from representing the Wilpinjong mine is unlikely to impact on additional GDEs, but could enhance the hydrological changes at the sites that have already been identified as potentially impacted. The area of greater than 0.2 m of drawdown under the baseline, shown in Figure 81, does not intersect any additional GDEs to those already identified as being in the zone. Additional drawdown from the new pit and nearby workings (on the eastern side of the Wilpinjong mine site) could increase the impact on a small area of dry sclerophyll forest on Wilpinjong Creek and potentially some forested wetlands on the Goulburn River (downstream of the junction with Wollar Creek), but most of the streams in this area are mapped as ephemeral and would be unlikely to be affected if the drawdown area were larger.

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Dataset 2 NSW Trade and Investment (2011) NSW Coalfield boundaries. Bioregional Assessment Source Dataset. Viewed 05 May 2017, http://data.bioregionalassessments.gov.au/dataset/c93d9cbc-22f9-459d-a2d8-e530332393b0.

Dataset 3 Bioregional Assessment Programme (2016) HUN Landscape Classification v03. Bioregional Assessment Derived Dataset. Viewed 05 May 2017, http://data.bioregionalassessments.gov.au/dataset/79a84caf-2782-4088-b147-ac47f50b52ac.

Dataset 4 Bioregional Assessment Programme (2016) HUN SW GW Mine Footprints for IMIA 20160908. Bioregional Assessment Derived Dataset. Viewed 05 May 2017, http://data.bioregionalassessments.gov.au/dataset/b45ee133-cc63-44bc-b10f-6642b26a9e40.

Dataset 5 Bioregional Assessment Programme (2017) HUN ZoPHC and component layers 20170220. Bioregional Assessment Derived Dataset. Viewed 05 May 2017, http://data.bioregionalassessments.gov.au/dataset/eb09503b-26ad-4ef5-9056-5672412aac67.

Dataset 6 Bioregional Assessment Programme (2017) HUN Analysis boundaries 20170106 v03. Bioregional Assessment Derived Dataset. Viewed 05 May 2017, http://data.bioregionalassessments.gov.au/dataset/20d25db8-75fd-46f2-a64c-c249c8b40a95.

Dataset 7 Bioregional Assessment Programme (2017) HUN West Muswellbrook Mine Assessment area v01. Bioregional Assessment Derived Dataset. Viewed 17 May 2017, http://data.bioregionalassessments.gov.au/dataset/2c70644b-19cd-443f-8a27-fc3c7ea97134.

3.7 Conclusion

Summary

The bioregional assessment (BA) of the Hunter subregion has identified a risk of potentially significant hydrological changes and ecosystem impacts due to additional coal resource development in a small number of catchments within the subregion. These include the perennial Wyong River and potentially Dora Creek in the Macquarie-Tuggerah lakes basin; relatively small intermittent streams – Loders Creek, Saddlers Creek, Dry Creek and a couple of unnamed streams – that drain additional coal resource developments in the Hunter Coalfield; and the intermittent Wollar Creek in the Western Coalfield.

Larger changes are associated with the low-flow part of the flow regime in these systems, including the number of zero-flow days per year.

Results from receptor impact modelling suggest a risk to the instream habitat of Wyong River due to modelled changes in zero-flow days. However, when the predictions of groundwater drawdown are constrained using local hydrogeological information, the impacts on Wyong River flow are substantially smaller and less likely to lead to adverse ecological impacts.

Potentially large impacts on instream habitat of intermittent streams may occur in Loders Creek and Saddlers Creek. Forested wetlands along the Goulburn River could also experience changes in projected foliage cover. Decreases of up to 0.1 in projected foliage cover are possible, although median results indicate the likelihood of negligible change due to additional coal resource development.

The BA of the Hunter subregion has been conducted using the best available information within the operational constraints and timing of the Bioregional Assessment Programme. There are opportunities to build on this Assessment and address science gaps to reduce predictive uncertainty and improve the utility of the results.

The Assessment is regional and cumulative, and provides an important framework for local-scale environmental impact assessments of new coal resource developments, and the local geological, hydrogeological and hydrological modelling that support them. The results do not replace the need for detailed site-specific studies, nor should they be used to supplant the results of detailed studies that may be required under state legislation. There are opportunities to tailor the BA modelling results for more local analyses (e.g. combining detailed local geological information with the groundwater emulators developed through BA, where appropriate).

There are also opportunities to consider alternative futures through different combinations of these developments and the inclusion of new developments, or to assess the potential impact of individual or small groups of developments.

Incorporating additional data that were not readily available at the time the geological model was constructed might reduce some of the uncertainties carried forward into the hydrological

modelling. These additional data would include well and bore logs and seismic data. The greatest potential to reduce predictive uncertainty lies in better characterisation of hydraulic properties of the sedimentary rocks, especially the porosity and storage parameters.

Improved mapping of depth to groundwater, including its spatial and temporal variation, has potential to constrain drawdown and baseflow predictions, and provide better context for interpreting the ecological impacts due to hydrological change. Interactions between changes in groundwater availability and the health and persistence of terrestrial groundwater-dependent vegetation remain uncertain due, in part, to sparse mapping of groundwater depths outside of alluvial layers.

More closely coupled surface water and groundwater models could incorporate feedback mechanisms not included in the current Assessment. This could reduce predictive uncertainty and help to ensure that any dependencies between hydrological response variables, particularly between groundwater and surface water hydrological response variables, is carried through to receptor impact modelling.

A more extensive set of surface water model nodes would improve the interpolation of surface water hydrological response variables, resulting in more reaches with quantifiable changes and fewer stream reaches assessed as 'potentially impacted'.

Additional high-resolution vegetation mapping and ongoing research to identify groundwater-dependent ecosystems (GDEs) in the subregion would improve the assessment of impacts on water-dependent assets. Receptor impact models and qualitative models for the 'Forested wetland', 'Freshwater wetland' and 'Rainforest' landscape classes contain knowledge gaps or are not considered appropriate for subsets of those landscape classes.

Identifying water-dependent assets valued by the local Indigenous communities would provide a more comprehensive account of sociocultural assets, even if many of those assets are already in the water-dependent asset register through other sources, for example, a wetland may have both ecological and Indigenous value.

Future monitoring of groundwater levels in the five discrete drawdown zones due to additional coal resource development is recommended. Suggested priorities, based on potentially impacted bores, are the Sydney Basin – North Coast groundwater source and Jilliby Jilliby, Tuggerah Lake and South Macquarie Lake water sources, and the area west of the proposed West Muswellbrook mine, where it appears likely that drawdown from this development will extend into that from other nearby mines.

It is recommended that the streams modelled to experience large changes in flow regime, particularly the Wyong River, but also possibly Loders Creek, Saddlers Creek and Wollar Creek, be monitored. Local information is needed to better determine the priorities. Streamflow monitoring could be of value for Dora, Mannering, Morans, Stockton, Wallarah and Wyee creeks given potential changes in flow regime that may arise from the proposed Mandalong Southern Extension and Wallarah 2. Monitoring of the Goulburn and Hunter rivers should continue, given potential changes in baseflow. Additional streamflow monitoring in the

Wybong Creek catchment would help to assess potential impacts from the proposed West Muswellbrook mine.

3.7.1 Key findings

3.7.1.1 Coal resource development

There is a long history of coal mining in the Hunter subregion, dating back to the 1790s. As of December 2012, there were 42 open-cut and underground mines commercially producing coal. An additional 22 developments were identified as potentially starting after this time.

A large number of regulatory requirements has been introduced over time to manage the risks associated with coal mining, both on and off site. The planning and approval processes cover a range of areas relating to management of water resources, including mine dewatering, discharges to and extractions from the stream network, treatment and reuse of water and subsidence, which are intended to minimise risks from coal resource development.

3.7.1.2 Hydrological changes

The modelled additional coal resource development in the Hunter subregion results in five discrete drawdown zones. Drawdowns of greater than 0.2 m are *very likely* (greater than 95% chance) to occur at distances of 5 km from mine sites and *very unlikely* (less than 5% chance) to occur at distances greater than 20 km. A less extensive area of drawdown is predicted around the proposed Wallarah 2 mine when the regional result set is constrained using local information.

Changes in baseflow due to groundwater drawdown, plus changes in catchment runoff due to disruptions in surface drainage around the mine site, contribute to changes in streamflow that exceed the thresholds defined in Table 6 within and downstream of the drawdown areas. River modelling indicates that these thresholds are also exceeded at the tidal limit of the Hunter River (near Greta) from the cumulative impact due to additional coal resource development throughout the Hunter river basin.

Potentially large changes in flow regime are predicted in the Wyong River, Loders Creek, Saddlers Creek, Wollar Creek and two unnamed creeks near the Mount Pleasant and Mount Thorley–Warkworth coal mines. The unnamed creeks are small, hence impacts are localised.

The Hunter Regulated River, into which these creeks flow, is not very sensitive to changes in inflows from these creeks. Wollar Creek, Saddlers Creek and Loder Creek drain somewhat larger catchments and have a discernible effect on the Goulburn and Hunter rivers into which they flow. However, changes in baseflow to the Goulburn and Hunter rivers due to groundwater drawdown could be more significant than changes in tributary inflows.

Results for the Hunter Regulated River show that decreases in mean annual flow of between 1% and 2% are *very likely*, and decreases of more than about 2% upstream of the junction with Loders Creek, or 3% to 4% downstream of this point to Greta, are *very unlikely*. These changes need to be interpreted with caution, since the Australian Water Resources Assessment river model (AWRA-R) has not been constructed to specifically represent operational management of releases from Glenbawn and Glennies Creek storages.

Generally, the modelled changes are small relative to the interannual variability due to climate, especially for annual flow and high-flow days. There is a chance that increases in low-flow days could affect flow regimes in streams near all the mining areas, with smaller intermittent and perennial streams close to additional coal resource developments in the Central Hunter and Lower Hunter particularly at risk.

In the Wyong River, which is part of the water supply system to Wyong, there is a risk of potentially significant changes in flow regime from the proposed Wallarah 2 mine, and also possibly the proposed Mandalong Southern Extension. Based on the regional analysis, changes in low-flow days of more than 200 days per year are possible (5% chance) and are outside the range of previously experienced low-flow days per year. When the regional-scale results are constrained using local hydrogeological information, the predicted changes in flow regime due to additional coal resource development are substantially smaller and unlikely to result in a change in flow regime that is substantially different to that experienced under the baseline.

Seven mining proposals identified as additional coal resource developments (at September 2015) were not included in the surface water and/or groundwater modelling. Austar underground, Chain Valley underground and Mount Arthur open-cut are considered unlikely to result in significant hydrological change. Changes in the flow regimes of Dora, Mannering, Morans, Stockton, Wallarah and Wyee creeks are assessed as likely from the Mandalong Southern Extension Project and Wallarah 2, with potential impacts on forested wetlands and wet and dry sclerophyll communities along these creeks. The new West Muswellbrook mine could expand the groundwater zone of potential hydrological change further into the Wybong Creek catchment, with potentially more significant impacts on Wybong Creek flow, and contribute to greater reductions in baseflow to Dart Brook and the Hunter River. Additional hydrological changes at Wambo underground and Wilipinjong open-cut mines will likely impact areas that have been or will be affected by baseline developments. The magnitude of additional change is uncertain, but based on the size of the proposed mining projects and results from the modelled additional coal resource development, it appears that spatial extent will be relatively contained and not result in impacts on instream habitat and GDEs beyond those likely to be affected by hydrological changes under the baseline.

3.7.1.3 Ecological impacts

Results from receptor impact modelling of perennial streams, as indicated by changes in the probability of presence of riffle-breeding frogs and density of Hydropsychidae larvae, suggest that instream habitats of Wyong River could be impacted. Elsewhere in the subregion, it is *very unlikely* that instream habitats of perennial streams will be impacted, except possibly Dora Creek, which was not modelled but likely to experience similar drawdowns to those in the Wyong River catchment. However, local information from the Wyong River catchment suggests that the hydrological changes predicted using the regional parameter sets are grossly over estimated and that the risk to instream and riparian habitats is probably much lower.

Results from receptor impact modelling on intermittent streams, as indicated by changes in the probability of presence of riffle-breeding frogs and richness of hyporheic taxa, suggest that the instream habitats of Saddlers and Loders Creeks in the Hunter river basin could be impacted. Instream habitats of other intermittent streams around all additional coal resource developments are also potentially impacted, but the hydrological changes in these streams were not modelled. To improve the predictions of risk to instream habitat in these streams, more consideration needs to be given to local factors. This was not within the scope of this regional assessment, although geological and hydrogeological information from the Wyong River catchment, and stream salinity and stream condition information for Loders and Saddlers creeks, were used to illustrate this step.

The median result from receptor impact modelling suggests little likelihood of wet and dry sclerophyll forest being impacted, however, there is at least a 5% chance, as indicated by changes in projected foliage cover, that 10 to 15 km^2 of these landscape classes will be impacted, predominantly in the Macquarie-Tuggerah lakes basin. It is *very unlikely* that more than 8.6 km^2 will be subjected to groundwater drawdown of more than 2 m.

The median result from receptor impact modelling suggests little likelihood of riverine forested wetlands being impacted, however, there is at least a 5% chance, as indicated by changes in projected foliage cover, that 10 to 15 km^2 of riverine forests along the Goulburn River will be impacted. The ecological impact on the coastal swamp community within the ‘Forested wetland’ landscape class was not represented in the receptor impact model.

Most of the rainforest communities in the ‘Rainforest’ landscape class (in the ‘GDE’ landscape group) are unlikely to be impacted because, if they are dependent on groundwater at all, it is from local groundwater sources. The exceptions are rainforests along the perennial Wyong River, the water-dependency of which represents a gap in the BA of the Hunter subregion.

Of the 1652 water-dependent ecological assets in the Hunter subregion, 921 are *very unlikely* to be impacted by additional coal resource development because they are outside the zone of potential hydrological change. Of the remaining 731 assets, 210 are 'more at risk of hydrological changes' owing to their association with potentially impacted landscape classes.

3.7.1.4 Economic impacts

Five groundwater sources and 19 surface water sources are potentially impacted by hydrological changes due to additional coal resource development.

Changes in water availability, as indicated by the modelled change in mean annual flow, are *very likely* to exceed 5 GL/year in the Hunter Regulated River at Greta, but *very unlikely* to exceed 12 GL/year over the period from 2013 to 2042. Reductions of 3 to 6 GL/year in the Singleton, Muswellbrook, Jerrys and Wyong River water sources are possible (at least 5% chance). In the Wyong River, the median decrease in cease-to-pump days over the three 30-year periods is predicted to be between 6 and 8 days per year, with a less than 5% chance of 145 days per year (2043 to 2072).

The reliability of supply, as indicated by change in the number of cease-to-pump days, is likely to be affected in Singleton, Muswellbrook, Jerrys and Wyong River water sources.

‘Make good’ provisions under the *NSW Aquifer Interference Policy* (DPI Water, 2012) might be necessary (greater than 5% chance) for 11 bores, located in the Sydney Basin – North Coast groundwater source (7) and the Jilliby Jilliby Creek (2), Tuggerah Lakes and South Lake Macquarie water sources. Another 159 bores were identified as likely to experience drawdowns of at least 2 m due to additional coal resource development, but since they are on mining and exploration leases, the requirement to 'make good' on these impacts was considered less likely.

3.7.2 Future monitoring

Post-assessment monitoring is important to test and (in)validate the risk predictions of the Assessment. At the highest level, monitoring efforts should reflect the risk predictions, and focus the effort where the changes are expected to be the largest. However, it is important to place some monitoring effort at locations with lower risk predictions so as to confirm the range of potential impacts and identify unexpected outcomes.

The BA of the Hunter subregion has identified that potential hydrological or ecosystem impacts due to additional coal resource development are likely in a small number of catchments within the subregion. Groundwater monitoring effort should be concentrated in the five discrete drawdown zones. In most cases, it is the hydraulic properties of the aquitards that determine impacts at the surface from stresses at depth. Nested piezometers that can monitor the changes in hydraulic gradients between layers are required to determine impacts at the surface from mining-induced stresses. The Sydney Basin – North Coast groundwater source has the largest number of bores where 'make good' provisions might apply and would be expected to be a focus of the groundwater monitoring to determine impacts from mining. Monitoring changes in hydraulic gradients between geological layers below the Jilliby Jilliby Creek, Tuggerah Lake and South Macquarie Lake water sources, where potential changes in streamflow from mining at Wallarah 2 and Mandalong Southern Extension have generated considerable concern, would permit early detection of mining-induced changes and more timely management responses.

Results from the surface water modelling would seem to suggest that Wyong River, Loders Creek, Saddlers Creek, Wollar Creek and two unnamed creeks near the Mount Pleasant and Mount Thorley–Warkworth coal mines should be considered for future streamflow monitoring. Given similar levels of drawdown in Dora Creek to Wyong River, it should also be considered for future streamflow monitoring. However, local information on, for example, stream condition, habitat value, recovery potential and existence of other stressors, is needed to determine actual priorities. Monitoring of the Goulburn and Hunter rivers should continue given the potential for changes in baseflow. The Singleton, Muswellbrook, Jerrys and Wyong River water source areas may warrant monitoring given potential changes in water availability.

There are also lengths of stream that are noted as potentially impacted because risk predictions are not made in some cases (e.g. because it is not sensible to interpolate from the stream model nodes used) whose impacts could be quantified through monitoring streamflow, ideally with as much lead in time as possible before new developments commence.

Seven mining proposals identified as additional coal resource developments were not included in the surface water and/or groundwater modelling. Streamflow monitoring may be necessary in Mannering, Morans, Stockton, Wallarah and Wyee creeks given potential changes in flow regime that may arise from the Mandalong Southern Extension development, and in the Wyong River catchment due to changes from the new West Muswellbrook mine. Monitoring of groundwater levels and hydraulic gradients in the vicinity of the proposed West Muswellbrook mine area, which was not modelled in this BA, would contribute to understanding the risk to Wybong Creek flows from this development.

To accompany the hydrological monitoring, monitoring of changes in select ecosystem indicators in potentially at risk streams and GDEs is recommended. The large uncertainties reflected in the receptor impact models from the expert elicitations can be reduced through collecting data on measurable ecosystem components that are sensitive to changes in hydrology (two of the criteria for selection of the receptor impact variables by experts for receptor impact modelling). How frogs, hyporheic invertebrate populations, Hydropsychidae larvae and/or tree canopies respond to changes in water availability and flow regime in different environments and the extent to which changes in these ecosystem components propagate through to other components of the ecosystems they occupy require greater understanding.

3.7.3 Using this impact and risk analysis

Findings from BAs can help governments, industry and the community provide better informed regulatory water management and planning decisions.

Assessment results flag where future efforts of regulators and proponents can be directed, and where further attention is not necessary. The zone of potential hydrological change is the area where the magnitude of the hydrological changes due to additional coal resource development suggests the possibility of impacts to water-dependent ecosystems and assets; outside the zone, adverse impacts on water-dependent ecosystems and assets due to additional coal resource development are considered *very unlikely*.

This Assessment predicts the likelihood of exceeding levels of potential hydrological change at a regional level. It also provides important context to identify potential issues that may need to be addressed in local-scale environmental impact assessments of new coal resource developments. It should help project proponents to meet legislative requirements to describe the environmental values that may be affected by the exercise of underground water rights, and to adopt strategies to avoid, mitigate or manage the predicted impacts. This Assessment does not investigate the broader social, economic or human health impacts of coal resource development, nor does it consider risks of fugitive gases and non-water-related impacts.

BAs are not a substitute for careful assessment of proposed coal mine or coal seam gas (CSG) extraction projects under Australian or state environmental law. Such assessments may use finer scale groundwater and surface water models and consider impacts on matters other than water resources. However, the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (a federal government statutory authority established in 2012 under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*) can use these Assessment results to formulate their advice

BAs have been developed with the ability to be updated, for example, to incorporate new coal resource developments in the groundwater model. Existing datasets such as the water-dependent asset register remain relevant for future assessments. If new coal resource developments emerge in the future, the data, information, analytical results and models from this Assessment would provide a comprehensive basis for subregion-scale re-assessment of potential impacts under an updated coal resource development pathway (CRDP). It may also be applicable for other types of resource development.

The full suite of information, including information for individual assets, is provided at www.bioregionalassessments.gov.au with more detailed results available for:

- potential hydrological changes at www.bioregionalassessments.gov.au/explorer/HUN/potentialhydrologicalchanges
- potential impacts on landscapes at www.bioregionalassessments.gov.au/explorer/HUN/landscapes
- potential impacts on water-dependent assets at www.bioregionalassessments.gov.au/explorer/HUN/assets.

Access to underpinning datasets, including shapefiles of geographic data and modelling results, can assist decision makers at all levels to review the work undertaken to date; to explore the results using different thresholds; and to extend or update the assessment if new models or data become available. Additional guidance about how to apply the Programme's methodology is also documented in detailed scientific submethodologies (Table 1).

The Programme's rigorous commitment to data access is consistent with the Australian Government's principles of providing publicly accessible, transparent and responsibly managed public-sector information.

3.7.4 Gaps, limitations and opportunities

This impact and risk analysis allows governments, industry and the community to focus on areas that are potentially impacted when making regulatory, water management and planning decisions. Due to the conservative nature of the modelling, the greatest confidence in results is for those areas that are *very unlikely* to be impacted (that is, outside the zone of potential hydrological change). Where potential impacts have been identified, further work may be required to obtain better predictions of the potential magnitude of impacts to ecosystems and individual assets.

Key knowledge gaps have been identified in each of the companion products for the Hunter subregion. The next section is a summary of the key knowledge gaps where understanding the potential impacts of coal resource development can be improved through further work.

3.7.4.1 Overall

The probabilistic approach to modelling undertaken in the Assessment was specifically chosen to deal with data and knowledge gaps. The Assessment team focused on integrating data and information that was quality assured and relevant for this regional-scale analysis. However, this meant that some data and information about the Hunter subregion were not used to inform the modelling – for instance, because it was localised and ad hoc in its coverage; lacked reliable metadata to quality assure the data; not available to the Assessment team at the time of analysis;

or because operational constraints prevented collating and scrutinising the data to the standards set out in the BA.

Note that the probabilistic approach to both hydrological and ecological modelling did not consider structural errors in the modelling. As a result, the calculated probabilities are not strict probability, but are rather constrained by the model structures chosen. This issue is dealt with in greater detail in Section 2.6.2.8 in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b).

The use of regional-scale models and the characterisation of uncertainty were done specifically to deal with shortcomings in data and conceptual understanding. By modelling a wide array of parameterisations to represent the possibility of highly conductive, highly connected landscapes through to low-conductivity, poorly connected landscapes, result sets were generated that effectively put an upper limit on the area of potentially significant hydrological change. Another strength of the approach is that the development of emulators of the groundwater model allowed more localised, rapid assessments of groundwater drawdown and changes in baseflow based on local information. In flagging gaps and identifying opportunities for improvement in the following sections, it is important to be aware that more and better data will not necessarily improve the model predictions from the regional-scale model, but could potentially contribute to constraining model results for more local-scale application using the model emulators.

3.7.4.2 Geology model

The geological model constructed to underpin the groundwater modelling, described in Section 2.1.2 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a), did not make use of all the data that were available at the time. NSW Department of Industry was identified as having additional data and, at the time the Hunter geological model was being built, was in the process of building a geological model for the Hunter Coalfield within the geological Sydney Basin. The feasibility of incorporating their model into the geological model of the subregion was investigated, but it was agreed that in terms of timing it introduced too great a risk to delivery on the BA, and the collaboration was not progressed. The opportunity to improve the Hunter geological model remains.

Additional data that could improve the geological model include:

- Well data that were not publicly available from the Digital Imaging Geological System (DIGS) database when the Hunter geological model was being developed could better constrain the geological framework.
- Logs from coal and groundwater bores could improve the lithological and stratigraphic detail of the shallower layers of the model.
- Depth interpretation seismic reflection data could contribute to better definition of geological structures in the Permo-Triassic strata.

The wide range in groundwater model parameters explored in the groundwater modelling partly accommodates and compensates for uncertainties in the geological model. A more detailed geological model has the potential to reduce the degree of conservatism in the predicted range of hydrological change. Especially at a local scale, combining detailed geological information with the groundwater emulators has great potential to refine the predictions, as shown through the Wallarah example in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b).

Faults were not represented in the geological model and, hence, were also not represented in the groundwater model. The extent to which faults act as conduits for groundwater flow between strata over different depths in the Hunter subregion is not well understood. The range of hydraulic conductivity parameters used in the groundwater modelling varies from corresponding to a conceptualisation close to faults impermeable to flow, to corresponding to a conceptualisation in which aquitards are compromised by local flow through faults on a regional scale. Results from stochastic representations of fault distributions in the Gloucester subregion groundwater modelling found that the faults had minimal impact on changes in groundwater due to additional coal resource development in that subregion. However, the conclusions of this local study may not be transferrable to the Hunter subregion. There remains a knowledge gap in the Hunter geological model regarding the distribution of faults and their influence on inter-aquifer connectivity.

Inferences can be made about the hydrological function of faults by measuring stream salinity and chemistry with a run of river. Targeted monitoring would be required to obtain a set of measurements that are sensitive to changes in river chemistry due to discharges from a fault. This means selecting sites with the right flow conditions and unimpeded flow – for example, not influenced by dam operations or discharges under the Hunter River Salinity Trading Scheme.

Sensitivity analysis of the modelling results indicated that the greatest potential to reduce predictive uncertainty lies in improved characterisation of hydraulic properties of the sedimentary rocks, especially the porosity and storage parameters. In order to unlock the information of historical groundwater levels to constrain these properties, it is essential that uncertainty of boundary conditions in the regional model, such as the geomorphology of the river network or recharge, is reduced.

3.7.4.3 Groundwater data

Groundwater data are often only available at a very limited number of sites, and are often poorly documented, particularly for regional applications. This was an issue in the Hunter subregion, particularly for depth to watertable, recharge and contributions to baseflow from groundwater.

Groundwater data from state databases primarily include monitoring data for shallow groundwater systems and aquifers used for irrigation, stock and domestic purposes. These data are usually in the form of water level measurements and major ion analyses, which support knowledge of groundwater recharge processes and interactions between rivers and groundwater. However, it provides limited understanding of deeper groundwater systems. Local monitoring of the effect on groundwater levels by proponents of their mining activities is less relevant. Such data, rather than constraining the predictions, can bias the predictions if the historical stresses and local geological conditions of this monitoring data are not well understood and represented in the regional model. This has been factored into the Assessment’s uncertainty analysis and modelling. Future assessments would be assisted by improved information on deeper groundwater systems.

Improved mapping of depth to groundwater, and its spatial and temporal variation, not only have potential to constrain hydrological change predictions, they provide much needed context for the interpretation of the ecological impacts due to hydrological change. Interactions between changes in groundwater availability and the health and persistence of terrestrial groundwater-dependent vegetation remain uncertain due, in part, to sparse mapping of groundwater depths outside of alluvial layers.

3.7.4.4 Integrated hydrological modelling

More closely coupled surface water and groundwater models could incorporate feedback mechanisms not included in this Assessment. For example, a reduction in baseflow to a stream could induce small groundwater drawdowns in downstream regions where the stream is leaking to the groundwater system.

A choice was made to not build a detailed river management model; rather a few key river management rules were incorporated into AWRA-R. There is an opportunity for NSW Department of Primary Industries to integrate modelled runoff and baseflow changes into a river management model such as IQQM for water resource planning.

While not undertaken as part of this BA, the surface water and groundwater models can be run with different permutations of the additional coal resource developments to explore alternate development futures. An opportunity for further consideration is tailoring the models to receive the results of site-scale modelling undertaken by the mining companies to assess off-site, cumulative impacts.

In the Hunter modelled stream network, the distribution of model nodes was too sparse to enable a comprehensive extrapolation to network reaches, resulting in many 'potentially impacted' reaches, where hydrological changes could not be quantified with any accuracy. A higher density of model nodes, located immediately upstream of major stream confluences and upstream and downstream of mine operations, would allow the point-scale information to be extrapolated to a greater proportion of the stream network. A more extensive quantification of hydrological changes along the stream network would enable better spatialisation of the results of the receptor impact modelling.

There is an opportunity to consider the dependency between hydrological response variables, particularly between groundwater and surface water hydrological response variables, more fully in any further assessment. This may be important if additional receptor impact models are considered where that dependency is more important to address.

3.7.4.5 Water quality

Changes in water quality parameters that could occur due to reductions in surface runoff and groundwater to streamflow or due to enhanced connectivity between aquifers of differing water quality, for example, are not represented in the models. Modelling the changes in water quality was not part of the scope of the BAs. Potential changes in stream salinity were considered in Section 3.3.4, having regard to salinity hazard mapping, stream salinity data and existing management arrangements. Saline discharges from the mining and power generation sites along the Hunter Regulated River are managed through the Hunter River Salinity Trading Scheme. Salinity hazard mapping indicates extensive areas of risk associated with Permian coal measures, and changes in the relative contributions of surface runoff and groundwater could result in changes in stream salinity to smaller, unregulated streams near mines. The risk of adverse impacts will depend on local conditions, including current stream salinities and stream condition more generally.

There are opportunities to develop water quality modules to accompany the regional hydrological models, although results from this BA identify areas where more local investigation of the potential for adverse water quality changes might be warranted.

3.7.4.6 Assessing ecological impacts

The approach adopted does not consider how different ecosystems within a given landscape class might respond differently to the same hydrological change. It also does not consider ecological interactions between landscape classes. It also does not consider how response models for one functional group might underestimate complex ecosystem functions, interactions and cascade effects.

In the Hunter subregion, the ‘Forested wetland’ landscape class includes two distinct types of forested wetlands: Eastern Riverine forested wetlands, which predominate in the Hunter river basin; and Coastal Swamp forested wetlands, which predominate in the Macquarie-Tuggerah lakes basin. The receptor impact modelling was premised on the Eastern Riverine forested wetlands, which represent about half of the forested wetlands in the zone of potential hydrological change. Thus, the potential impacts of hydrological changes on the coastal swamp communities represents a knowledge gap in this Assessment.

Similarly, the qualitative model developed for the ‘Rainforest’ landscape class was premised on rainforests that occupy low-order stream and gully habitats, and that were considered to use groundwater from perched watertables and local hillslope aquifers opportunistically. The mapped distribution of rainforests (NSW Office of Water, Dataset 1) showed that within the ‘Rainforest’ landscape class, there is also a riparian rainforest associated with the alluvium of the perennial Wyong River. The qualitative model for the ‘Rainforest’ landscape class is not considered appropriate for these riparian rainforests. Potential impacts of changes in flow regime along the Wyong River is a gap in this Assessment.

Experts at the qualitative modelling workshop were uncertain about aspects of the hydrology of the ‘Freshwater wetland’ landscape class. The extent to which these features interact with a regional watertable was unknown. The dependence of these systems on overbank flows from rivers was also uncertain. Thus the risk to freshwater wetlands from the Wallarah 2 and Mandalong Southern Extension projects is a knowledge gap. The assumptions and limitations of the receptor impact modelling are described in Table 4 in companion product 2.7 for the Hunter subregion (Hosack et al., 2018a).

Additional vegetation mapping and ongoing research to identify GDEs in the subregion would improve assessment of impacts on water-dependent assets. Additionally, tracking the biophysical processes, such as rate of actual evapotranspiration and vegetation growth rates, of the GDEs and interpreting these in an ecohydrological framework would improve understanding of the interactions between changes in groundwater availability and the health of terrestrial vegetation that relies on groundwater. This can be performed by field measurement and/or use of time series remote sensing.

As actual water requirements of different plant communities are only approximately known, future assessments would be assisted by more work to identify suitable bio-indicators of ecosystem condition, or alternative methods of assessing the condition of water-dependent ecosystems. Again, this is likely best performed using field measurement and/or time series remote sensing.

3.7.4.7 Sociocultural assets

Many sociocultural assets in the Hunter subregion from the Register of the National Estate are built infrastructure, such as historic buildings or bridges. The Bioregional Assessment Programme does not have the expertise to comment on potential impacts of changes in hydrological regimes to built infrastructure.

Although the NSW Department of Primary Industries Water were commissioned to engage with Indigenous communities to collect information on Indigenous water assets for several bioregions and subregions in BAs, this did not occur for the Hunter subregion. Thus the water-dependent asset register does not include sociocultural assets that have been specifically identified by the local Indigenous communities. However, many of the assets that are in the asset register are likely to be associated with Indigenous assets. Cultural sensitivities often attach to Indigenous assets, and the Indigenous communities may prefer that details of their location and value are retained with their Elders or within their communities. Thus, it is not clear what opportunity there might be to address this gap in the water-dependent asset register.

3.7.4.8 Climate change and land use

The implications of climate change and changes in land use were not considered in the modelling. A more complete picture of the potential impacts due to additional coal resource development could be obtained by considering these changes in the context of a warming climate and changing demands for water. This Assessment identified the risk to water-dependent landscape classes and assets from additional coal resource development, but how this information is used and the decisions made could differ if for example, coal-fired power stations were closed down in the subregion, or if more land were set aside for strategic agricultural uses, or if the water demands of coastal populations changed.

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Datasets

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Glossary

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

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

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

additional drawdown: the maximum difference in drawdown (dmax) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development

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

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.

assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The assessment extent is created by revising the preliminary assessment extent on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

assessment unit: for the purposes of impact analysis, a geographic area that is used to partition the entire assessment extent into square polygons that do not overlap. The spatial resolution of the assessment units is closely related to that of the bioregional assessment groundwater modelling and is, typically, 1 x 1 km. Each assessment unit has a unique identifier. The partitioned data can be combined and recombined into any aggregation supported by the conceptual modelling, causal pathways and model data.

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 component: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a coal seam gas (CSG) operation or coal mine. For example, components during the development life-cycle stage of a coal mine include developing the mine infrastructure, the open pit, surface facilities and underground facilities. Components are grouped into life-cycle stages.

conceptual model: abstraction or simplification of reality

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

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

consequence: synonym of impact

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

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

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

depressurisation: in the context of coal seam gas operations, depressurisation is the process whereby the hydrostatic (water) pressure within a coal seam is reduced (through pumping) such that natural gas desorbs from within the coal matrix, enabling the gas (and associated water) to flow to surface

dewatering: the process of controlling groundwater flow within and around mining operations that occur below the watertable. In such operations, mine dewatering plans are important to provide more efficient work conditions, improve stability and safety, and enhance economic viability of operations. There are various dewatering methods, such as direct pumping of water from within a mine, installation of dewatering wells around the mine perimeter, and pit slope drains.

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

dmax: maximum difference in drawdown, obtained by choosing the maximum of the time series of differences between two futures. For example, to calculate the difference in drawdown between the coal resource development pathway (CRDP) and baseline, use the equations dmax = max (dCRDP(t) – dbaseline(t)) where d is drawdown, or dmax = max (hbaseline(t) – hCRDP(t)) where h is groundwater level and t is time.

dmaxRef: maximum difference in drawdown under the baseline future or under the coal resource development pathway future relative to the reference period (1983 to 2012). This is typically reported as the maximum change due to additional coal resource development.

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

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

ecosystem function: the biological, geochemical and physical processes and components that take place or occur within an ecosystem. It refers to the structural components of an ecosystem (e.g. vegetation, water, soil, atmosphere and biota) and how they interact with each other, within ecosystems and across ecosystems.

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

ephemeral stream: a stream that flows only briefly during and following a period of rainfall, and has no baseflow component

EventsR0.3: the mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 0.3 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbench flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development.

EventsR3.0: the mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 3.0 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbank flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development.

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

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

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

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

goaf: That part of a mine from which the coal has been partially or wholly removed; the waste left in old workings.

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

groundwater system: see water system

groundwater zone of potential hydrological change: outside this extent, groundwater drawdown (and hence potential impacts) is very unlikely (less than 5% chance). It is the area with a greater than 5% chance of exceeding 0.2 m of drawdown due to additional coal resource development in the relevant aquifers.

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 (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'.

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

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

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

landscape group: for the purposes of bioregional assessments (BAs), a set of landscape classes grouped together based on common ecohydrological characteristics that are relevant for analysis purposes

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).

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 to 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.

marine transgression: the landward spreading of the sea over a large area within relatively short space of geological time (a few million years or less). The reverse of transgression is regression.

material: pertinent or relevant

mine pit exclusion zone: areas in the zone of potential hydrological change that are within or near open-cut mine pits, and where (i) modelled drawdowns are highly uncertain due to the very steep hydraulic gradients at the mine pit interface; (ii) changes in the drawdown are inevitable where the mine pit intersects the regional watertable; (iii) other factors, such as physical removal of a wetland or creek, may have a larger impact on a landscape class than the predicted decrease in groundwater level; and (iv) impacts are predominantly site-scale, assumed to be adequately addressed through existing development approval processes, and hence not the primary focus of bioregional assessments. The modelled estimates of drawdown in the mine pit exclusion zone are considered unreliable for use in the receptor impact modelling.

model emulator: a computationally efficient statistical approximation of a process model that mimics the effect of parameter values on a model prediction. In uncertainty analysis a slow, complex process model is replaced by an emulator, which, for a given parameter combination, will provide a prediction that is very close to the prediction that would be obtained by running the process model.

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.

more at risk of ecological and hydrological changes: assessment units that overlap a landscape class are considered ‘more at risk of ecological and hydrological changes’ relative to other assessment units if modelled hydrological changes result in ecological changes that exceed the upper thresholds of risk. These bioregion-specific thresholds are based on expert opinion and are defined using receptor impact variables. Categorisation assists the rule-out process and in identifying where further local-scale assessment is warranted.

more at risk of hydrological changes: assessment units that overlap an asset are considered ‘more at risk of hydrological changes’ relative to other assessment units if modelled hydrological changes exceed bioregion-specific thresholds of risk. These thresholds are based on expert opinion and are defined using hydrological response variables. Categorisation assists the rule-out process and identifying where further local-scale assessment is warranted.

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

overbench flow: high-flow condition where a river channel is partially or completely filled for a period of weeks to months. All habitats within the river channel will be wet including boulders, logs and lateral benches, and the entire length of the channel is connected with relatively deep water, allowing movement of biota freely along the river.

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

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

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

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.

preliminary assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The PAE is estimated at the beginning of a bioregional assessment, and is updated to the 'assessment extent' on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

probability distribution: the probability distribution of a random variable specifies the chance that the variable takes a value in any subset of the real numbers. It allows statements such as 'There is a probability of x that the variable is between a and b'.

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'.

receptor impact variable: a characteristic of the system that, according to the conceptual modelling, potentially changes due to changes in hydrological response variables (for example, condition of the breeding habitat for a given species, or biomass of river red gums)

recharge: see groundwater recharge

return period: An event has a return period (or recurrence interval) of T years if its magnitude is equalled or exceeded once on average every T years. The reciprocal of the return period is the exceedance probability of the event, that is, the probability that the event is equalled or exceeded in any one year. For example, a flood with a return period of 10 years has a 0.1 or 10% chance of being exceeded in any one year and a flood with a return period of 50 years has a 0.02 or 2% chance of being exceeded in any one year. The actual number of years between floods of any given size varies a lot because of climatic variability.

riparian: An area or zone within or along the banks of a stream or adjacent to a watercourse or wetland; relating to a riverbank and its environment, particularly to the vegetation.

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.

saturated zone: the part of the ground in which all the voids in the rocks or soil are filled with water. The watertable is the top of the saturated zone in an unconfined aquifer.

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

severity: magnitude of an impact

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.

stressor: chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode

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

surface water zone of potential hydrological change: outside this extent, changes in surface water hydrological response variables due to additional coal resource development (and hence potential impacts) are very unlikely (less than 5% chance). The area contains those river reaches where a change in any one of nine surface water hydrological response variables exceeds the specified thresholds. For the four flux-based hydrological response variables (annual flow (AF), daily flow rate at the 99th percentile (P99), interquartile range (IQR) and daily flow rate at the 1st percentile (P01)), the threshold is a 5% chance of a 1% change in the variable. That is, if 5% or more of model runs show a maximum change in results under CRDP of 1% relative to baseline. For four of the frequency-based hydrological response variables (high-flow days (FD), low-flow days (LFD), length of longest low-flow spell (LLFS) and zero-flow days (ZFD)), the threshold is a 5% chance of a change of 3 days per year. For the final frequency-based hydrological response variable (low-flow spells (LFS)), the threshold is a 5% chance of a change of two spells per year.

tmax: year of maximum change

tmaxRef: the year that the maximum difference in drawdown relative to the reference period (1983 to 2012) (dmaxRef) occurs

transmissivity: A parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow).

transparency: a key requirement for the Bioregional Assessment Programme, achieved by providing the methods and unencumbered models, data and software to the public so that experts outside of the Assessment team can understand how a bioregional assessment was undertaken and update it using different models, data or software

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.

unconfined aquifer: an aquifer whose upper water surface (watertable) is at atmospheric pressure and does not have a confining layer of low-permeability rock or sediment above it

unsaturated zone: the zone in soils and rocks occurring above the watertable, where there is some air within the pore spaces

very likely: greater than 95% chance

very unlikely: less than 5% chance

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-dependent asset register: a simple and authoritative listing of the assets within the preliminary assessment extent (PAE) that are potentially subject to water-related impacts

water make: the groundwater extracted for dewatering mines

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

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

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

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

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).

zero-flow days (averaged over 30 years) (ZQD): the number of zero-flow days per year, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.

ZMA: the maximum length of spells (in days per year) with zero flow over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.

zone of potential hydrological change: outside this extent, hydrological changes (and hence potential impacts) are very unlikely (less than 5% chance). Each bioregional assessment defines the zone of potential hydrological change using probabilities of exceeding thresholds for relevant hydrological response variables. The zone of potential hydrological change is the union of the groundwater zone of potential hydrological change (the area with a greater than 5% chance of exceeding 0.2 m of drawdown due to additional coal resource development in the relevant aquifers) and the surface water zone of potential hydrological change (the area with a greater than 5% chance of exceeding changes in relevant surface water hydrological response variables due to additional coal resource development).

Landscape classification

Definitions for landscape classes and landscape groups for the Hunter subregion are provided below. The register of terms and definitions for the landscape classification for each bioregion and subregion in the Bioregional Assessment Programme is available online at http://environment.data.gov.au/def/ba/landscape-classification.

- 'Coastal lakes and estuaries' landscape group: Coastal lakes, wetlands and rivers with intermittent or permanent direct connection to the sea
  - ‘Barrier river’ landscape class: The ‘Barrier river’ landscape class is characterised by permanently open systems that are typically mature barrier riverine estuaries or mature forms of wave-dominated estuaries. Estuary volumes range from 0.1 to 3 times the total annual inflow and flush times range from 3 to 30 days. For the Hunter subregion, the Hunter and Karuah rivers fall within this landscape class.
  - ‘Creeks’ landscape class: The ‘Creeks’ landscape class is characterised by streams or channels primarily affected by tidal movement.
  - ‘Drowned valleys’ landscape class: The ‘Drowned valleys’ landscape class is characterised by permanently open systems with large dilution capacities. That is, the volume of the estuary is greater than 3 times the average annual inflow. Water quality may only experience minor deterioration during rainfall. Tidal flushing times range from 10 to 1000 days. For the Hunter subregion, the Port Stephens Estuary falls within this landscape class.

- 'Lagoons' landscape class: Lakes and lagoons in the 'Lagoons' landscape class are characterised by intermittently open lakes and lagoons. Dilution factors range from very small values (0.001) to 3. That is, the lagoon's volume is 0.001 to 3 times the volume of the flow into the system. Water quality in these systems quickly reflects that of the inflowing water; this inflow can completely displace existing water. Tidal flushing times are short when open. -For the Hunter subregion, Avoca and Cochrone lakes, and Glenrock and Terrigal lagoons, fall within this landscape class.
- 'Lakes' landscape class: The 'Lakes' landscape class is characterised by permanently open systems with large dilution capacities. That is, the volume of the estuary is greater than 3 times the average annual inflow. Water quality may only experience minor deterioration during rainfall. Tidal flushing times range from 10 to 1000 days. For the Hunter subregion, systems such as Lake Macquarie and Tuggerah Lakes fall within this landscape class.
- 'Saline wetlands' landscape class: Wetlands in the 'Saline wetlands' landscape class occur on areas of impeded drainage with high levels of salt, such as estuarine areas or inland lakes where high levels of evaporation lead to the accumulation of surface salts. Saline wetlands are dominated by halophilic species, including mangroves and saltmarshes (Somerville, 2009) but exclude seagrasses.
- 'Seagrass' landscape class: The 'Seagrass' landscape class are characterised by simple communities ranging from open to dense in their cover, usually with just a single flowering plant species (Keith, 2004). They are fully submerged, although the leaves may float on the water surface. There may be many species of algae present as epiphytes on their leaves.

* 'Economic land use' landscape group: Land classes managed primarily for economic activities
  - 'Dryland agriculture' landscape class: The 'Dryland agriculture' landscape class includes land that is used principally for primary production, based on dryland farming systems. Native vegetation has largely been replaced by introduced species through clearing, the sowing of new species, the application of fertilisers or the dominance of volunteer species. The range of activities in this landscape class includes pasture production for stock, cropping and fodder production, and a wide range of horticultural production.
  - 'Intensive use' landscape class: The 'Intensive use' landscape class includes land uses that involve high levels of interference with natural processes, generally in association with closer settlement. The level of intervention may be high enough to completely remodel the natural landscape – the vegetation, surface water and groundwater systems, and the land surface.
  - 'Irrigated agriculture' landscape class: The 'Irrigated agriculture' landscape class includes agricultural land uses where water is applied to promote additional growth over normally dry periods, depending on the season, water availability and commodity prices. This includes land uses that receive only one or two irrigations per year, through to those uses that rely on irrigation for much of the growing season.
  - 'Plantation or production forestry' landscape class: The 'Plantation or production forestry' landscape class includes land on which plantations of trees or shrubs (native and exotic species) have been established for production, or environmental and resource protection purposes.

- 'Water' landscape class: The 'Water' landscape class includes water features important for natural resource management, agricultural production and as points of reference in the landscape. This landscape class includes both natural and artificial water bodies that are not otherwise defined in this classification.

- 'GDE' landscape group: Terrestrial ecosystems that rely on groundwater for some or all of their water requirements
  - 'Dry sclerophyll forest' landscape class: Forests in the 'Dry sclerophyll forest' landscape class are characterised by open forests (canopy cover >50%, <75%) that include a wide range of structural and floristic types. In general they occur on nutritionally poorer substrates or in relatively drier situations than the wet sclerophyll forests. On moderately poor soils these forests may develop a dense, grassy understorey with a more open shrub layer (shrub/grass subformation), while on the poorest substrates (sands and sandstones) a dense, sclerophyllous shrub layer dominates. Fire often plays an important role in the ecology of these forests.
  - 'Forested wetland' landscape class: Wetlands in the 'Forested wetland' landscape class are made up of various wetlands dominated by tree species occurring on major riverine corridors and floodplains. These communities are dominated by sclerophyllous species similar to those in drier sclerophyll communities, but with hydrophilic species dominating an inundated understorey.
  - 'Freshwater wetland' landscape class: Wetlands in the 'Freshwater wetland' landscape class occur on areas where permanent inundation by water, either still or moving, dominates ecological processes. They occur in a range of environments where local relief and drainage result in open surface water at least part of the time, and often play a range of vital roles in the functioning of ecosystems. The periodicity and duration of inundation in wetlands often determines to a large extent the suite of species present, as do the extent and depth of water.
  - 'Grassy woodland' landscape class: Woodlands in the 'Grassy woodland' landscape class are a prominent feature of the landscape over much of the drier (500 to 900 mm) parts of the Hunter subregion on soils of medium-to-high fertility. They are characterised by an open-to-very-open canopy dominated by eucalypts, particularly various box and red gum species. The ground layer is typically dense and composed of a diverse range of tussock grasses and other grasses and herbs.
  - 'Heathland' landscape class: Landscapes in the 'Heathland' landscape class are characterised by a general lack of tree species. This formation occurs typically on low-nutrient, silica-rich soils, and many of the common species have adapted in various ways to acquiring trace amounts of nutrients and water from these soils.
  - 'Rainforest' landscape class: Forests in the 'Rainforest' landscape class have a closed canopy (>75%) generally dominated by non-eucalypt species with soft, horizontal leaves, although various Eucalyptus species may be present as emergents. Rainforests tend to be restricted to relatively fire-free areas with consistently higher moisture and nutrient levels than the surrounding sclerophyllous forests.

- 'Semi-arid woodland' landscape class: Woodlands in the 'Semi-arid woodland' landscape class are characterised by those lands where average annual rainfall is between 250 and 500 mm. Dominant tree species are a few species of eucalypts, wattles, sheoaks and cypress pines. Communities on floodplains tend to have a grassy understorey, while communities on more elevated sites tend to have a shrubby understorey.
- 'Spring' landscape class: Springs in the 'Spring' landscape class are characterised by a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water.
- 'Wet sclerophyll forest' landscape class: Forests in the 'Wet sclerophyll forest' landscape class are restricted to areas of higher rainfall and moderate fertility and often include a dense understorey of soft-leaved rainforest shrubs and small trees in moister situations (shrubby subformation). In drier situations these forests may have an open, grassy understorey (grassy subformation) with a sparse, sclerophyllous shrub layer. Wet sclerophyll forests are dominated by trees of the Myrtaceae family, particularly of the genera Eucalyptus, Angophora, Corymbia, Syncarpia and Lophostemon. Dominant tree species tend to have smaller, hard leaves and be adapted, to varying extents, to the occurrence of wild fires.

- 'Non-GDE vegetation' landscape group: Native forests, open forests or other natural vegetation communities not dependent on groundwater
  - 'Non-GDE vegetation' landscape class: Landscapes in the 'Non-GDE vegetation' landscape class are characterised by native forests, open forests or other natural vegetation communities that are not dependent on groundwater.
- 'Riverine' landscape group: Related to, formed by, or resembling a river, or situated on the banks of a river or stream
  - 'Highly intermittent or ephemeral' landscape class: Rivers or streams characterised by long no-flow spells (i.e. rarely flow). Flow regimes in these systems are dominated by runoff.
  - 'Lowly to moderately intermittent' landscape class: Rivers or streams in the 'Lowly to moderately intermittent' landscape class are characterised by streams that cease flowing more often than perennial streams and have a lesser proportion (0.15 to 0.20) of baseflow contribution (Kennard et al., 2008). This landscape class corresponds broadly to the 'unstable baseflow' and 'rarely intermittent' classes from Kennard et al. (2010; Classes 4 and 5).
  - 'Moderately to highly intermittent' landscape class: Rivers or streams in the 'Moderately to highly intermittent' landscape class are characterised by streams that regularly cease to flow. Flow regimes are dominated by runoff and groundwater discharge, which may represent only a minor contribution to flow.
  - 'Permanent or perennial' landscape class: Rivers or streams in the 'Permanent or perennial' landscape class have flow at least 80% of the year, and an appreciable contribution of groundwater to baseflows corresponding to the 'stable baseflow' classes from Kennard et al. (2010; Classes 1, 2 and 3).

4 Risk analysis for the Hunter subregion

Originally the risk analysis was intended to be reported independently of the impact analysis. Instead it has been combined with the impact analysis as product 3-4 to improve readability. For risk analysis see Section 3 of this product.

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