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Hydrogeological and ecohydrological connections in the CSG development areas of the Namoi region

Kate Holland, Dennis Gonzalez, Patrick Mitchell, Anthony O'Grady, Sreekanth Janardhanan

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Executive summary

This report improves the conceptualistion of the hydrogeological and ecohydrological connections of groundwater dependent ecosystems (GDEs) in the Namoi region for the Gas Industry Social and Environmental Research Alliance (GISERA) project on “Impact of coal seam gas development on GAB flux in the Namoi region”. The study uses knowledge developed for the Bioregional Assessments (BA) programme (refer www.bioregionalassessments.gov.au) to simplify and improve the conceptualisation and assessment of potential hydrological changes associated with coal seam gas (CSG) development in the Namoi subregion. The simplification and aggregation of landscape classes necessary for receptor impact modelling indicates that there is an opportunity to simplify the BA landscape classification for the Namoi subregion and an opportunity to explicitly link GDEs to relevant groundwater model layers to improve future assessments.

A simplified landscape classification is developed using fewer classifiers (i.e. habitat, water-regime, geomorphology and vegetation type) and the IBRA subregion descriptions (climate, physiography, land and soil capability, land cover, vegetation, wetlands, land use). The simplified classification includes explicit linkages to landscape water sources, specifically surficial source aquifers for groundwater-dependent vegetation, deeper spring aquifer sources, and surface water systems for surface water-dependent vegetation. The simplified classification reduced the total number of classes from 29 to 17. This includes 4 classes of groundwater-dependent remnant vegetation, 2 classes of surface water-dependent remnant vegetation, 2 classes of surface water-dependent non-remnant vegetation, 1 groundwater-dependent stream class and 2 classes of springs based on source aquifer. This explicit linkage to groundwater-dependent water sources enables improved analysis of ecological consequences of potential hydrological changes associated with CSG development.

Qualitative models and receptor impact models developed for the Namoi subregion are used to improve conceptualisation of potential ecological impacts to groundwater-dependent ecosystems. Five hydrological response variables (dmaxRef, tmaxRef, EventsR3.0, ZQD, ZME) describe relevant hydrological changes for these ecosystems. Receptor impact models for two simplified landscape classes (Groundwater-dependent riparian vegetation and Groundwater-dependent stream) predict responses to hydrological changes for projected foliage cover and families of aquatic macroinvertebrates. Qualitative models for four simplified landscape classes (Groundwater-dependent floodplain vegetation, Groundwater-dependent grassy woodland vegetation, Groundwater-dependent rainforest vegetation, Springs (includes GAB springs and non-GAB springs)) are relevant to the assessment of potential impacts to groundwater-dependent ecosystems.

A total of 201 receptors to represent groundwater-dependent landscapes and 199 receptors to represent economic bore were randomly selected to the north of and within 30 km of the Narrabri Gas Project area. Based on the predicted groundwater drawdown impacts at these receptors, a shortlist of these will be used by the GISERA “Spatial design of monitoring networks” project for data-worth analysis to inform potential monitoring strategies for improving the predictive reliability at these receptor locations.

1 Introduction

1.1 Overview

The proposal for coal seam gas (CSG) development in the Pilliga forest in northern NSW has raised concerns about potential environmental impacts. This includes potential impacts on groundwater-dependent ecosystems (GDEs) due to hydrological changes associated with gas resource development. GDEs provide many ecosystem services and are an important component of groundwater management. Assessment of potential impacts associated with gas resource development should consider GDEs, which are sensitive to changes in water quantity and quality.

The Bioregional Assessment Programme classified the diverse natural and human-modified ecosystems (including GDEs) in the Namoi subregion, which includes the Pilliga forest, based on broad-scale patterns in geomorphology, soils, hydrology and land use (Figure 1; Herr et al., 2017).

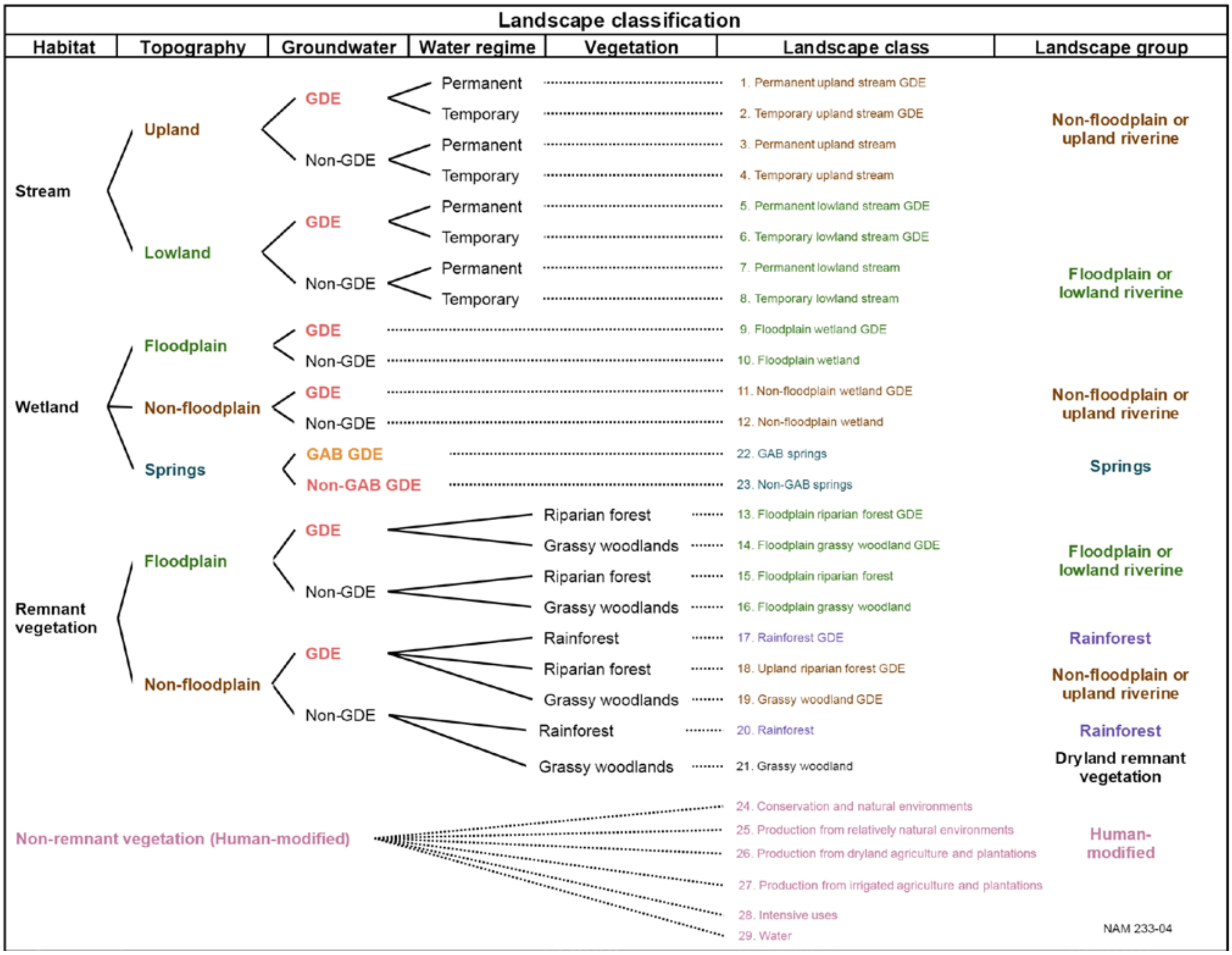

Figure 1 Bioregional Assessment landscape classification for the Namoi subregion

Classification criteria are shown across the top row and the corresponding typology of landscape classes and groups are shown in the right hand columns.
GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem
Source: Conceptual modelling for the Namoi subregion (Herr et al., 2017)

1.2 Objectives

A key objective of the GISERA NSW project on 'Impacts of CSG depressurization on GAB flux' is to refine the conceptual understanding of the hydrogeological system in the Narrabri Gas Project area (CDM Smith, 2016) in order to better assess potential impacts of gas resource development. This includes collection of hydrogeological data, improved confidence in flux and water balance estimates and improved conceptualisation of the hydrogeological connection of GDEs in the Namoi region.

Specifically, this study reports the following:

- Simplified landscape classification for the Namoi subregion with explicit linkages to important surficial aquifers for GDEs
- Improved conceptualisation of GDEs in relation to important groundwater sources to evaluate potential groundwater impacts and risks associated with proposed gas resource development.

2 Simplified landscape classification

2.1 Bioregional assessment landscape classification

The bioregional assessment (BA) landscape classification used existing classifications and regionalisation approaches and conceptual models to develop a conceptual understanding of how hydrological regimes link to ecosystem level water requirements. The classification for the Namoi subregion uses broad-scale geomorphological, soil, hydrological and habitat information for a diverse range of landscape features to produce 29 landscape classes that capture key distinctions using one or more of the following classifiers (Figure 1):

- broad habitat type (remnant/human-modified/aquatic)
- geomorphology (floodplain/non-floodplain)
- vegetation type (riparian/woodland floodplain/grassy woodland/rainforest)
- water regime (near-permanent/temporary)
- groundwater (groundwater dependent/non-groundwater dependent) or, in the case of springs, groundwater source (Great Artesian Basin (GAB)/non-GAB).

Prioritisation was assigned in order of highest to lowest as:

- aquatic ecosystems (e.g. wetlands, streams, lakes and springs)
- remnant vegetation – mapped in the NSW regional native vegetation mapping, excluding 'non-native' or 'candidate native grasses' (Keith, 2004)
- 'human-modified' – all remaining landscapes not classified as aquatic or remnant vegetation.

The BA landscape classification is described in Conceptual modelling for the Namoi subregion (Herr et al., 2017) and summarised by landscape group in Table 1. In BA, the assessment extent is the geographic area where potential impacts on water-dependent assets due to coal resource development are assessed. Most of the Namoi assessment extent (35,630 km^2) was classified as 'Human-modified' (59.3%), which includes agricultural, urban and other intensive land uses. The next biggest group was 'Dryland remnant vegetation' (24.2%), which is assumed to be non-water dependent as it does not intersect with floodplain, wetland or GDE features. Smaller parts of the assessment extent were classified as 'Floodplain or lowland riverine' (6.2%), 'Non-floodplain or upland riverine (9.8%) or 'Rainforest' (0.5%).

Table 1 Extent of each landscape group in the assessment extent for the Namoi subregion

Landscape group [a]	Area, length or number	Extent in assessment extent	Percentage of assessment extent
Floodplain or lowland riverine	Area of remnant vegetation (km^2)	2,205	6.2%
	Stream network length (km)	10,708	36.2%
Non-floodplain or upland riverine	Area of remnant vegetation (km^2)	3,490	9.8%
	Stream network length (km)	18,850	63.8%
Rainforest	Area of remnant vegetation (km^2)	197	0.5%
Springs	Number of springs	22	100%
Dryland remnant vegetation	Area of remnant vegetation (km^2)	8,624	24.2%
Human-modified	Area of non-remnant vegetation (km^2)	21,144	59.3%
Total	**Area of remnant vegetation (km^2)**	**14,516**	**40.7%**
	Area of non-remnant vegetation (km^2)	**21,144**	**59.3%**
	Stream network length (km)	**29,558**	**100%**
	Number of springs	**22**	**100%**

[a] Definitions for landscape classes and landscape groups for the Namoi subregion are available online at environment.data.gov.au/def/ba/landscape-classification/namoi-subregion.
Source: Outcome synthesis for the Namoi subregion (Herr et al., 2017)

Most (9 of the 13) landscape classes containing remnant vegetation (e.g. 'Floodplain wetland', Upland riparian forest GDE') cover less than 0.5% of the total assessment extent area for the Namoi subregion. Seven qualitative models were developed for the Namoi subregion that describe how 16 of the 29 landscape classes are dependent on groundwater and/or surface water (Table 2). Qualitative models were not developed for the 'Dryland remnant vegetation' or 'Human-modified' landscape groups that are not considered to be water dependent.

Eight receptor impact models were developed for components of three of the seven qualitative models ('Floodplain and lowland riverine', 'Upland riverine', 'Pilliga riverine (upland and lowland)') that are relevant to the Upper-, Mid- and Lower-Namoi, Pilliga and Pillga Outwash reporting regions. These ecosystems occur in areas where hydrological changes associated with additional coal resource development were predicted. Receptor impact models were not developed for the other four qualitative models ('Grassy woodland GDE', 'Non-floodplain wetland (GDE and non-GDE)', 'Rainforests (GDE and non-GDE)' and 'GAB springs' (Table 2).

Table 2 Qualitative and receptor impact models, landscape classes and reporting regions in the Namoi subregion

Qualitative and receptor impact model	BA landscape class	Percentage of assessment extent
Upper Namoi, Mid Namoi and Lower Namoi reporting regions		
Floodplain and lowland riverine qualitative model 1. Floodplain riparian forests - projected foliage cover	Floodplain riparian forest, Floodplain riparian forest GDE	0.4%
Floodplain and lowland riverine qualitative model 2. Floodplain wetland (GDE and non-GDE) - Probability of presence of tadpoles from Limnodynastes genus (Dumerilii, Salmini, Interioris and Terraereginae) in pools and riffles	Floodplain wetland, Floodplain wetland GDE	0.5%

Qualitative and receptor impact model	BA landscape class	Percentage of assessment extent
Floodplain and lowland riverine qualitative model 3. Permanent and temporary lowland streams (GDE and non-GDE) - average number of families of aquatic macroinvertebrate in edge habitat	Permanent lowland stream, Permanent lowland stream GDE, Temporary lowland stream, Temporary lowland stream GDE	36.2%
Upland riverine qualitative model 6. Upland riparian forest - projected foliage cover	Upland riparian forest GDE	0.2%
Upland riverine qualitative model 7. Permanent and temporary upland streams (GDE and non-GDE) - average number of families of aquatic macroinvertebrates in instream pool habitat sampled using the NSW Ausrivas method for pools	Permanent upland stream, Permanent upland stream GDE, Temporary upland stream, Temporary upland stream GDE	65.2%
Upland riverine qualitative model 8. Upland riverine - probability of presence of tadpoles from *Limnodynastes* genus (*Dumerilii, Salmini, Interioris and Terraereginae*)	Permanent upland stream, Permanent upland stream GDE, Temporary upland stream, Temporary upland stream GDE	2.5%
Pilliga and Pilliga Outwash reporting regions		
Pilliga riverine (upland and lowland) qualitative model 4. Pilliga riverine - projected foliage cover 5. Pilliga riverine - average number of families of aquatic macroinvertebrates in instream pool habitat sampled using the NSW Ausrivas method for pools	Permanent lowland stream, Permanent lowland stream GDE, Temporary lowland stream, Temporary lowland stream GDE, Permanent upland stream, Permanent upland stream GDE, Temporary upland stream, Temporary upland stream GDE, Upland riparian forest GDE	
All reporting regions		
Grassy woodland GDE No receptor impact model	Grassy woodland GDE	
Non-floodplain wetland (GDE and non-GDE) No receptor impact model	Non-floodplain wetland, Non-floodplain wetland GDE	
Rainforests (GDE and non-GDE) No receptor impact model	Rainforest, Rainforest GDE	
GAB springs No receptor impact model	GAB springs	

GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem
Adapted from Table 5 in Receptor impact modelling for the Namoi subregion (Ickowicz et al., 2017)

The simplification and aggregation of landscape classes necessary for receptor impact modelling indicates that there is an opportunity to simplify the BA landscape classification for the Namoi subregion, particularly with regards to assessment of potential impacts from coal seam gas development. Further, there is an opportunity to explicitly link GDEs to the groundwater model layers to improve future assessment of impacts from coal seam gas development.

2.2 Simplified surficial hydrogeology

Hydrogeological conceptualisation relevant to the numerical groundwater model is described in Product 2.6.2 Groundwater numerical modelling (Janardhanan et al., 2018) and summarised briefly below. Groundwater flow in the Namoi subregion is contained in, from oldest to youngest, the Permian Gunnedah Basin, the Jurassic to Cretaceous Surat Basin and the Cenozoic alluvium. Water sources in the Namoi subregion can be conceptualised as consisting of three distinct but connected groundwater flow systems: 1) shallow alluvial groundwater sources, 2) deep groundwater sources in the GAB, primarily in the Pilliga Sandstone and other confined aquifers, and 3) surface water sources within the Namoi River and connected streams and creeks.

Quaternary-age alluvial deposits along the Namoi River and creeks feeding into the river are important sources of fresh groundwater for agriculture in the subregion and have higher hydraulic conductivities than the underlying sedimentary rocks. The Pilliga Sandstone is the other major regional groundwater source in the Surat Basin in the Namoi subregion. Non-alluvial, near-surface rock units including shale and siltstone layers are typically more weathered and have lower permeabilities. The eastern side of the subregion is defined by the Hunter-Mooki Thrust Fault and is assumed to be a zero-flow boundary in the numerical groundwater model. Regional-scale groundwater flow generally follows the direction of the topography from an east to north-westerly to westerly direction.

Surface water – groundwater interactions are predominantly losing (i.e recharge from the stream to the groundwater) in the Lower Namoi and gaining (i.e. baseflow to the river) in the Upper Namoi where the watertable is shallow. The degree of connectivity between the alluvium, GAB and Gunnedah Basin aquifers is a significant knowledge gap;

Most GDEs in the Namoi subregion rely on water from the alluvial formations, Pilliga Sandstone or localised sources in the outcrop of other formations such as basalt, sandstone, siltstone and shale layers. The important aquifer formations were conceptualised as independent layers in the numerical groundwater model, which can be simplified into three simple classes when considering hydrogeological connectivity to GDEs (Table 3). Groundwater-dependent landscape classes associated with each groundwater source are summarised below:

- Alluvium in lowland areas – 'Floodplain wetland GDEs', 'Floodplain grassy woodland GDEs', Floodplain riparian forest GDEs', 'Permanent lowland stream GDE' and 'Temporary lowland stream GDE'
- Alluvium in upland areas – 'Non-floodplain wetland GDE', 'Upland riparian forest GDE', 'Permanent upland stream GDE' and 'Temporary upland stream GDE'
- Pilliga Sandstone – 'Grassy woodland GDE', 'Permanent upland stream GDE', 'Temporary upland stream GDE' and 'GAB springs'
- Low permeability rock – 'Grassy woodland GDE', 'Non-floodplain wetland GDE', 'Upland riparian forest GDE', 'Permanent upland stream GDE', 'Temporary upland stream GDE' and 'Rainforest GDE'.

Table 3 Simplified hydrostratigaphy of the geological and groundwater model layers for the Namoi subregion

Geological model layer name	Geological model layer	Numerical model layer	Geological units	Simplified surficial hydrogeology
Alluvium 1	1	1	Narrabri Formation	Alluvium
Alluvium 2	2	1	Gunnedah Formation Cubbaroo Formation	Alluvium
Interburden 1	3	2-5	Warrumbungle Volcanics Liverpool Range Volcanics Rolling Downs Group	Low permeability rock
Pilliga Sandstone	4	6	Pilliga Sandstone	Pilliga Sandstone

Geological model layer name	Geological model layer	Numerical model layer	Geological units	Simplified surficial hydrogeology
Interburden 2	5	7-9	Purlawaugh Formation Garrawilla Volcanics Napperby and Deriah formations Black Jack Group – Coogal and Nea subgroups	Low permeability rock
Hoskissons Coal	6	10	Hoskissons Coal	Low permeability rock
Interburden 3	7	11-13	Black Jack Group – Brothers subgroup Watermark Formation Porcupine Formation	Low permeability rock
Maules Creek Formation	8	14	Maules Creek Formation	Low permeability rock
Basement	9	15	Boggabri Volcanics	Low permeability rock

Adapted from Table 5 (Janardhanan et al., 2018)

The probabilistic approach used for the Namoi groundwater model, which requires thousands of model-runs with different parameter combinations, means that the groundwater model must be computationally efficient, represent just the key processes for a regional-scale assessment and have an appropriate spatial resolution to represent local- to regional-scale effects of coal resource development. For this reason, it uses a simplified representation of the hydrostratigraphy in comparison to mapped regional-scale surface geology. While there are some differences between the two representations of the surficial hydrogeology relevant to GDEs, the major features of each geological layer are well represented in the vicinity of the Narrabri gas project (Figure 2). Importantly, the colluvium and sand areas in the Pilliga Outwash area to the west of Narrabri are modelled as Pilliga Sandstone or Interburden (Low permeability rock), which have overlapping hydraulic parameter ranges. This linkage between GDEs (i.e. source aquifer) and potential hydrological changes in the surficial hydrogeology (i.e. surface groundwater model layer) is critical when assessing potential impacts to GDEs for any future assessments.

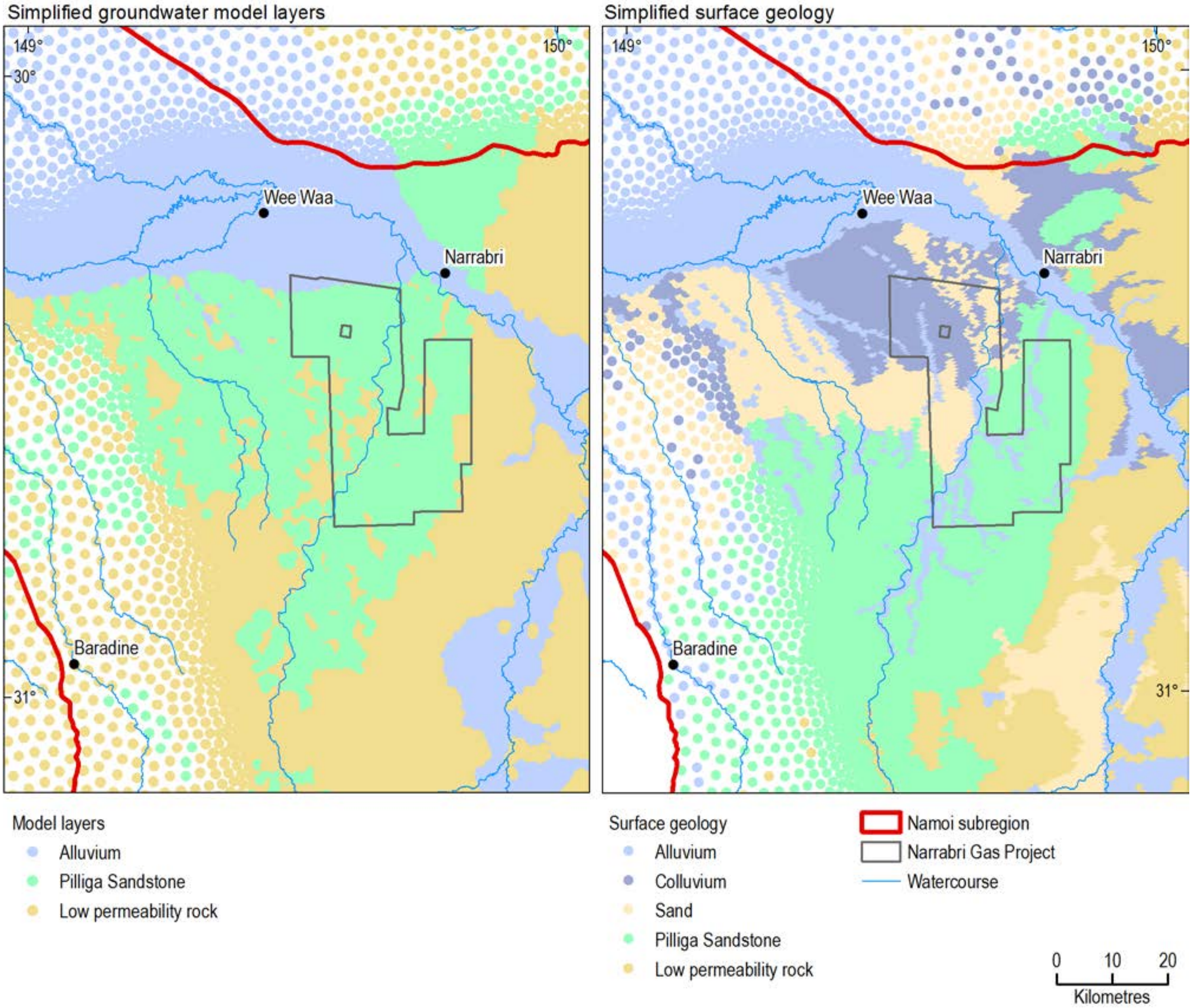

Figure 2 Simplified surficial hydrogeology in the Namoi regional groundwater model (left) and surface geological mapping (right)

Data: Bioregional Assessment Programme (2016), Geoscience Australia (2012)

2.3 Interim Biogeographic Regionalisation for Australia (IBRA)

The Interim Biogeographic Regionalisation for Australia (IBRA) describes the environmental gradients in climate and physiognomy that support a variety of ecosystems at a regional-scale. Physical characteristics, including soils, land and soil capability, land cover and land use, are similar within each subregion. There are four IBRA subregions that describe the broad geographic zones in the Namoi subregion that are relevant when assessing water-related impacts (Table 4). Surface water flows generally increase from east to west, from the elevated areas, including the Peel, Northern Basalt, Northern Outwash and Kaputar IBRA subregions to the Liverpool Plains and Castlereagh-Barwon IBRA subregions. Surface water flows from the elevated Pilliga and Pilliga Outwash subregions into the Castlereagh-Barwon IBRA subregion (Figure 3).

Table 4 Interim Biogeographic Regionalisation for Australia (IBRA) subregions in the Namoi subregion

	Castlereagh-Barwon	Liverpool Plains	Merriwa-Nandewar uplands [a]	Pilliga and Pilliga Outwash
Mean annual rainfall (mm)	<600	650–750	>750	600–750
Climate	Semi-arid (hot, dry)	Sub-humid; no dry season	Warm, dry, slight summer dominance	Sub-humid; no dry season
Physiography	Overlapping, low-gradient alluvial fans	Alluvial fans and outwash slopes	Basalt over sandstone slopes and tablelands	Quartz sandstone plateau; long gentle outwash slopes
Soil	Clay soils on plains; sandy soils along older streams	Black earths on low slopes; brown clays, alluvial soils and texture contrast soils	Clay or loam soils; black earths; red or brown, well-structured clays	Thin stony, sandy soils; texture contrast soils on slopes; deep sands, grey clays and texture contrast soils in valleys
Land and soil capability	Moderate with areas of few limitations	Moderate with areas of few limitations	Extreme limitations: steep, rocky, erosion	Severe limitations: erosion, sodicity, salinity, scalding
Land cover	Pasture and crops; sparse trees	Crops and pasture	Sparse – closed trees	Sparse – open trees
Vegetation	River red gum (*Eucalyptus camaldulensis*); coolibah-black box (*E. coolabah, E. largiflorens)*; poplar box (*E. populnea*); weeping myall (*Acacia pendula*)	Plains (*Austrostipa aristiglumis*), panic (*Digitaria brownii*), windmill (*Chloris truncata*) and blue grasses (*Dicanthium sericeum*) on black earths with occasional box woodlands (*E. melliodora*); cypress pine (*Callitris* spp.), occasional belah and mulga (*A. aneura*) on slopes	Open box woodlands (*E. melliodora, E. leucoxylon*); barrow-leaved ironbark/cypress pine woodlands	Poplar box, pilliga box (*E. pilligaensis*), narrow-leaved ironbark (*E. crebra*), Blakely's red gum (*E. blakelyi*), cypress pine (*Callitris* spp.) on coarser soils; belah (*Casuarina cristata*), brigalow (*A. harpophylla*); river red gum in creek lines
Wetlands	Namoi River floodplains	Lake Goran, floodplain wetlands	Not applicable	Gilgai wetlands
Land use	Dryland cropping; grazing (native pasture); irrigated crops; forestry	Dryland cropping; grazing (modified pasture); irrigated crops	Nature conservation; grazing	Nature conservation; forestry
Important landscape classes	Floodplain riparian forest, Floodplain riparian forest GDE, Floodplain wetland, Floodplain wetland GDE, Permanent lowland stream, Permanent lowland stream GDE, Temporary lowland stream, Temporary lowland stream GDE	Floodplain riparian forest, Floodplain riparian forest GDE, Floodplain wetland, Floodplain wetland GDE, Permanent lowland stream, Permanent lowland stream GDE, Temporary lowland stream, Temporary lowland stream GDE	Permanent upland stream, Permanent upland stream GDE, Temporary upland stream, Temporary upland stream GDE, Upland riparian forest GDE, Grassy woodland GDE, Rainforest, Rainforest GDE, Non-floodplain wetland, Non-floodplain wetland GDE, GAB springs, Non-GAB springs	Permanent upland stream, Permanent upland stream GDE, Temporary upland stream, Temporary upland stream GDE, Upland riparian forest GDE, Grassy woodland GDE, Non-floodplain wetland, Non-floodplain wetland GDE, GAB springs, Non-GAB springs

[a] Merriwa-Nandewar uplands include the Kaputar, Liverpool Range, Northern Basalt, Northern Outwash and Peel IBRA subregions
Adapted from Table 5 in Conceptual modelling for the Namoi subregion (Herr et al., 2018)

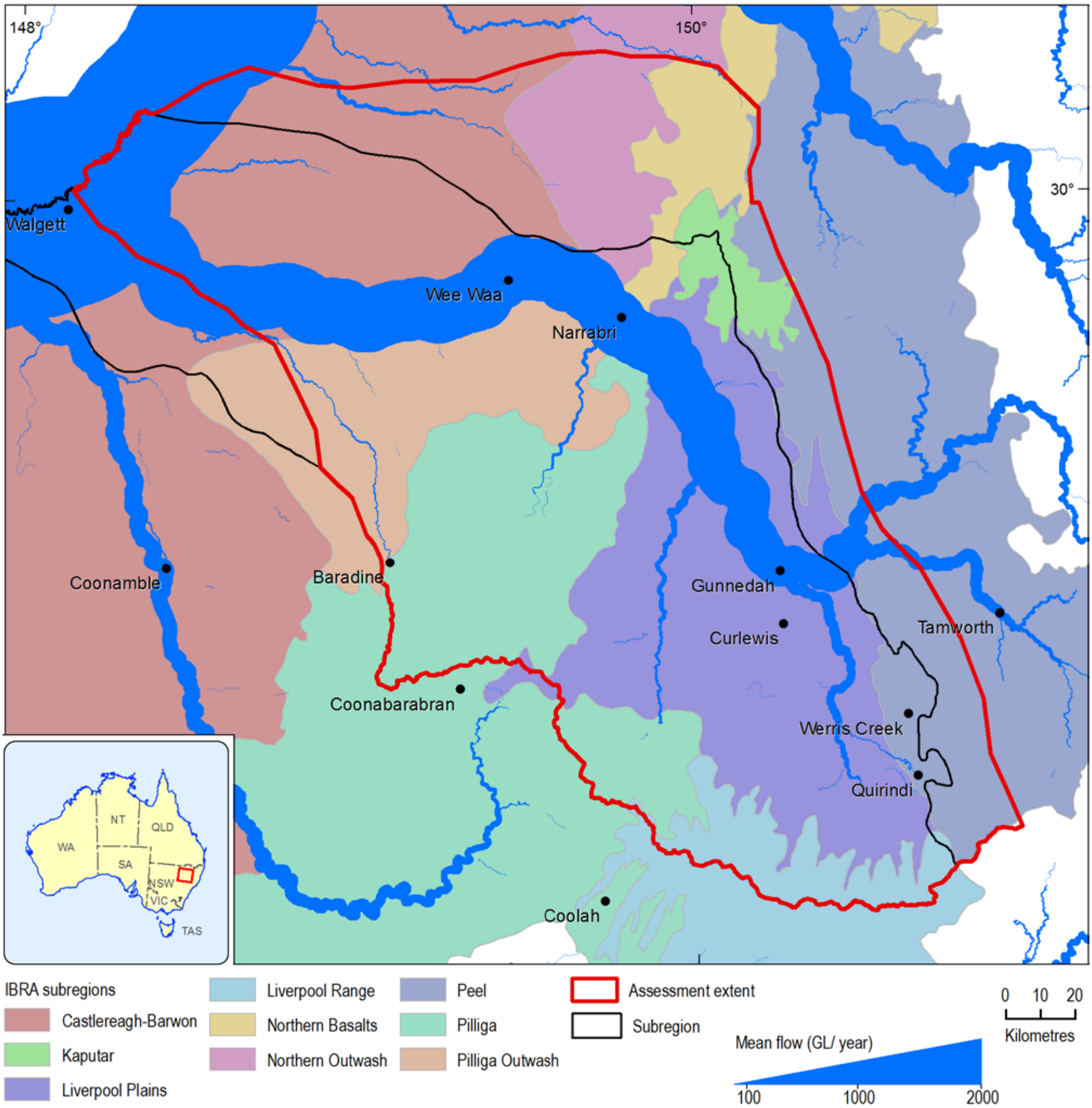

Figure 3 Interim Biogeographic Regionalisation for Australia (IBRA) subregions and surface water flows for river basins in the Namoi subregion

Long-term annual flow is estimated using the water balance technique of Budyko (1974), which does not consider any impounding or regulation of river flow.
Data: Bioregional Assessment Programme (2015), SEWPaC (2013)

While the Bioregional assessment landscape classification includes greater detail with respect to water-dependent ecosystems and particularly GDEs, the IBRA subregions provide a convenient means to aggregate groups of landscape classes based on the dominant physiography. Future assessments should consider the physiography of each IBRA subregion when aggregating landscape classes.

2.4 Simplified landscape classification for CSG impact assessment

There is an opportunity to build on the landscape classification approach used for Bioregional assessments to develop a simplified classification scheme that includes explicit linkages to ecosystem water sources, including surficial aquifers and surface water systems. Specifically, GDE landscape classes should include spatially explicit linkages to surficial aquifers represented in the numerical groundwater model, which is critical when assessing potential impacts to GDEs for any future assessments. Future assessments should also consider the physiography of each IBRA subregion when aggregating landscape classes.

This study has used simplified the BA landscape class at each groundwater model node to demonstrate this simplified landscape classification approach for CSG impact assessment as part of the GISERA "GAB flux" project. This approach uses the following criteria in order from highest to lowest priority:

1. Habitat – 'remnant vegetation and wetlands', 'non-remnant vegetation', 'streams' or 'springs'
2. Water regime – 'groundwater-dependent' (includes 'surface water dependent'), 'surface water-dependent' or 'not water-dependent'
3. Geomorphology – 'floodplain or lowland riverine' or 'non-floodplain or upland riverine' with consideration of the dominant physiography of the IBRA subregion
4. Surficial hydrogeology (only GDEs) – 'alluvium' or 'basalt, sandstone, low permeability rock' for vegetation and 'alluvium, basalt, low permeability rock' or 'sandstone' for springs based on surficial aquifers represented in the numerical groundwater model
5. Vegetation – vegetation type for 'remnant vegetation' or land use for 'non-remnant vegetation'
    - Vegetation type (Keith form): 'riparian' (including riverine forests, forested wetlands, floodplain wetlands), 'floodplain' (including grassy woodlands on floodplains), 'grassy woodland' or 'rainforest' (including rainforest, wet sclerophyll forest)
    - Land use: 'vegetation' (including conservation and natural environments, production from relatively natural environments), 'agriculture and plantations' (including intensive uses, production from dryland agriculture and plantations, production from irrigated agriculture and plantations) and 'human-modified stream' (including modified water bodies).

The simplified classification reduced the number of classes from 29 defined for the BA classification to 17 (Figure 4). This includes:

- eight remnant vegetation classes:
    - four groundwater-dependent remnant vegetation classes
    - two surface water-dependent remnant vegetation classes
    - two classes of remnant vegetation that are not water-dependent
- four non-remnant vegetation classes:
    - two surface water-dependent non-remnant vegetation classes
    - two classes of non-remnant vegetation that are not water-dependent
- three classes of streams:

– one groundwater-dependent stream class
– two surface water-dependent classes based on geomorphology

- two classes of springs based on source aquifer.

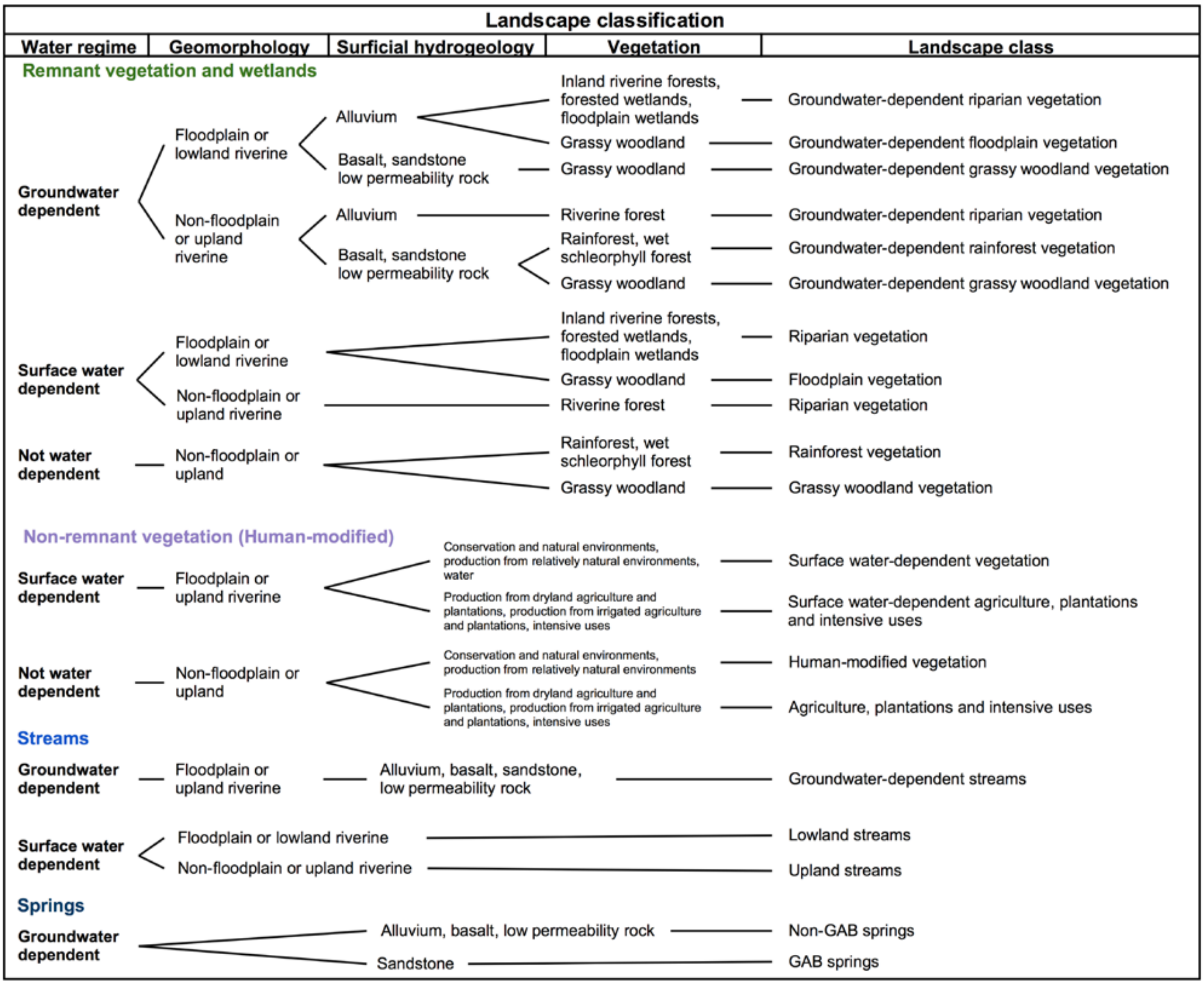

Figure 4 Simplified landscape classification for the Namoi subregion

GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem
Adapted from Figure 19 in Conceptual modelling for the Namoi subregion (Herr et al., 2018)

While this is a greater number of classes than the four aggregated landscape groups used for the Namoi subregion, this approach enables groundwater- and surface water-dependent landscape classes to be more easily distinguished. For example, the BA landscape groups do not distinguish between surface water-dependent and not water-dependent vegetation in the human-modified landscape group, which covers almost 60% of the assessment extent (Figure 5). The simplified classification is able to identify riparian vegetation in upland and lowland environments. The explicit spatial linkage between landscape class and surficial aquifers represented in the numerical groundwater model mean that potential impacts associated with hydrological changes to the surficial aquifers are linked to the appropriate ecosystems represented by each landscape class. This also enabled the identification of a subset of nodes from the regional scale numerical groundwater model to enable hypothesis testing and predictive uncertainty analysis of the impacts of CSG depressurization.

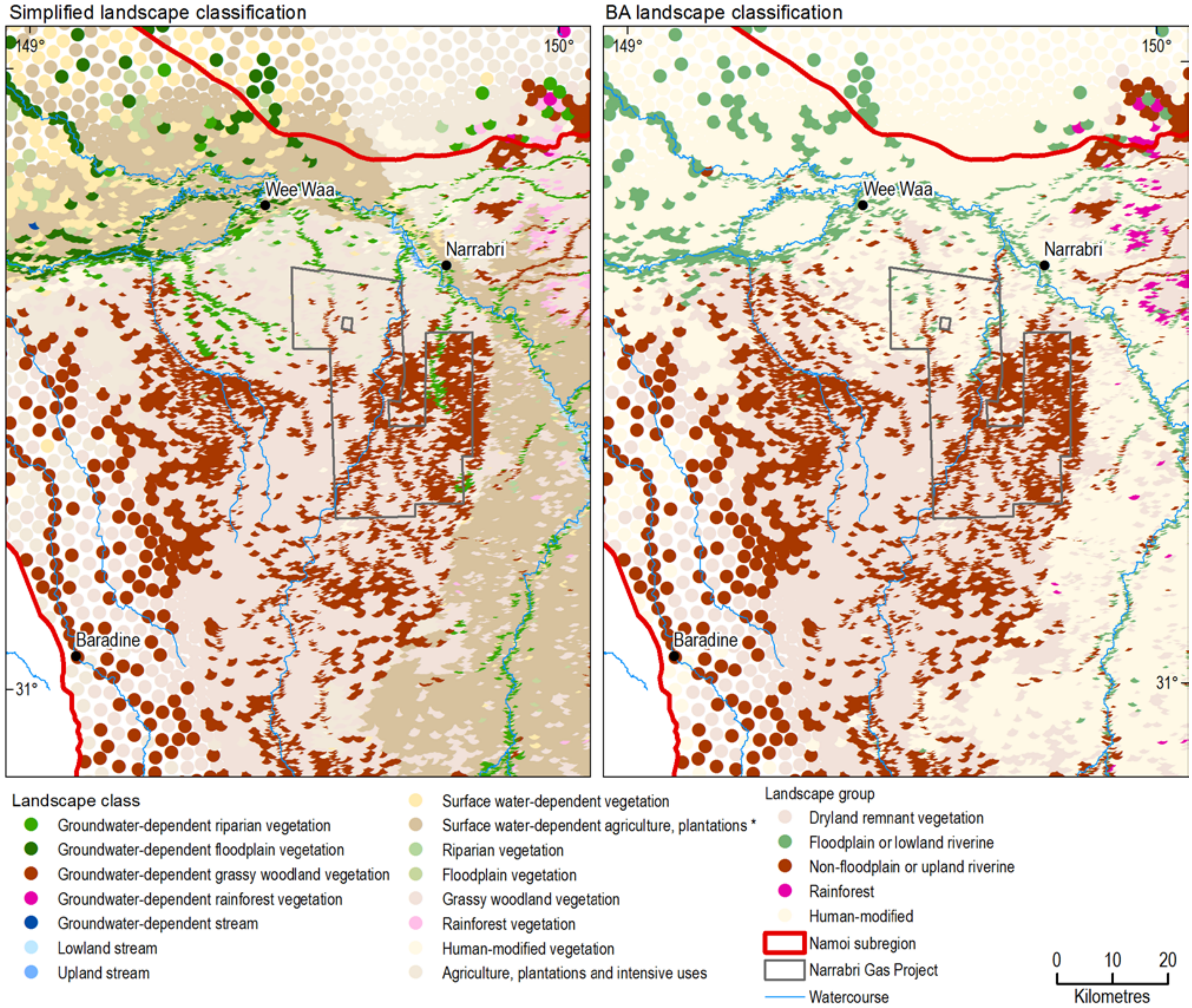

Figure 5 Simplified (left) and BA (right) landscape classifications for the Namoi subregion

Maps show landscape classification for each numerical groundwater model node in the vicinity of the Narrabri gas project
Data: Bioregional Assessment Programme (2016), Bioregional Assessment Programme (2017)

Most (10 of 17) simplified landscape classes include more than 5% of the total assessment extent (vegetation area, stream length or number of springs). The seven remaining classes include small areas of rainforest, riparian and floodplain vegetation that represent important, ecologically distinct ecosystems. Qualitative models were developed for each of these ecosystems for the Namoi subregion.

Table 5 Extent and proportion of Namoi assessment extent in each simplified landscape class

Landscape class	Landscape class extent	Percentage of assessment extent
Groundwater-dependent riparian vegetation (km^2)	324	0.9%
Groundwater-dependent floodplain vegetation (km^2)	1,445	4.1%
Groundwater-dependent grassy woodland vegetation (km^2)	3,248	9.1%
Groundwater-dependent rainforest vegetation (km^2)	43	0.1%
Riparian vegetation (km^2)	249	0.7%
Floodplain vegetation (km^2)	400	1.1%
Grassy woodland vegetation (km^2)	8,624	24.2%
Rainforest vegetation (km^2)	153	0.4%
Total remnant vegetation area (km^2)	**14,487**	**40.7%**
Surface water-dependent vegetation (km^2)	2,099	5.9%
Surface water-dependent agriculture, plantations and intensive uses (km^2)	13,864	38.9%
Human-modified vegetation (km^2)	840	2.4%
Agriculture, plantations and intensive uses (km^2)	4,342	12.2%
Total non-remnant vegetation area (km^2)	**21,145**	**59.3%**
Groundwater-dependent stream (km)	1,657	5.6%
Lowland stream (km)	9,739	33.0%
Upland stream (km)	18,143	61.4%
Total stream length (km)	**29,539**	**100%**
GAB springs (number)	7	32%
Non-GAB springs (number)	15	68%
Total springs (number)	**22**	**100%**

Adapted from Tables 7 to 9 in Conceptual modelling for the Namoi subregion (Herr et al., 2018)

3 Improved hydrogeological and ecohydrological conceptualisation

Table 6 summarises the qualitative and receptor impact models, and their respective hydrological response variables for each simplified landscape class (Ickowicz et al., 2018). Landscape classes and hydrological response variables related to changes to groundwater levels are highlighted and discussed below.

Table 6 Qualitative model and receptor impact models relevant for each simplified landscape class

Simplified landscape class	Qualitative model, receptor impact model and hydrological response variables
Groundwater-dependent riparian vegetation	**Floodplain and lowland riverine qualitative model** 1. Floodplain riparian forests – projected foliage cover (Events R3.0, **dmaxref**, tmaxref) **Pilliga riverine (upland and lowland) qualitative model** 4. Pilliga riverine – projected foliage cover (ZQD, **dmaxref**, tmaxref) **Upland riverine qualitative model** 6. Upland riparian forest – projected foliage cover (Events R3.0, **dmaxref**, tmaxref)
Riparian vegetation	**Floodplain and lowland riverine qualitative model** 2. Floodplain wetland (GDE and non-GDE) – Probability of presence of tadpoles from Limnodynastes genus (*Dumerilii, Salmini, Interioris* and *Terraereginae*) in pools and riffles (Events R3.0)
Groundwater-dependent stream	**Pilliga riverine (upland and lowland) qualitative model** 5. Pilliga riverine – average number of families of aquatic macroinvertebrates in instream pool habitat sampled using the NSW Ausrivas method for pools (ZQD, ZME, **dmaxref**, tmaxref)
Lowland stream	**Floodplain and lowland riverine qualitative model** 3. Permanent and temporary lowland streams (GDE and non-GDE) – average number of families of aquatic macroinvertebrate in edge habitat (ZQD, ZME)
Upland stream	**Upland riverine qualitative model** 7. Permanent and temporary upland streams (GDE and non-GDE) – average number of families of aquatic macroinvertebrates in instream pool habitat sampled using the NSW Ausrivas method for pools (ZQD, ZME) 8. Upland riverine – probability of presence of tadpoles from *Limnodynastes* genus (*Dumerilii, Salmini, Interioris and Terraereginae*) (ZQD, ZME)
Qualitative model developed, but no receptor impact model developed	
Floodplain vegetation, **GAB springs**, **Groundwater-dependent floodplain vegetation**, **Groundwater-dependent grassy woodland vegetation**, **Groundwater-dependent rainforest vegetation**, Rainforest	
No qualitative model or receptor impact model developed	
Agriculture, plantations and intensive uses, Grassy woodland vegetation, Human-modified vegetation, **Non-GAB springs**, Surface water-dependent agriculture, plantations and intensive uses, Surface water-dependent vegetation	

GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem
Simplified landscape classes relevant to improved hydrogeological conceptualisation are highlighted with bold font
Source: adapted from Table 5 in Receptor impact modelling for the Namoi subregion (Ickowicz et al., 2018)

Important hydrological response variables defined for receptor impact models include:

- 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)
- tmaxRef – year that the maximum difference in drawdown occurs, across all years. tmaxRef is negative if before the end of the relevant period or positive if after the end of the relevant period. The short-term period is 2013 to 2042 and the long-term period is 2073 to 2102.

- EventsR3.0 – mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in floods 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 flows in future 30-year periods.
- ZQD – number of zero-flow days per year, averaged over a 30-year period
- ZME – maximum length of spells (in days per year) with zero flow, averaged over a 30-year period.

3.1 Receptor impact models

Receptor impact models developed for the Namoi subregion are described in Product 2.7 Receptor impact modelling (Ickowicz et al., 2018). Four of the eight receptor impact models developed for the Namoi subregion are relevant to the assessment of potential impacts to groundwater-dependent ecosystems for two simplified landscape classes:

- Groundwater-dependent riparian vegetation – projected foliage cover
- Groundwater-dependent stream – families of aquatic macroinvertebrates.

3.1.1 Groundwater-dependent riparian vegetation

Three receptor impact models for projected foliage cover from three qualitative models are relevant to this simplified landscape class, which are summarised below:

Floodplain and lowland riverine qualitative model

1. Floodplain riparian forests – projected foliage cover (Events R3.0, dmaxref, tmaxref)

Pilliga riverine (upland and lowland) qualitative model

4. Pilliga riverine – projected foliage cover (ZQD, dmaxref, tmaxref)

Upland riverine qualitative model

6. Upland riparian forest – projected foliage cover (Events R3.0, dmaxref, tmaxref).

In **Floodplain and lowland riverine** environments, the key hydrological determinants of ecosystem function identified by the experts is the response of the floodplain riparian forests to changes in hydrological regime and groundwater levels in the alluvium (Events R3.0, dmaxref, tmaxref). The **'Floodplain riparian forests'** receptor impact model describes changes to projected foliage cover of forests dominated by river red gum (*E. camaldulensis*) along alluvial river and creek flats in the Namoi subregion. Projected foliage cover is the mean annual value measured in a 100 m x 100 m (1 ha) plot. The experts' opinion provides strong evidence that:

- Antecedent foliage cover has a strong effect on future foliage cover, which reflects the lag in the response of canopy cover to changes in hydrological response variables that would be expected of mature trees with long life spans.
- Mean percent foliage cover would decrease from approximately 15% to 10% if groundwater depth increases by 20 m and all other model variables are held at their median values.
- Mean percent foliage cover would increase from approximately 12% to 18% as the number of flood events with peak daily flow exceeding the 1983 to 2012 2-year return period (Events

R3.0) increases from the reference level of 0.33 in 2012 to 0.7 and all other model variables are held at their median values.

There is considerable uncertainty in these predictions, particularly related to the effect of groundwater levels on projected foliage cover. There is an 80% chance that projected foliage cover is between 5% and 30% in the short-term assessment period, and between 2% and 20% in the long-term assessment period. It is likely that long term drawdown will cause a greater decrease in projected foliage cover than short-term drawdown.

In the **Pilliga riverine** environments, the key hydrological determinants of ecosystem function identified by the experts are related to changes in zero-flow regime and groundwater levels in the alluvium (ZQD, dmaxref, tmaxref). The '**Pilliga riverine – projected foliage cover**' receptor impact model describes changes to projected foliage cover of riparian vegetation, including yellow box, white cypress pine, *Eucalyptus crebra*, dirty gum, Blakely's red gum, *Angophora floribunda*, *Eucalyptus fibrosa* and Fuzzy box. Projected foliage cover is the mean annual value measured along a 50 m x 20 m transect that extends from the first bench ('toe') on both sides of the stream. The experts' opinion provides strong evidence that:

- Antecedent foliage cover has a strong effect on future foliage cover, which reflects the lag in the response of canopy cover to changes in hydrological response variables that would be expected of mature trees with long life spans.
- Mean projected foliage cover would decrease from approximately 25% to 20% if groundwater depth increases by 150 m and all other model variables are held at their median values.
- Mean percent foliage cover would increase from approximately 12% to 18% as the number of flood events with peak daily flow exceeding the 1983 to 2012 2-year return period (Events R3.0) increases from the reference level of 0.33 in 2012 to 0.7 and all other model variables are held at their median values.

There is considerable uncertainty in these predictions, particularly related to the effect of groundwater levels on projected foliage cover. There is an 80% chance that projected foliage cover is between 15% and 30% in the short-term assessment period, and between 10% and 30% in the long-term assessment period with a 6-m decrease in groundwater levels. It is likely that short-term drawdown will cause a greater decrease in projected foliage cover than long-term drawdown.

In **Upland riverine** environments, the key hydrological determinants of ecosystem function identified by the experts are related to changes in hydrological regime and groundwater levels in the alluvium (Events R3.0, dmaxref, tmaxref). The '**Upland riparian forest**' receptor impact model describes changes to projected foliage cover of riparian vegetation, including Casuarina, yellow box, Blakely's red gum, *Acacia salicina*, *Angophora floribunda* and grey box. Projected foliage cover is the mean annual value measured along a 50 m x 20 m transect that extends from the first bench ('toe') on both sides of the stream. The experts' opinion provides strong evidence that:

- Antecedent foliage cover has a strong effect on future foliage cover, which reflects the lag in the response of canopy cover to changes in hydrological response variables that would be expected of mature trees with long life spans.

- Mean projected foliage cover would decrease from approximately 25% to 20% if groundwater depth increases by 150 m and all other model variables are held at their median values.
- Mean percent foliage cover would increase from approximately 24% to 30% as the number of flood events with peak daily flow exceeding the 1983 to 2012 2-year return period (Events R3.0) increases from the reference level of 0.33 in 2012 to 0.8 and all other model variables are held at their median values.

There is considerable uncertainty in these predictions, particularly related to the effect of groundwater levels on projected foliage cover. There is an 80% chance that projected foliage cover is between 15% and 30% in the short-term assessment period, and between 10% and 30% in the long-term assessment period with a 6-m decrease in groundwater levels. It is likely that long-term drawdown will cause a greater decrease in projected foliage cover than short-term drawdown.

3.1.2 Groundwater-dependent stream

One of the receptor impact models that describes changes to aquatic macroinvertebrates is relevant to this simplified landscape class, which is summarised below:

Pilliga riverine (upland and lowland) qualitative model

5. Pilliga riverine – average number of families of aquatic macroinvertebrates in instream pool habitat sampled using the NSW Ausrivas method for pools (ZQD, ZME, dmaxref, tmaxref)

In the **Pilliga riverine** environments, the key hydrological determinants of ecosystem function in groundwater-dependent streams identified by the experts are related to changes in zero-flow regime and groundwater levels in the alluvium (ZQD, ZME, dmaxref, tmaxref). The '**Pilliga riverine – aquatic macroinvertebrates**' receptor impact model describes the average number of families of aquatic macroinvertebrates in instream pool habitat sampled using the NSW Ausrivas method for pools. The experts' opinion provides strong evidence that:

- Number of aquatic macroinvertebrates families would decrease from approximately 15 to 20 under constant flow conditions (ZQD = zero) to 13 under very intermittent flow conditions (ZQD > 150 days) when all other model variables are held at their median values. Uncertainty of the expert's predictions increased for the long-term assessment period. The model indicated that there is likely to be very little lag in the response of this short-lived species to changes in the hydrological response variables.
- Number of aquatic macroinvertebrates families would decrease by 50% from approximately 12 families if groundwater levels decrease by 55 m and all other model variables are held at their median values.

There is considerable uncertainty in these predictions, particularly related to the effect of groundwater levels on number of aquatic macroinvertebrates families. There is an 80% chance that the number of aquatic macroinvertebrates families is between 1 and 12 in both the short- and long-term assessment periods. It is likely that short-term drawdown will cause a greater decrease in number of aquatic macroinvertebrates families than long-term drawdown.

3.2 Qualitative models

Four of the six qualitative models developed for the Namoi subregion (Ickowicz et al., 2018) are relevant to the assessment of potential impacts to groundwater-dependent ecosystems:

- Groundwater-dependent floodplain vegetation
- Groundwater-dependent grassy woodland vegetation
- Groundwater-dependent rainforest vegetation
- Springs (includes GAB springs and non-GAB springs).

3.2.1 Groundwater-dependent floodplain vegetation

The **Floodplain and lowland riverine qualitative model** includes off-channel water bodies, which are filled by connections to overbank floods and groundwater. These water bodies provide habitat for plankton (Boon et al., 1996), macrophytes (Bunn and Boon, 1993) and populations of fish (Closs et al., 2005), off-channel frogs (Ocock et al., 2014), and still-water invertebrates such as shrimps and snails (Boulton and Lloyd, 1991). Slow-water native fishes and some water bird species are major predators of the off-channel frogs. Floodplain grasses, shrubs and trees provide inputs of coarse particulate organic matter to the stream system, and habitat for mammals, reptiles, frogs and birds (Bunn and Boon, 1993). Floodplain trees (i.e. trees outside of the riparian zone on top of river terraces such as black box) are dependent on groundwater for their growth and survival, but recruitment is not dependent on any specific overbank flow regime.

Overbank floods facilitate the transport of organic matter from the floodplain into the stream channel that may lead to hypoxic blackwater events (so-called because high concentrations of dissolved organic matter leached from inundated detritus darkens the water) (Whitworth et al., 2012). Blackwater events severely lower pH and dissolved oxygen in floodwaters, adversely affecting many fish and aquatic invertebrates such as crayfish (Hladyz et al., 2011); (McCarthy et al., 2014). Flood inundation duration is important for populations of long-lived tadpoles, the composition of and emergence from the microinvertebrate ‘egg bank’ (Jenkins and Boulton, 2007), and the proportions of families of aquatic invertebrate communities. Floods can also increase the relative dominance of hyporheic fauna over phreatic fauna (obligate stygobites) in aquifers alongside stream channels.

The ‘Floodplain or lowland riverine’ qualitative and receptor impact models focus on the riparian forests and aquatic fauna rather than floodplain vegetation. Hydrological response variables for floodplain riparian trees are changes to hydrological regime (EventsR3.0) and maximum groundwater drawdown (dmaxref) in the alluvium. Qualitative model predictions are generally negative, neutral (zero) or ambiguous for biological variables within floodplain or lowland riverine environments, with the exception of off-channel frogs, which can be attributed, in part, to a predicted decline in their native fish predators. Riparian trees were predicted to decrease, while riparian vegetation (sedges and rushes) is predicted to decrease only in response to an increase in zero-flow days. Hyporheic and phreatic fauna are predicted to decrease in response to decreases in overbank flows. The qualitative model predicts that the response of floodplain trees is ambiguous, but with an 80% chance of a negative response to groundwater drawdown.

3.2.2 Groundwater-dependent grassy woodland vegetation

Most groundwater-dependent grassy woodland vegetation is located in the Pilliga and Pilliga Outwash parts of the Namoi subregion. The qualitative model describes ecological processes associated with trees, shrubs and grasses, with three functional groups of shrubs defined by their relationship with fire, which is fuelled by large woody debris, leaf litter and grasses. This includes fire-sensitive shrubs that are suppressed by fire; fire-obligate shrubs that require fire for regeneration; and fire-tolerant shrubs that can survive fire (Purdie, 1976). Stores of woody debris and litter that are not consumed by fire contribute, through decomposition, to the soil microbial community and populations of ground-dwelling insects (York, 1999). These insects are a primary food resource for ground-dwelling invertebrates and burrowing frogs, both of which benefit from the habitat structure provided by grass communities.

Trees (specifically large old-growth trees) provide tree hollows for arboreal vertebrates (i.e. birds and mammals). Trees also affect local climate by enhancing the production of rain clouds, leading to increased rates of local precipitation that contribute to local stores of groundwater (Nair, 2011). The level of the watertable is a critical factor for the survival of burrowing frogs, both clay-cocooning and sandy-soil aestivators, and also the growth and survival of trees and fire-tolerant shrubs. Maximum groundwater depth is a potentially important hydrologic response variable that could affect the growth and survival of trees.

A single hydrological response variable was identified for groundwater-dependent grassy woodland, maximum groundwater drawdown (dmaxref) in the regional watertable, which includes outcropping parts of the Pilliga Sandstone. However, the qualitative model predictions are ambiguous or neutral for all biological variables within the groundwater-dependent grassy woodland ecosystem, which is a result of positive feedback in a number of subsystems of this model, including the grass – large woody debris and leaf litter-soil microbial community system, and the grass-fire-fire sensitive shrub system.

3.2.3 Groundwater-dependent rainforest vegetation

'Rainforest' vegetation includes forests with a closed canopy generally dominated by non-eucalypt species with soft, horizontal leaves, however, various eucalypt species may be present as emergents (Keith, 2004). Rainforest in the Peel, Kaputar and Northern Basalts IBRA subregions is predominantly notophyll vine thicket dominated by *Ficus rubiginosa* and *Notelaea macrocarpa* at higher elevations on scree slopes and gullies in Mt Kaputar National Park and other similar mountainous terrain (Curran et al., 2008; Benson et al., 2010). Whereas, rainforest vegetation in the Liverpool Plains and Liverpool Plains and Northern Outwash IBRA subregions is predominantly semi-evergreen thicket on basalt outcrops and sandstone hills (dominated by *Notelaea microcarpa, Geijera parviflora* and *Ehretia membranifolia*) and low microphyll vine forest (dominated by *Cadellia pentastylis*) (Curran et al., 2008).

The 'Rainforest' qualitative model focuses on the functional aspects of tree, shrub (tall and short) and vine vegetation, their ecological roles, and their dependency on soil moisture and / or groundwater. Tall shrubs provide shade, which under optimal conditions, benefits shorter shrubs and contributes to a humid microclimate close to the ground. Shrubs also produce fruits that sustain populations of fruit-eating birds, mammals and arboreal invertebrates. Shrubs and vines provide habitat structure important for arboreal invertebrates and their leaf litter maintains surface soil moisture and is a food resource for soil-dwelling invertebrates. Both groups of invertebrates are a key food resource for frogs, birds, mammals and reptiles. These insectivores are in turn preyed upon by snakes, insectivorous reptiles, birds and mammals, which in turn are consumed by predatory birds and goannas. A significant threat is feral pigs, which consume the fruits of shrubs and plough through the upper soil layers in search of roots as well as frogs, reptiles and insects (OEH, 2010). They are a major source of disturbance to the system that destroys the humid microclimate of the forest floor. Fragmentation from land clearing similarly compromises the humid microclimate, and decreases the amount of shade and habitat structure (OEH, 2010).

Rainforest vegetation relies predominantly on soil water derived from incident rain supplemented by localised surface runoff and / or localised groundwater discharge from fractured or porous substrates. Declines in tree water status across many different dry rainforest communities were observed during drought periods (Curran et al., 2010), which suggest limited or no access to the watertable and a heavy reliance on rainfall supply. Decreases in groundwater levels could limit replenishment of deep soil moisture or even make it too deep to be accessed by tree roots. Fauna from adjacent lowlands may use rainforests as a seasonal refuge, which may increase if the lowland watertable is drawn down.

A single hydrological response variable was identified for groundwater-dependent grassy woodland, maximum groundwater drawdown (dmaxref) in the regional watertable, which includes outcropping parts of basalt aquifers. The qualitative model predicts a generally negative response to groundwater drawdown for most biological variables within the rainforest ecosystem. A predicted decrease in pigs leads to reduced predation of insectivorous reptiles, a predicted increase of which also favours goannas.

3.2.4 Springs

Springs are surface expressions of groundwater that create water flow at the surface and can discharge into wetlands and streams. Importantly, workshop participants “identified a general lack of knowledge about the actual location of springs in the basin” (Ickowicz et al., 2018). Recharge springs (Fensham and Fairfax, 2003) were considered most likely to be impacted by coal resource development. The experts at the workshop defined the flow path of these springs as originating from water that is absorbed into sandstone sediments that outcrop on the margins of the GAB and discharged locally after relatively short residence times.

In the Namoi subregion, GAB springs are surface expressions of groundwater sourced from aquifers contained in the Triassic, Jurassic and Cretaceous sedimentary sequences associated with the GAB (Habermehl, 1982). GAB springs may form surface water bodies that support aquatic ecosystems and typically contain endemic species and plant communities that have significant ecological, economic and cultural values (Fensham and Fairfax, 2003). GAB springs can be associated with faults or aquitards, thinning of the confining layer or topographic conditions, such as a change of slope or a depression into an aquifer, that allow groundwater to discharge at the surface (Queensland Water Commission, 2012). Springs can be classed as ‘recharge’ or ‘discharge’ springs. Recharge springs form where the sediments that make up the aquifers of the GAB have surface expressions and tend to be situated within the recharge zones of the eastern margin of the GAB (Fensham and Fairfax, 2003). Groundwater recharge into the GAB aquifers in these areas occurs along sandstone outcrop areas that can include hilly upland areas, where rainwater percolates into the GAB aquifers between confining layers. The discharge of localised recharge is also termed ‘rejected recharge’. All other springs associated with GAB aquifers are known as discharge springs and tend to occur down-gradient from recharge areas, due to the presence of faults or where an aquifer comes to the surface (Fensham and Fairfax, 2003).

‘Non-GAB springs’ are associated with local flow systems in the basalt aquifers in the eastern portions of the assessment extent and are disconnected from the underlying GAB aquifers. In the Namoi assessment extent, there are no artesian spring communities listed under the Commonwealth’s *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), but there is one artesian spring community listed under the NSW *Threatened Species Conservation Act 1995* that is predicted to occur on the Liverpool Plains (OEH, 2016).

The saturated zone or water depth of the spring is a critical threshold in the Springs qualitative model; water depths above this threshold increased the amount of vegetation surrounding the spring (i.e. fringe vegetation), the amount of open water in the spring, and the amount of outflow. Below this threshold many of the ecological values of the spring cease to exist. Fringe vegetation provides habitat and other resources for populations of semi-aquatic and terrestrial invertebrates, which in turn are a food resource for frogs and terrestrial invertebrates, also living in the fringing vegetation (Fensham et al., 2004). Populations of submerged macrophytes depend on the amount of open-water habitat, and contribute to stores of organic matter, which is a primary resource for tadpoles and aquatic invertebrates that also depend on the volume of open-water habitat.

The amount of open-water habitat in a spring, and its depth, can be controlled by the structural influence of dams, excavations, and mud mounds (Fensham et al., 2012). The intensity of cattle grazing and populations of pigs, however, can dramatically diminish the depth of the open-water habitat by trampling and eroding its edges.

Subsurface habitats are vulnerable to drying when the watertable falls below the base of the spring, which can diminish the groundwater biota and invertebrate egg bank (Lamontagne, 2002). This invertebrate egg bank, which exists in the bottom and near-surface sediments of the spring, is an important source of propagules that allow the spring’s invertebrate community to recover after drying spells (Ponder, 1986).

A single hydrological response variable was identified for springs, maximum groundwater drawdown (dmaxref) in the inferred source aquifer, which includes Pilliga Sandstone for GAB springs and basalt aquifers for non-GAB springs. Qualitative model predictions are generally ambiguous or negative for all biological variables within recharge–rejection springs in response to a decrease in the watertable.

4 Analysis of CSG-induced groundwater impacts

The simplified landscape classification and improved conceptualization of hydrogeological connection describe 17 landscape classes, of which 5 include explicit linkages to groundwater sources. These five landscape classes are present within 30 km of the proposed coal seam gas development. Key hydrological determinants of ecosystem function for these landscape classes include changes in hydrological regime of surface water sources and groundwater levels in the surficial hydrogeological layer for terrestrial GDEs or the deeper source aquifers for springs. Explicit elicitation of the ecohydrological and hydrogeological connection of landscape classes enables the application of the numerical groundwater model to quantify hydrological responses to coal seam gas development at the relevant model nodes.

Ecohydrological receptors to assess potential CSG-induced groundwater impacts to water-dependent assets were selected from all regional model nodes across multiple layers within the 30-km buffer area. A subset of these receptors selected using the following criteria are shown in figure 6.

1) Selection to the north along the predominant groundwater flow direction
2) Groundwater-dependent landscape classes
3) Proximity to mapped springs, watercourses and economic bores
4) Connectivity to shallow (water table) and deep aquifers.

The representative set of receptors for groundwater-dependent landscapes is shown in figure 6 (Figure 6a and Table 7).

4.1 Groundwater-dependent landscape classes

Model nodes corresponding to receptors were randomly selected to represent GDEs that are potentially vulnerable to the impacts of CSG development. The 201 receptors include six of the seven groundwater-dependent simplified landscape classes (Table 7). This includes two receptor nodes located closest to the mapped springs (Figure 6). The ecohydrological risk receptor nodes receptors include eight of the ten BA landscape classes, but not the ‘Permanent upland stream GDE’ and ‘Temporary upland stream GDE’, which have limited representation in the area.

Table 7 Number of receptors in each groundwater-dependent landscape class

Simplified landscape class	BA landscape class	Receptors	Percent total
Groundwater-dependent floodplain vegetation	Floodplain grassy woodland GDE	7	3.5%
Groundwater-dependent riparian vegetation	Floodplain riparian forest GDE Floodplain wetland GDE Non-floodplain wetland GDE Upland riparian forest GDE	42	20.9%
Groundwater-dependent grassy woodland vegetation	Grassy woodland GDE	142	70.6%

Groundwater-dependent rainforest vegetation	Rainforest GDE	2	1.0%
Groundwater dependent stream	Temporary lowland stream GDE area	6	3.0%
GAB springs	GAB springs	2	1.0%
Non-GAB springs	Non-GAB springs	0	0%
	Total	201	100%

BA landscape classes are shown for reference

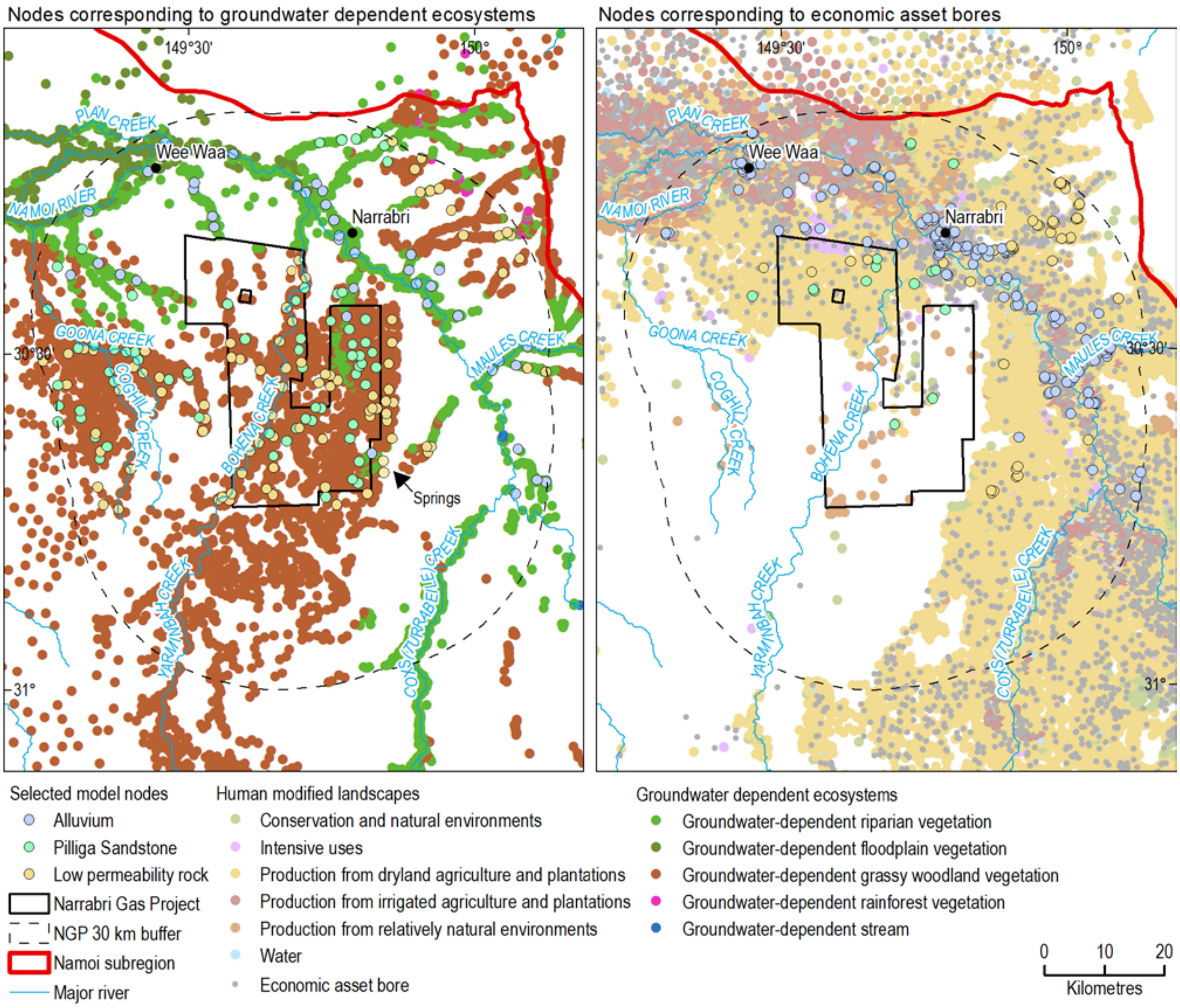

Figure 6 Model nodes corresponding to ecohydrological and economic risk receptors in the CSG development area

4.2 Economic bores

Economic bores are used to extract water for irrigation, water supply and stock and domestic purposes from the alluvial and sandstone aquifers in the Namoi region. A subset of economic risk receptors representing the groundwater bores in the region are also selected for impact analysis. The area to the north of the project area is along the predominant groundwater flow direction. The economic bores within 30 km of Narrabri Gas Project area are shown in figure 6b. A subset of 199 bores that extract water from different aquifers were randomly selected for predictive analysis of impacts from CSG development (Figure 7).

4.3 Predictive analysis of CSG induced groundwater impacts

The selection of ecohydrological and economic risk receptors shown in figure 6., indicates that these receptors are spatially spread and include some receptors within the Narrabri Gas Project area. They are also connected to multiple layers of the groundwater model. Predictive analysis of CSG induced groundwater impacts including pressure and water level changes at selected receptors will be reported in the final report of the GISERA 'GAB flux' project. Receptors identified here will also be used by the GISERA "Spatial design of monitoring networks" project to assess groundwater travel times to these receptors. 'Particle-tracking' will be used to assess the travel times to the selected receptors spatially. Particle tracking simulates travel times and distances travelled by individual particles from CSG wells to receptors. Alternatively, particles can be tracked backward in time from each receptor to assess the likelihood of individual receptors receiving contaminants in the event of accidental release of contaminants from a CSG well. This can also be used to inform future monitoring strategies.

5 Conclusions

The simplified landscape classification approach builds on existing landscape classification approaches by using fewer classifiers (i.e. habitat, water-regime, geomorphology and vegetation type) and using the IBRA subregion descriptions (climate, physiography, land and soil capability, land cover, vegetation, wetlands, land use) to guide these choices. The simplified classification describes explicit linkages to landscape water sources, specifically surficial source aquifers for groundwater-dependent vegetation, deeper spring aquifer sources, and surface water systems for surface water-dependent vegetation. The explicit linkage between GDEs (i.e. source aquifer) and potential hydrological changes in the surficial hydrogeology (i.e. surface groundwater model layer) is critical when assessing potential impacts to GDEs for any future assessments.

Receptor impact models developed for the Namoi subregion are used to predict likely responses to hydrological changes for projected foliage cover and families of aquatic macroinvertebrates associated with groundwater-dependent riparian vegetation and streams. Qualitative models developed for the Namoi subregion summarise expert understanding of potential impacts to groundwater-dependent ecosystems, including important hydrological response variables and likely ecosystem responses to hydrological change. Qualitative models developed for the Namoi subregion are relevant to groundwater-dependent floodplain vegetation, grassy woodland vegetation, rainforest vegetation and springs (includes GAB springs and non-GAB springs).

A total of 201 receptors to represent groundwater-dependent landscapes and 199 receptors to represent economic bore were randomly selected to the north of and within 30 km of the Narrabri Gas Project area. Based on the predicted groundwater drawdown impacts at these receptors, a shortlist of these will be used by the GISERA “Spatial design of monitoring networks” project for data-worth analysis to inform potential monitoring strategies for improving the predictive reliability at these receptor locations.

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CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

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