A generalised ecohydrological landscape classification for assessing ecosystem risk in Australia due to an altering water regime

Alexander Herr[1], Linda E. Merrin[1], Patrick J. Mitchell[1], Anthony P. O'Grady[1], Kate L. Holland[1], Richard E. Mount[2], David A. Post[1], Chris R. Pavey[1], Ashley D. Sparrow [1,3]

[1] Commonwealth Scientific and Industrial Research Organisation, Australia
[2] formerly at: Bureau of Meteorology, Australia
[3] Arthur Rylah Institute, Melbourne, Australia

Correspondence to: Dr Alexander Herr (alexander.herr@csiro.au)

Abstract

Describing and classifying a landscape for environmental impact and risk assessment purposes is a non-trivial challenge because this requires region specific landscape classifications that cater for region specific impacts. Assessing impacts on ecosystems from the extraction of water resources across large regions requires a causal link between landscape features and their water requirements. We present the rationale and implementation of an ecohydrological classification for regions where coal mine and coal seam gas developments may impact on water. Our classification provides the essential framework for modelling the potential impact of hydrological changes from future coal resource developments at the landscape level.

We develop an attribute-based system that provides representations of the ecohydrological entities and their connection to landscape features and make use of existing broad-level, classification schemes into an attribute-based system. We incorporate a rule-set with prioritisation, which underpin risk modelling and make the scheme resource efficient, where spatial landscape or ecosystem classification schemes, developed for other purposes, already exist.

A consistent rule-set and conceptualised landscape processes and functions allow combining diverse data with existing classification schemes. This makes the classification transparent, repeatable, and adjustable, should new data become available. We apply the approach in three geographically different regions, with widely disparate information sources, for the classification, and provide a detailed example of its application. We propose that it is widely applicable around the world for linking ecohydrology to environmental impacts.

Keywords: Typology, ecology, hydrology, causal pathway, bioregional assessments, environmental impact, risk analysis

1 Introduction

The categorisation of the Earth's surface into geo-ecological landscape classes provides a way to simplify the complexity of the form and function of the landscape and provides vital contextual information to support land and water management, and policy initiatives. This includes identifying geographical regions within which landscape-scale attributes, such as climate, topography, geology, and land cover, that are homogeneous and distinctive compared to other regions. It involves identifying broad-scale, general patterns, processes, and functions. Landscape class units are 'ecologically equivalent', having the same dominant processes that sustain a similar suite of species, and are likely to respond in similar ways to management initiatives or environmental changes. This ecological equivalence enables the selection of assessment locations for monitoring, measurement or experimentation, and it enables the extrapolation of results to all areas within the same ecological class (Hawkins and Norris, 2000; MacMillan et al., 2003; Cullum et al., 2016a; Cullum et al., 2016b).

Such a landscape classification also explains variation in ecological characteristics (e.g. assemblage structure) and is predictive of the ecological attributes of those areas. This predictive quality is useful for defining ecological criteria, identifying reference and degraded sites, defining conservation goals, including the assessment of biodiversity, and the setting of restoration objectives (Hawkins et al., 2000; McMahon et al., 2001; Snelder et al., 2004).

In summary, landscape classification is a way of dividing a landscape into components where the characteristics within the components are more similar than the characteristics between the components. That is, the components have their own distinct features that separate them from the other components.

However, describing and classifying a landscape for environmental impact and risk assessment purposes is a non-trivial challenge, where hydrological records are limited (see e.g. Wolfe et al., 2019). This is the case for many regions in Australia, where low population densities, high urbanisation and limits in (water) resource management information exist. For our purpose, which was the assessment of risk to ecosystems within the regions of the Bioregional Assessments Programme (Bioregional Assessments, 2018), we needed a landscape classification that reflected the hydrological connectivity of surface and groundwater with ecosystems in the landscape. The Bioregional Assessment Programme, an Australian regional scale impact assessment, investigated the impacts and risks of coal seam gas (CSG) and large coal mining developments on water resources and water-dependent assets via a water pathway (Bioregional Assessments, 2018). This investigation focussed on the landscape level, that is on areas within the regions where the landscape is made up of different interacting land-uses and ecosystems.

In our case, the broad scale assessments of impacts from resource developments on ecosystems required an understanding of landscape composition and structure, and how these relate to the ecosystems embedded in the landscape. The type and composition of the landscape components are dependent on the focus of the assessment and therefore require careful consideration of the questions the assessment seeks to answer (Wiens and Milne, 1989; Eigenbrot, 2016). For Australia, there are several landscape level classifications available (see e.g. Thackway and Cresswell, 1995; Pain et al., 2011; Hall et al., 2015; NVIS Technological Working Group, 2017; Gharari et al., 2011). Unfortunately, these available classifications are not directly applicable for our assessment regions because there is no alignment between the regions and existing classification boundaries, or the classifications, even if they include ecohydrological elements, are limited to their locations or domain of interest.

Identifying the water dependency of landscape components is a prerequisite when analysing the potential impacts of proposed coal and gas resource developments on water resources at a regional scale. For example, coal resource developments generally need to manage both groundwater and surface water as part of their operations. With multiple developments within the one region, impacts are likely to go beyond the local scale and affect ecosystems at the landscape level (see for example

Bioregional Assessments, 2018, 2019). In this context, there is a need for an ecological classification of the landscape that identifies and causally connects the water dependency of its components to activities of resource extraction, in a spatially explicit manner. Further, there is a need to identify impact pathways between resource extraction sites and the ecosystems that show causal connectivity between extraction activities and ecosystem impacts.

Land classification systems reveal patterns and underlying drivers of ecosystem structure and function, or produce a tractable unit of assessment for evaluating environmental change (Hobbs and Mcintyre, 2005; Poff et al., 2010). Many different classification approaches and methodologies currently exist to represent ecosystems in a landscape. This includes the interim bioregional classification for Australia (IBRA), which provides the basis for defining and managing the national reserve system and; the national vegetation information systems (NVIS), that describes the extent and distribution of vegetation ecosystems for the Australian continent (Thackway and Cresswell, 1995; Department of Agriculture, 2021). Classifications addressing hydrology in Australia incorporate a framework for river management that delineate boundaries between homogenous landscape components, based on either their dependency on surface water or groundwater regimes (Poff et al., 2010; Aquatic Ecosystems Task Group, 2012; Olden et al., 2012). However, none of these classifications describe ecohydrological connections between waters and the wider landscape. For example, IBRA and NVIS are based purely on vegetation classifications and so do not contain any hydrological details, while the available hydrological classifications focus purely on the streams and waterbodies within the landscape, as their focus is on aquatic organisms and environmental flows. While both these elements are part of the immediate landscape surrounding water bodies, they do not in themselves provide conceptual and direct linkages between changes in water and ecosystem responses in the wider landscape. Therefore, a standardised approach to formulating classifications that combine these two aspects, ecosystems and their water sources, is lacking.

This conundrum exists because different analysis contexts require classifications for different purposes, ranging from conservation planning, habitat mapping, resource assessment and vegetation modelling, and because there is contention between the generality of broad classifications and their applicability at the local scale (Leathwick et al., 2003; Abella et al., 2003; Poulter et al., 2011; Cullum et al., 2016b; Pyne et al., 2017). Hence, we needed a new classification system, when evaluating water dependency in the context of regional scale for multiple coal and coal seam gas resource developments. This new system must incorporate surface water and groundwater regimes into a spatial demarcation of ecosystem boundaries in the landscape. Including surface water and groundwater regimes will provide conceptual connection between impacts from developments on surface water and groundwater within the classification. The classification must also be spatially explicit to enable a landscape wide analysis of those impacts, so that changes in water at one part of the landscape can be linked to ecological responses at another part of the landscape.

With this context in mind, the objectives for this paper are to:

1. characterise a regional level landscape based on patterns in land use, ecology, geomorphology and hydrology,
2. develop landscape classes of water-dependent, remnant and human-modified features, and
3. ensure landscape classes sit within a common framework that aids in formulating conceptual models and patterns of water dependency across the landscape.

Here, we present the rationale, formulation and implementation of an ecohydrological landscape classification. Based on a generalised conceptual model of the typical hydrological connectivity within landscape features in a region, the classification integrates pre-existing, broad-level classification schemes into an attribute-based schema applied at the regional scale. It places the landscape classification within a common framework (i.e. a framework that is common to all landscape elements in the region) that aids in formulating conceptual models and patterns in water dependency across the landscape. This makes our approach generally applicable for assessments aimed at regional hydrological impacts on, and risks to, ecosystems. Importantly, the classification also provides the ability to develop a conceptual understanding of, and causally connect, hydrological changes at the landscape level, with impacts on ecological entities within the landscape. These causal pathways are the basis for spatially identifying the impacted areas, and for developing an appropriate mitigation response, including for extractive resource developments and water extraction.

We have applied this approach to several regions across eastern Australia with coal and CSG resource developments. Here we will focus on its application in three regions; Namoi, Maranoa–Balonne–Condamine and Galilee, and subsequently discuss why the approach is transferable to other regional developments that may carry a hydrological based risk to ecosystems, even those in a different contextual setting with regards to data sources and existing landscape classifications.

The remainder of the paper is structured as follows: the Methods section describes the general approach for achieving the classification, including descriptive examples of existing data sources. It also provides a description of the three study regions in which we applied and tested the classification. The Results section provides evidence of the general applicability of our approach in that it shows the detailed ecological landscape classification for the three distinctively different region in terms of location, topography, and climate. In the Discussion we provide an example on the use of the landscape classification. Here we describe an impact assessment in the Namoi region using modelling that includes expert assessments. In the last section we provide a discussion of the landscape classification, including limitations, and provide our conclusions.

Figure 1 provides a visual outline of the paper and workflow applied. It incorporates Methods, Results and Discussion (unshaded parts), and indicates where we applied our classification using quantitative and qualitative risk modelling in combination with surface water and groundwater modelling (shaded parts; Section 4). Surface water and groundwater modelling establish a zone of hydrological change in which impacts are likely. The red, more lightly shaded circle shows the resulting risk assessment outcomes, where the landscape classification provided the crucial details for experts to assign risks to landscape elements and classes.

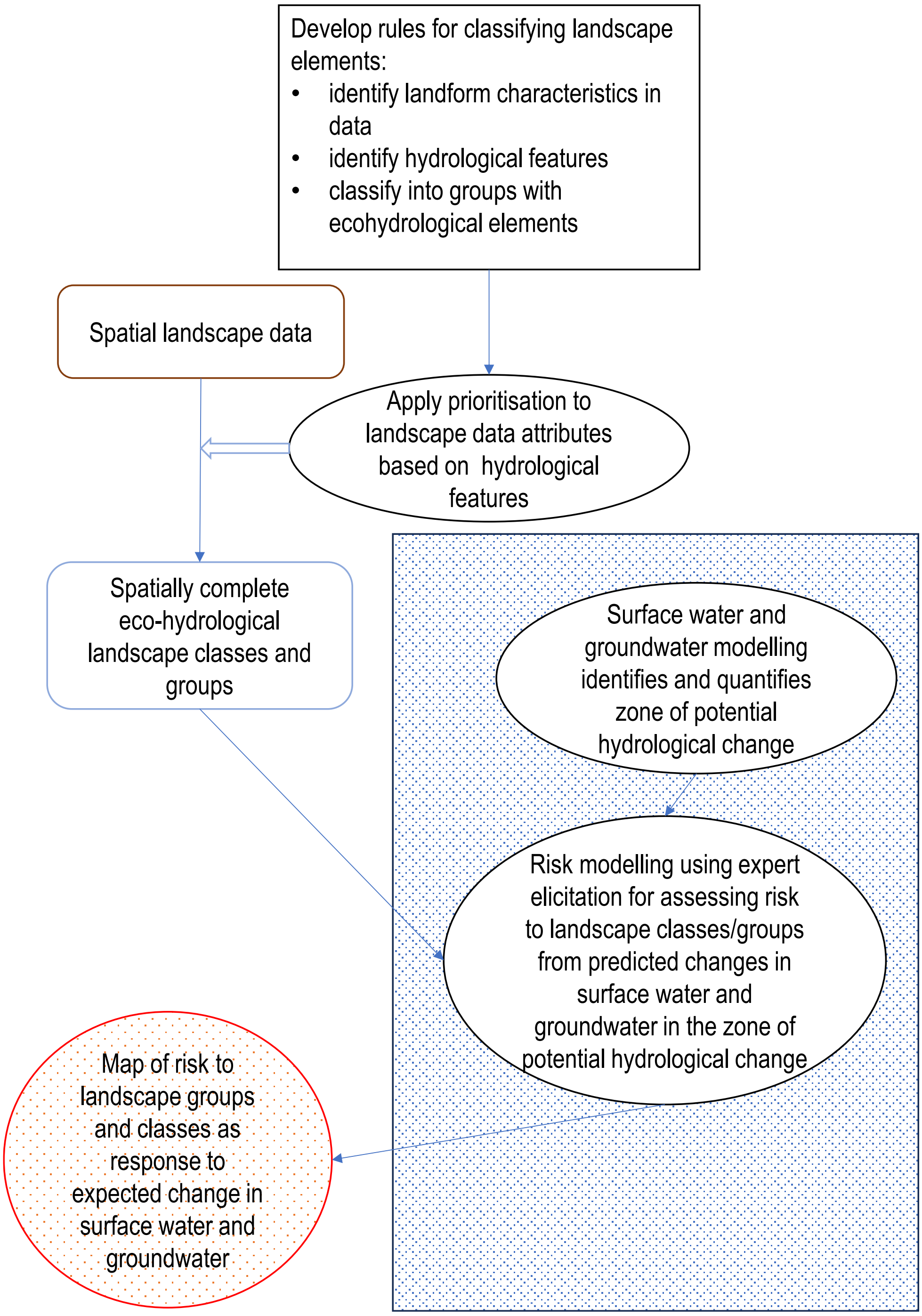

Figure 1: Visualisation of workflow for developing our ecological landscape classification (non-patterned, identifies focus of this paper) and its application in an ecological risk assessment, which we briefly summarise to show the classification's applicability (inside patterned rectangle, described in Section 4). The outcome of combining the landscape classification with hydrological modelling and risk modelling is the map of risk (identified in the lightly patterned red circle). Hydrological features are descriptors that have a hydrology component in their character. Ecohydrological elements are unique identifiable building blocks of the landscape that contain similar (hydrological) features.

2 Methods

In the following section, we show the development of a dataset-agnostic method to develop a regional-level landscape classification that is flexible in incorporating data sources at different scales, including region-specific datasets. Ecological systems are complex and work at a range of scales within regions/landscapes, and they exhibit interactions and feedbacks that work across scales.

Consequently, there is no one scale appropriate for a subsequent analysis of ecological impacts. Here we use a variable scale range that is relevant for ecological impacts of water changes from coal resource developments when using an expert assessment approach. Our classification focuses on a scale range (36,000 km^2 to 600,000 km^2) that is associated with eco-hydrological linkages (and associated causality) between the response of ecological components to predicted hydrological changes. This scale range is what most hydrologists would consider the "regional" scale range (Gleeson and Paszkowski, 2014). It provides the basis and flexibility for experts to build their conceptual understanding of causal pathways and use these to assess ecological impacts with the landscape classes (see also Figure 1).

2.1 Study areas

Our three study areas are the Namoi, the Maranoa–Balonne–Condamine and the Galilee regions in eastern Australia. Each of these regions have coal resource developments within them and have distinctly different landscape characteristics. They cover different state jurisdictions, or even cross state jurisdictions, and range from approximately 36,000 km^2 to 600,000 km^2 in size. Consequently, the classification is based on different state-based datasets. Each region's classification relies on the extent of surface water and groundwater systems that existing and potential future coal resource developments in the region may impact.

2.1.1 Namoi region

The Namoi region covers approximately 35,700 km^2 in eastern Australia, is located within New South Wales and forms one catchment of the Murray-Darling Basin. The long-term mean annual rainfall varies from 600 to 1100 mm and potential evapotranspiration (PET) varies from 1200 to 1400 mm. It contains six operational coal mines (one underground mine and five open-cut mines), nine potential future coal mines and one potential CSG development. The nine potential future coal mines consist of two underground, one combined open cut and underground, and seven open cut mines. The region covers most of the Namoi River catchment, with the Namoi River being the main river within the region. It also contains two major aquifer systems – the Namoi Alluvial aquifer and the Pilliga Sandstone aquifer (Figure 2).

The main land use within the region is agriculture, both dryland and irrigated cropping, and livestock grazing, as well as forestry. There is also a diverse range of landscapes and ecosystems within the region, including the Liverpool and Kaputar ranges, the Liverpool Plains floodplains, and Darling Riverine plains in the west of the region, open box woodlands on the slopes, and temperate and sub-alpine forests in the east of the region. A range of aquatic habitats occur downstream of Narrabri, with large areas of anabranches and billabong wetlands. The Pilliga Nature Reserve in the upper catchment of Bohena Creek, together with The Pilliga State Forest, form the largest remaining area of dry sclerophyll forest west of the Great Diving Range in New South Wales (Welsh et al., 2014).

2.1.2 Galilee region

The Galilee region covers approximately 612,300 km^2 and is located mostly within Queensland, Australia. PET far exceeds rainfall, particularly in the summer months. Yearly rainfall ranges from 300 to 700 mm and PET from 2200 to 2900 mm. There are 17 proposed coal resource developments in the Galilee region. These include three open-cut coal mines, two underground coal mines, five combined open-cut and underground coal mines, four coal mines of currently unknown type, and three CSG projects (Figure 3).

The Galilee region includes the headwaters of seven major drainage catchments. These catchments are Bulloo, Burdekin, Cooper Creek, Diamantina, Flinders, Paroo and Warrego. The largest of these catchments within the region are the Cooper Creek and Diamantina. Groundwater within the region is a very important resource, as most of the streams are ephemeral. Groundwater is used for town water, agriculture and industry. Most groundwater in the region is extracted from the Great Artesian Basin.

The region covers a range of environments, including mountains of the Great Dividing Range in the east, through to semi-arid and arid areas in the central and western parts of the region. The main land use in the region is livestock grazing on native vegetation. There is no intensive agriculture in the region, and a low human population density, largely due to the low and unpredictable rainfall (Evans et al., 2014).

2.1.3 Maranoa–Balonne–Condamine region

The Maranoa–Balonne–Condamine region covers approximately 130,000 km^2 and is located mostly within south-east Queensland with about half the area within the Murray-Darling Basin. From east to west, average annual rainfall decreases from 800 mm to 420 mm, as PET increases from 1500 to 2370 mm. The region overlies the Surat Basin and has five open-cut coal mines and five CSG projects, as well as two proposed open-cut coal mines (Figure 4).

The region contains the headwaters of the Condamine-Balonne, Moonie, Weir, Maranoa and Dawson rivers. Most of the rivers within the region are ephemeral. Groundwater is therefore an important water source and is used for stock and domestic purposes, and in some cases, town water supply. The Great Artesian Basin is the main source of groundwater used within the region (Welsh et al., 2015).

The main land use within the region is grazing on natural vegetation, with dryland cropping and production forestry also major land uses. The main vegetation type within the region is grassy woodlands, with river red gums, coolabah and river oak common riparian species. There are also six wetlands of national significance within the region: Balonne River Floodplain, Boggomoss Springs, Dalrymple and Blackfellow Creeks, Lake Broadwater, Palm Tree and Robinson Creeks, and The Gums Lagoon (Welsh et al., 2015).

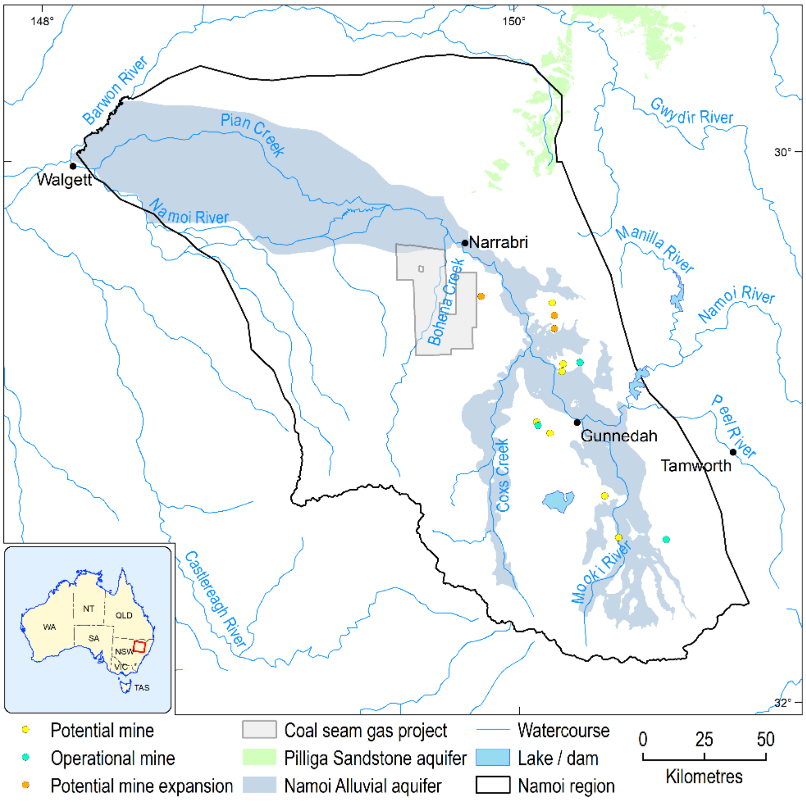

Figure 2. Namoi region study area, showing the potential coal resource development sites

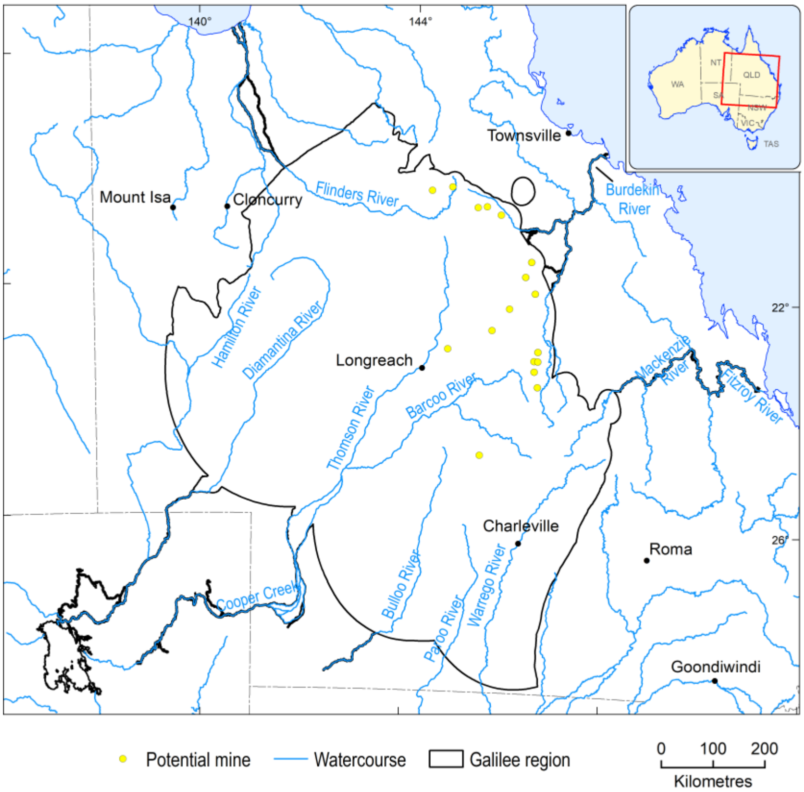

Figure 3. The Galilee region study area, showing the potential coal resource development sites

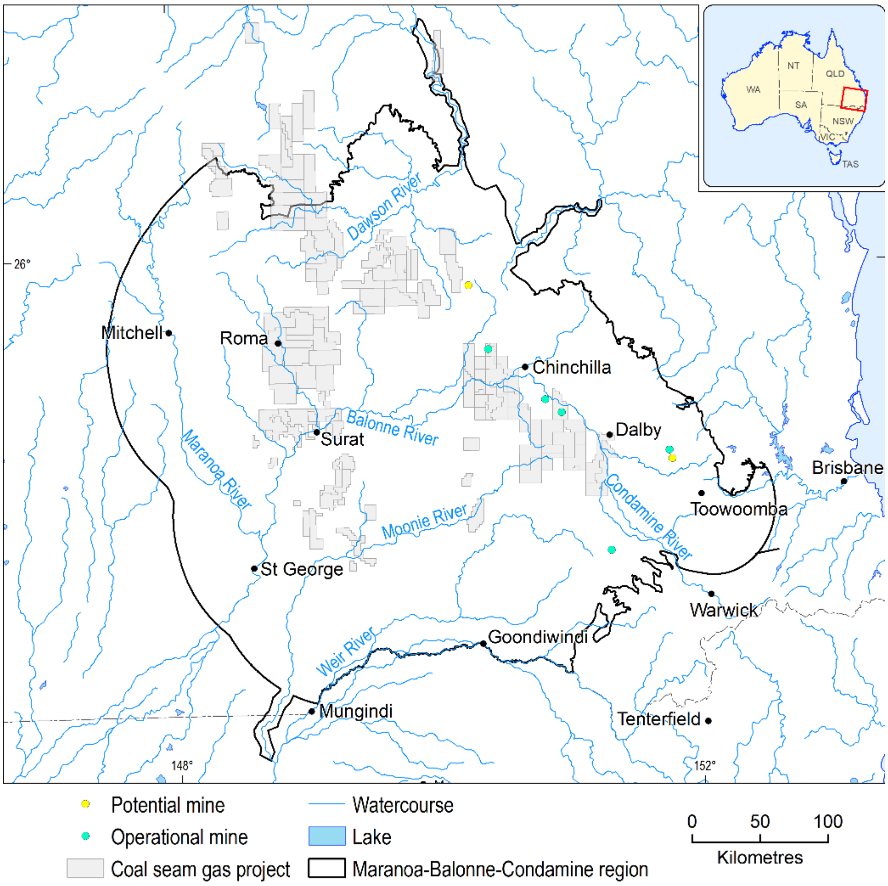

Figure 4. The Maranoa–Balonne–Condamine region study area, showing the potential coal resource development sites

2.2 Landscape classification development – overview and rationale

The purpose of this ecohydrological landscape classification is to characterise the landscape based on patterns in land use, ecology, geomorphology and hydrology, and from these, develop landscape classes of water-dependent, remnant and human-modified features. We chose these features because these three types represent a generally applicable delineation used in our spatial dataset. For example, in Australia the word remnant vegetation (our remnant features) describes all vegetation where there was no clearing or regrowth of (semi-) native vegetation, resulting in a vegetation community that resembles its predecessor's structure. It represents areas with low to very minimal human interference. This is opposed to human-modified, where human activities are the defining features of the area, such as urban areas or other infrastructure. Water dependency is essential for establishing a conceptual linkage of water across landscape elements. Our classification employs a geographical information system to overlay existing spatial data for each region. The spatial data are the basis for categorising the landscape features using a rule-set to prioritise the spatial data based on their attribute features.

The datasets have a regional, state or national coverage. Using a feature-based classification helps to place the landscape classes within a common biophysical system that aids in formulating conceptual models and patterns in water dependency across the landscape of each region. This provides a classification that is aligned with the idiosyncrasies of each region. Maintaining regionality is essential when developing conceptual models and quantitative models for assessing the risk to ecological components from hydrological changes. For example, arid and semi-arid regions have very different ecological environments, functions and processes than subtropical or temperate woodlands.

Our approach uses a defined rule-set and priorities, which we apply to regionally available datasets to achieve a landscape classification for each of our regions. Tables 1 to 3 provide a list of citations for example datasets used in this process. This is different to most other landscape classifications that may use climate, topography, hydrological assessment units and remote sensing data, and apply statistical dimensionality reduction and classifications such as proximity analysis (see e.g. Gharari et al., 2011; Leibowitz et al., 2014; Sawicz et al., 2014; Zhang et al., 2016; Addicott et al., 2021; Carlier et al., 2021; Jones et al., 2021).

When considering the characteristics of our regions, the following features form part of the rule-set for defining landscape classes:

- broad habitat/land use type (remnant/human-modified).
- wetland (wetland/non-wetland)
- topography (upland/lowland, floodplain/non-floodplain)
- groundwater (groundwater dependent/non-groundwater dependent, Great Artesian Basin (GAB)/non-GAB)
  Note: identifies groundwater dependency and classifies this with the presence/absence of Great Artesian basin groundwaters.
- vegetation type (riparian/woodland floodplain/grassy woodland/rainforest)
- water regime (permanent/ephemeral/null) of surface water

These features identify groups of landforms and use streams and springs.

The hydrological connectivity is the main reason for developing a new classification as this allows us to assess the potential impact of coal resource developments on the landscape via a water pathway. Therefore, the most important characteristics are the hydrological features. Describing the conceptual understanding of how water connects the landscape elements allows us to identify where in the landscape impacts are likely to occur. In line with this we developed a hierarchical approach, where hydrological features have priority over other landscape characteristics. This resulted in a spatially complete landscape classification, where there are no gaps in the mapping data. The method of prioritisation depended on region-specific characteristics and the data availability. This yielded a classification where the landscape classes have their origin in the spatial datasets, and included the water dependency, which was a pre-requisite of the prioritisation. An example prioritisation assigned in order of highest to lowest is:

- aquatic ecosystems (e.g. wetlands, streams and lakes)
- remnant vegetation
- other landscape components that are ‘non-remnant vegetation’ and are typically ‘human-modified’.

Subsequent use of the landscape classification for risk identification with expert input also required combining landscape classes into broader landscape groups. Landscape groups are sets of landscape classes that share ecohydrological properties. These landscape groups provided efficiencies in the expert elicitation process of the risk modelling, as they combined similar ecological system components based on our landscape classes while also accounting for region specific differences. For example, in the Namoi region there are two landscape groups where we do not expect any impact from coal resource developments. Firstly, the ‘Dryland remnant vegetation’ landscape group is ruled out from potential impacts because it comprises vegetation communities that are reliant on incident rainfall and local runoff and do not include features in the landscape that have potential hydrological connectivity to surface water or groundwater features. Secondly, the ‘Human-modified’ landscape group is excluded from the ecological impact assessment because it primarily comprises agricultural and urban landscapes that are highly modified by human activity. Here the impact assessment focus is on economic assets such as groundwater bores, and therefore beyond the scope of this publication.

2.2.1 Landform classification

Landform classification relied on the dominant land type of either habitat or land use to determine landscapes that are relatively natural and those that have been ‘human-modified’. Relatively intact areas are more likely to contain ecological assets, such as species and ecological communities, than highly modified areas. Location within the region (topography–upland/lowland, floodplain/non–floodplain), groundwater dependency and water regime, were part of classifying the landscape. Determining areas that are subjected to flooding, or that have persistent water, assists in identifying landscapes that support water-dependent habitat and vegetation, and aquatic ecosystems (Table 1).

2.2.2 Stream classification

Stream classification in each of the study regions was based on stream position within the catchment (e.g. upland/lowland), water regime (perennial/near permanent or ephemeral/temporary) and dependence and source of groundwater (Table 2). Catchment position is a potential indicator of stream morphology and flow patterns, while water regime is important when considering habitat suitability and physical processes within the channel and riparian zone. Streams can also gain and lose water to local and regional groundwater systems, interacting with groundwater-dependent ecosystems (Table 2).

2.2.3 Spring classification

The water source is the basis of spring classification. The source of groundwater is important when considering regional scale landscape classifications, due to the hydrological connectivity of aquifers and potential coal resource developments (Table 3).

Table 1. Landform classification criteria and example datasets

Characteristic	Classification	Example datasets
Habitat/land use	• Non-remnant • Remnant (and stream, Wetland)	Australian land use mapping (Australian Bureau of Agricultural and Resource Economics and Sciences, 2014) (national)
		NSW regional vegetation (NSW Office of Environment and Heritage, 2015) (regional)
Topography	• Floodplain • Non-floodplain	NSW regional vegetation (NSW Office of Environment and Heritage, 2015) (regional)
		Namoi Valley Flood Plain Atlas 1979 (NSW Office of Environment and Heritage, 1979) (regional)
		Murray-Darling Basin aquatic ecosystem classification (Department of Sustainability, Environment, Water, Population and Communities, 2014) (regional)
		GEODATA TOPO 250K Series 3 (Geoscience Australia, 2006) (national)
Groundwater	• Groundwater dependent (source)	Namoi groundwater dependent ecosystems (NSW Office of Water, 2015) (regional)
	• Non-groundwater dependent	Queensland Groundwater Dependent Ecosystems and Shallowest Watertable Aquifer (Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts, 2015) (state)
		Queensland Groundwater Dependent Ecosystems (Queensland Department of Science, Information Technology, Innovation and the Arts, 2013) (state)
Water regime	• Temporary • Near-permanent	Queensland wetland data version 3 - wetland areas (Queensland Department of Science, Information Technology, Innovation and the Arts, 2012) (state)
	• Fresh • Saline	Queensland wetland data version 3 - wetland areas (Queensland Department of Science, Information Technology, Innovation and the Arts, 2012) (state)
		Queensland Groundwater Dependent Ecosystems and Shallowest Watertable Aquifer (Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts, 2015) (state)
		South Australian Wetlands – Groundwater Dependent Ecosystems (GDE) Classification (Sa Department for Water, 2010) (state)
Vegetation	• Broad vegetation type	NSW regional vegetation (NSW Office of Environment and Heritage, 2015) (regional)

NSW = New South Wales

Table 2. Stream classification criteria and example datasets

Characteristic	Classification	Example datasets
Topography	• Upland • Lowland	Murray-Darling Basin aquatic ecosystem classification (Department of Sustainability, Environment, Water, Population and Communities, 2014) (regional) NSW regional vegetation (NSW Office of Environment and Heritage, 2015) (regional) MrVBF (CSIRO, 2000) (national)
Groundwater	• Groundwater dependent (source) • Non-groundwater dependent	Asset database for the Namoi subregion (Bioregional Assessment Programme, 2016) (regional) Queensland Groundwater Dependent Ecosystems and Shallowest Watertable Aquifer (Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts, 2015) (state) Queensland groundwater dependent ecosystems (Queensland Department of Science, Information Technology, Innovation and the Arts, 2013) (state)
Water regime	• Perennial • Ephemeral	Murray-Darling Basin aquatic ecosystem classification (Department of Sustainability, Environment, Water, Population and Communities, 2014) (regional) Geofabric Surface Cartography (Bureau of Meteorology, 2012) (national)

Table 3. Spring classification criteria and example datasets

Characteristic	Classification	Example datasets
Groundwater	• Groundwater dependent (source) • Non-groundwater dependent	Asset database for the Namoi subregion (Bioregional Assessment Programme, 2016) (regional) Asset database for the Maranoa–Balonne–Condamine subregion (Bioregional Assessment Programme, 2015) (regional) Spring vents assessed for the Surat Underground Water Impact Report 2012 (Office of Groundwater Impact Assessment, 2015) (regional)

3 Results

Below we present the resulting landscape classes for the three regions. For each region, we also combined the landscape classes into landscape groups, which were specific to each region and were based on distinctions in topography, water dependency and association with GAB or non-GAB GDEs, floodplain/non-floodplain or upland/lowland environments and remnant/human-modified habitat types. The purpose of the landscape groups was to combine non-water dependent landscape classes and relate water dependent landscape classes to region specific aspects of their water dependency. This enabled experts to develop a conceptualisation of the landscape for developing their ecological impact models. While the approach in defining the landscape classes is based on a consistent rule-set and prioritisation, each of the regions has different landscape classes, which is a consequence of the differences in location, jurisdictions and available spatial datasets.

The rule-set deriving from the landform classification (Tables 1 to 3) and prioritisation of hydrological features is the main outcome of our approach and we present the rule-set as a decision pathway visually below (Figure 5). For example, for the Namoi region, the rule-set includes: (1) identify the habitat (e.g. stream) (2) select by topography (e.g. upland), (3) identify the groundwater associations (e.g. GDE), and so on until one derives at the final landscape class level (see Figure 5).

3.1 Landscape classes in the Namoi region

There were 29 landscape classes within six landscape groups in the Namoi region (Figure 5). Of these landscape groups, 'human-modified' (non-remnant) was the largest (59.3%; Table 4), and included urban, agriculture, plantations and other intensive land uses. The dryland remnant vegetation was the second largest landscape group and consisted of the grassy woodland landscape class (24.2%; Table 4). This landscape class was considered non-water dependent as it did not intersect with floodplain, wetland or GDE features. The rainforest landscape group was the smallest (0.5%; Table 4), with only a limited distribution (Figure 6a).

The stream network consisted of two landscape groups (floodplain or lowland riverine and non-floodplain or upland riverine). The non-floodplain or upland riverine landscape group had a larger proportion of stream network length (63.8%) compared to the floodplain or lowland riverine landscape group (36.2%; Figure 6b). There were 22 springs identified within the Namoi region, with seven of these associated with the GAB (Figure 6b).

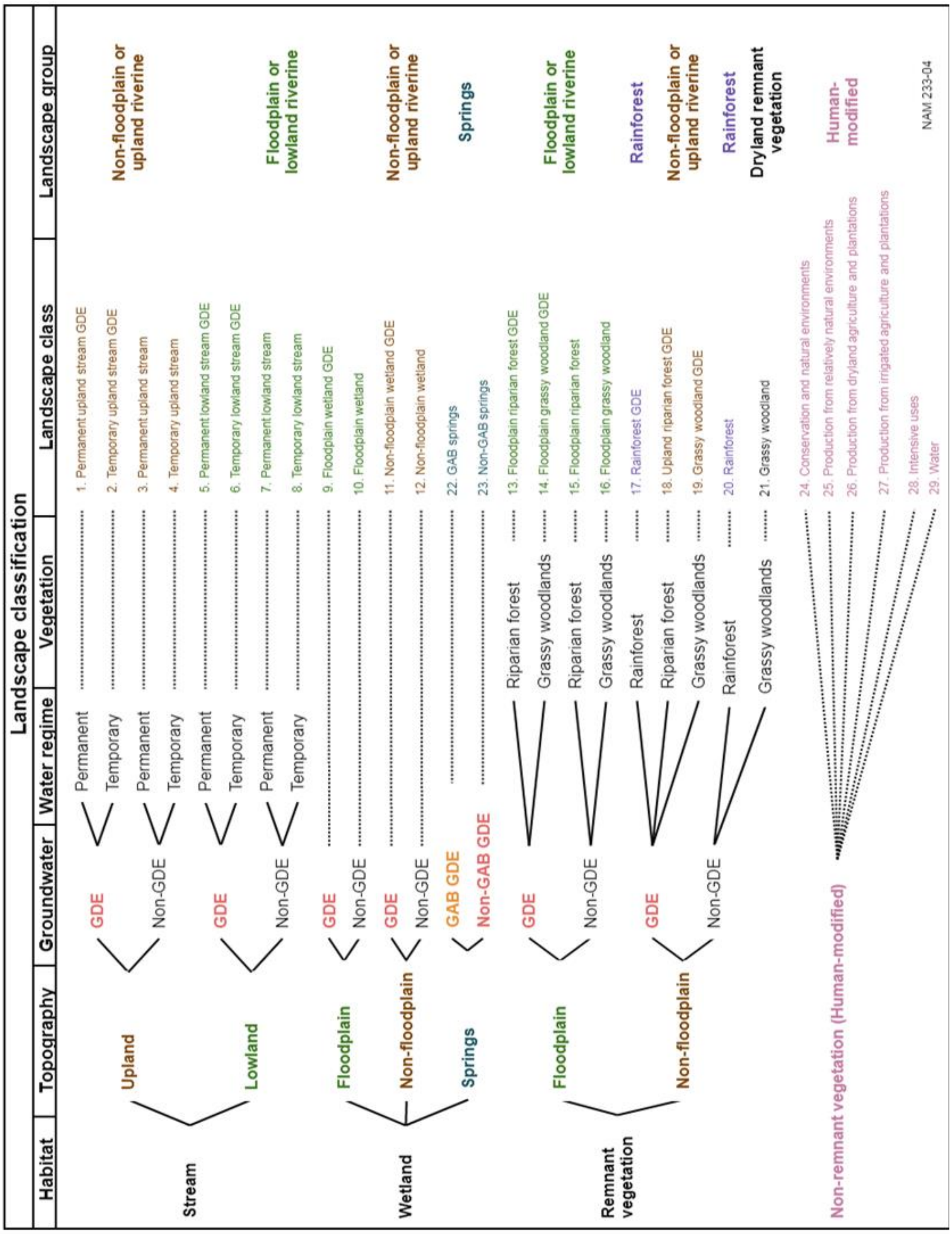

Figure 5. Overview of the Namoi landscape classification schema, including criteria and attributes resulting in six landscape groups

Table 4. Percentage of area of each landscape group for the Namoi region

Landscape group	Percentage of region (%)	Number of classes	Landscape classification attributes
Human-modified	59.3%	6	Conservation of natural environments, production from relatively natural environments, production from dryland agriculture and plantations, production from irrigated agriculture and plantations, intensive uses or waters for production/consumption
Dryland remnant vegetation	24.2%	1	Non-floodplain, non-GDE, grassy woodland remnant vegetation
Non-floodplain or upland riverine	9.8%	8	Upland or non-floodplain streams, wetlands or remnant vegetation
Floodplain or lowland riverine	6.2%	10	Lowland or floodplain streams, wetlands or remnant vegetation
Rainforest	0.5%	2	Non-floodplain GDE or non-GDE rainforest remnant vegetation
Springs	<0.1%	2	GAB or non-GAB springs

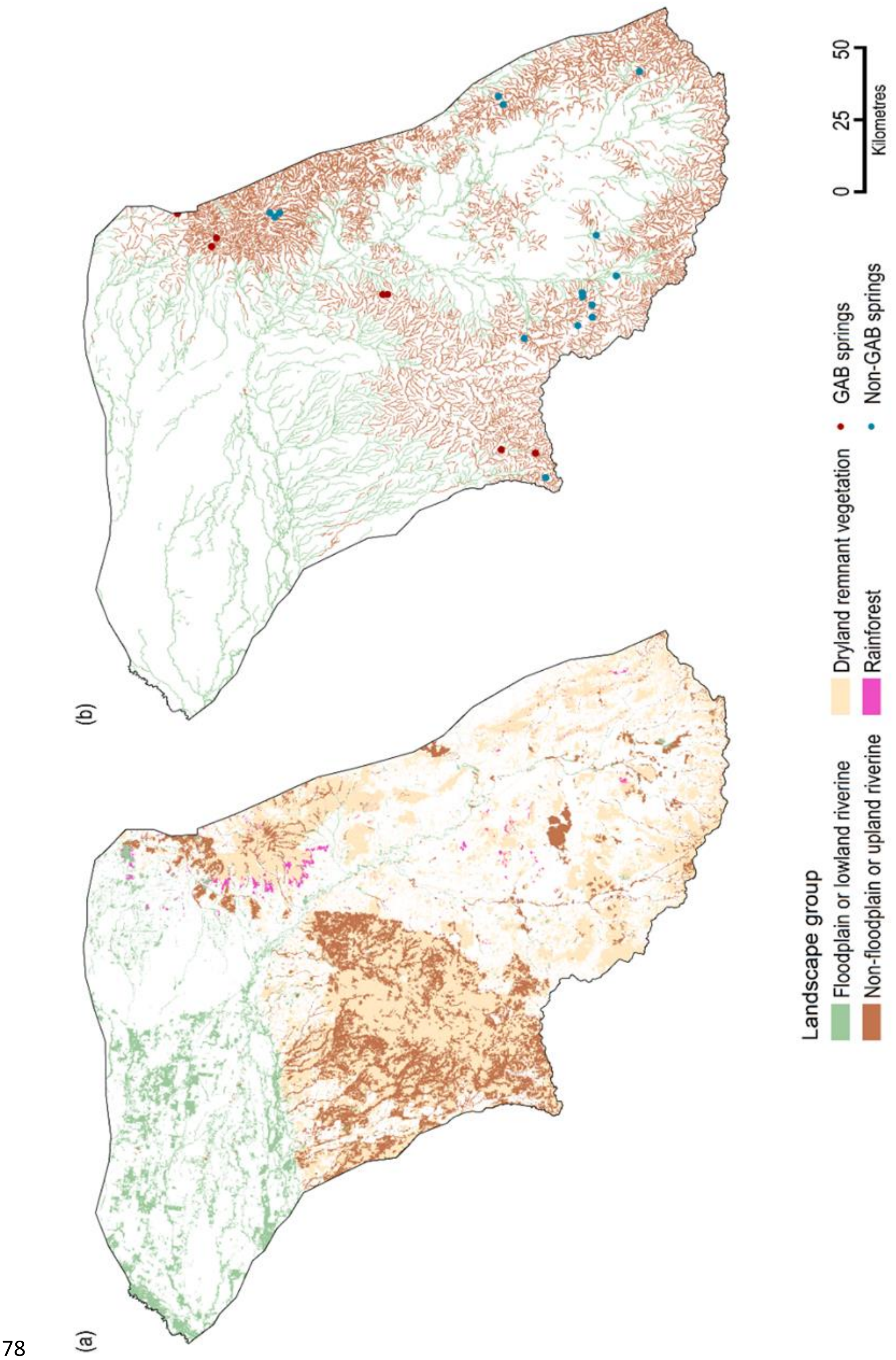

Figure 6. (a) Landscape groups (excluding the 'Human-modified'), and (b) Stream network classified as 'upland' or 'lowland' in the landscape classification and 'Springs' within the Namoi region. GAB = Great Artesian Basin
Data: Bureau of Meteorology (2012); Bioregional Assessment Programme (2017)

3.2 Landscape classes in the Galilee region

The Galilee region has 31 landscape classes organised into 11 landscape groups (Figure 7). The dryland landscape group was the largest group within the region and the only group to have no water dependency (68.5%; Table 5). The landscape groups that covered the floodplain areas were the next most dominant classes, with floodplain, terrestrial GDE (12.94%; Table 5) and floodplain, non-wetland (11.8%; Table 5). The remaining three non-floodplain landscape groups consisted of disconnected wetlands, and terrestrial and wetland GDEs (4.9% combined; Table 5).

The stream network was classified as groundwater dependent or non-groundwater dependent. Most of the streams in the region were non-GDEs (87.7% compared to 12.3% for the streams, GDE landscape group). There were also over 3000 springs in the region.

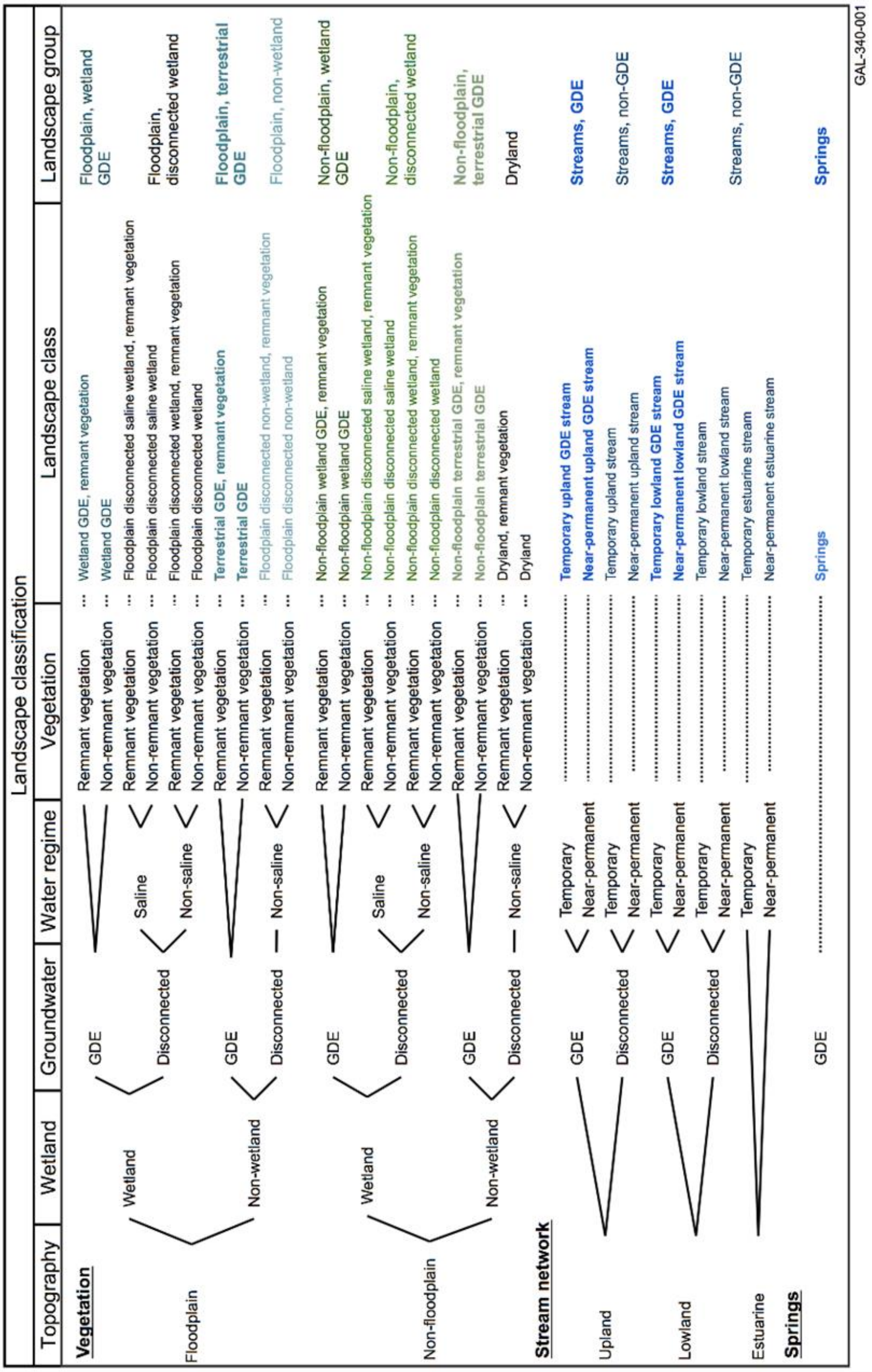

Figure 7. Landscape classification of the Galilee region

Table 5. Percentage of area of each landscape group for the Galilee region

Landscape group	Percentage of region (%)	Number of classes	Landscape classification attributes
Dryland	68.5%	2	Non-floodplain, non-wetland, disconnected and saline remnant or non-remnant vegetation
Floodplain, terrestrial GDE	12.9%	2	Floodplain, non-wetland and GDE remnant or non-remnant vegetation
Floodplain, non-wetland	11.8%	2	Floodplain, non-wetland, disconnected and non-saline remnant or non-remnant vegetation
Floodplain, disconnected wetland	1.1%	4	Floodplain, wetland, disconnected saline and non-saline remnant or non-remnant vegetation
Floodplain, wetland GDE	0.8%	2	Floodplain, wetland and GDE remnant or non-remnant vegetation
Non-floodplain, terrestrial GDE	3.4%	2	Non-floodplain, non-wetland and GDE remnant or non-remnant vegetation
Non-floodplain disconnected wetland	1.4%	4	Non-floodplain, wetland, disconnected, saline and non-saline remnant or non-remnant vegetation
Non-floodplain, wetland GDE	<0.1%	2	Non-floodplain, wetland and GDE remnant or non-remnant vegetation
Springs	<0.1%	1	GDE springs

3.3 Landscape classes in the Maranoa–Balonne-Condamine region

The landscape classification for the Maranoa–Balonne-Condamine resulted in 34 landscape classes within five landscape groups (Figure 8). The largest landscape group was the human-modified group (72.2%, Table 6), which included agricultural production, plantations and other intensive land uses. Of the remaining landscape groups, dryland remnant vegetation was the second most dominant (19.8%, Table 6). It was not considered water dependent, because it did not intersect with floodplain, wetland or GDE features.

There were three landscape groups that cover the stream network. The most dominant landscape group was floodplain or lowland riverine (including non-GAB GDEs) (47.8%), followed by non-floodplain or upland riverine (including non-GAB GDEs) (39.4%) and GAB GDEs (riverine, springs, floodplain or non-floodplain) (12.7%). There were 177 springs identified within the region. Most of the springs were GAB GDEs (riverine, springs, floodplain or non-floodplain) (86.4%, compared to 13.6% for non-floodplain or upland riverine (including non-GAB GDEs)).

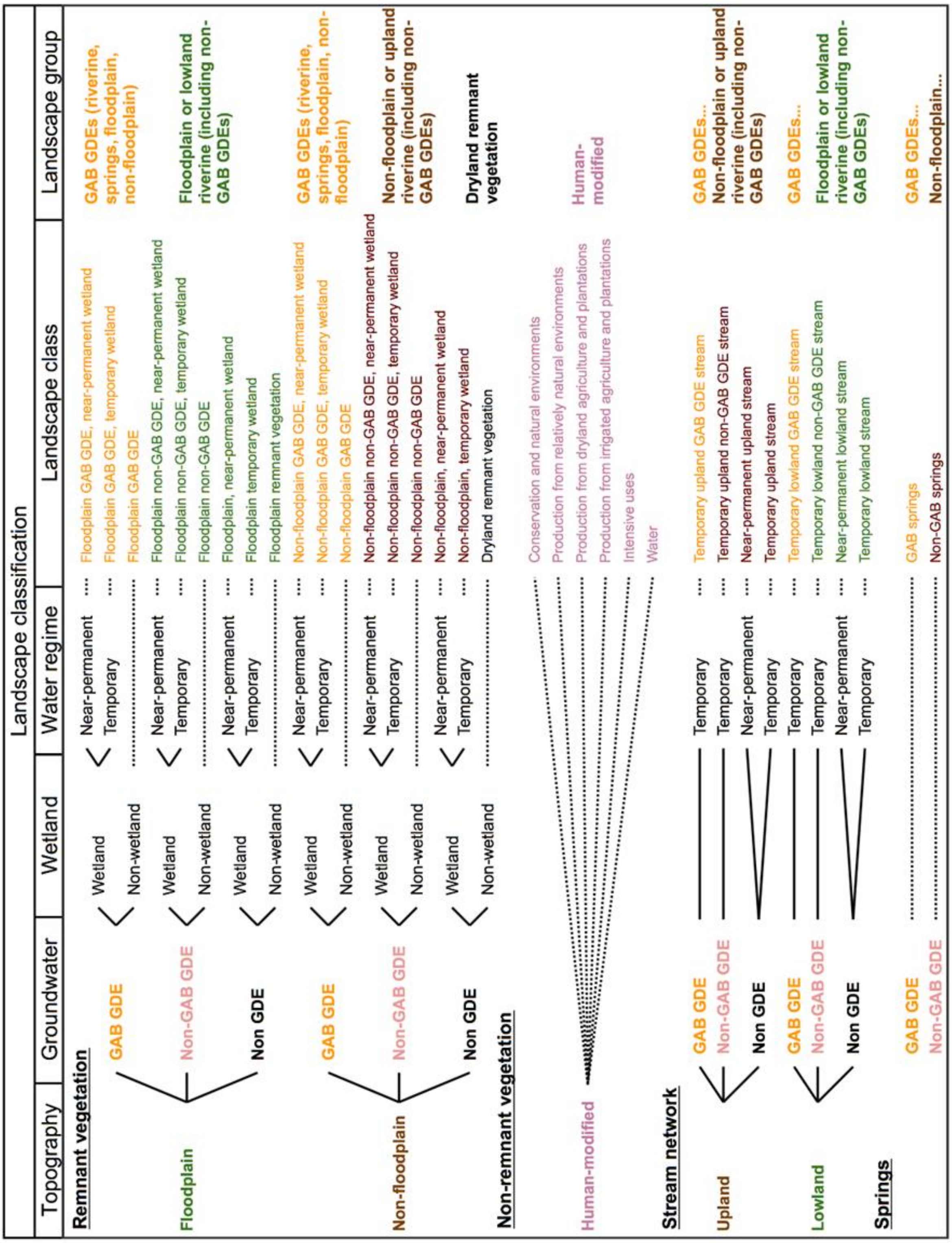

Figure 8. Landscape classification of the Maranoa–Balonne–Condamine region
GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem, GAB GDEs… = GAB GDEs (riverine, springs, floodplain, non-floodplain), Non-floodplain… = Non-floodplain or upland riverine (including or non-GAB GDEs)

Table 6. Percentage of area of each landscape group for the Maranoa–Balonne–Condamine region

Landscape group	Percentage of region (%)	Number of classes	Landscape classification attributes
Human-modified	72.2%	6	Conservation of natural environments, production from relatively natural environments, production from dryland agriculture and plantations, production from irrigated agriculture and plantations, intensive uses or waters for production/consumption
Dryland remnant vegetation	19.8%	1	Non-floodplain, non-GDE, non-wetland remnant vegetation
Floodplain or lowland riverine (including non-GAB GDEs)	4.5%	9	Floodplain or lowland, non-GAB GDE or non-GDE, temporary or near-permanent wetland, non-wetland or stream
Non-floodplain or upland (including non-GAB GDEs)	2.2%	9	Non-floodplain or upland, non-GAB GDE or non-GDE, temporary or near-permanent wetland, non-wetland, stream or spring
GAB GDEs (riverine, springs, floodplain or non-floodplain)	1.3%	9	Floodplain, non-floodplain or upland GAB-GDE, temporary or near-permanent wetland, non-wetland, stream or spring

GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem

4 Application of the landscape classification to the assessment of ecosystem risk

Here we show an application of our classification approach. It shows the potential impact coal resource developments can have on ecology using the Namoi region as an example, thus, demonstrating the useability of our classification approach.

The purpose of developing the landscape classification was to assess the risk of coal resource development on the ecology of a region via a water pathway. Our landscape classification provided the spatial framework on which experts could base their assessment of risk from coal resource development on the ecology of a region. Details of the predicted changes in surface water and groundwater for the Namoi and Galilee regions are in Post et al. (2020). Here, we demonstrate the assessment of potential ecological impacts using the Namoi region. For full details of the analyses in each of the three regions see Holland et al. (2017); Herr et al. (2018b); and Lewis et al. (2018). The models needed to identify water mitigated linkages between hydrological changes, ecosystem components and the landscape classes. We briefly describe the expert assessment approach in a 3-step process below. For details we direct the reader to the above references and those listed below.

The following describes an application of the landscape classification (see also Figure 1), and in doing so we demonstrate that it is a fit-for-purpose for assessing potential ecological impact from predicted surface water and groundwater changes. The 3-step process illustrates the utility of our landscape classification approach for assessing the risk to ecosystems. The process included experts identifying risk to landscape classes using their knowledge on local ecosystems within the landscape classes. Specifically, the experts used the broad landscape groups and their underlying hydrogeological features to develop initial qualitative models about priority ecosystem components. These then fed into building quantitative models. Here the experts used outputs from surface water and groundwater modelling. This hydrological modelling identified the potential changes in water, which experts used to reach a consensus on what impact these changes may have on ecological entities within the landscape classes and/or groups. These agreed impacts fed into quantitative models that outlined the future hydrological changes and risks to the ecosystems in the landscape groups (see also Figure 1).

Here we use the example of the upland riverine landscape class in the Namoi region to outline the 3-step process:

Step 1: Develop qualitative models to conceptualise and prioritise ecosystem components of each landscape class and their linkage to hydrological variables.

A qualitative model for the upland riverine landscape class agreed with the existing understanding that a reduction in overbank flows and lowering of the water table resulted in a reduction in several ecosystem components, including riparian habitat, amphibians and fish, and an increase in fine particulate matter, dissolved organic matter and cyanobacteria (Holland et al., 2017; Herr et al., 2018b; Hosack et al., 2018). A qualitative model has, at its basis, the conceptual understanding of ecosystem components and the direction of their interactions, that is a positive, negative, or neutral influence of one component on another. This understanding also incorporates feedback loops between the ecosystem components in the form of sign directed graphs, and it enables time intensive quantitative model development to be directed at variables with the highest importance. The method is based on a matrix level analysis of the component interactions (see for example Herr et al., 2016; Ickowicz et al., 2018).

In the process of building a qualitative model, the expert developed a consensus on the overall scope of the model, namely the model components and their interactions. The hydrological variables, and relationships between ecosystem components that the experts prioritised in the qualitative modelling process were the macroinvertebrate responses to riverine system change, presence of tadpoles and changes in projected foliage cover in the riparian trees along the stream channel (Table 7).

Step 2: Use qualitative model priorities to develop quantitative models.

In this context, qualitative models highlighted critical relationships and variables that became the focus of the quantitative models (see for example Herr et al., 2016; Hosack et al., 2018; Ickowicz et al., 2018). The focus of the quantitative models was on three elements within the upland riverine landscape classes (Table 7): (i) the response of upland riparian trees to changes in groundwater; (ii) macroinvertebrate assemblage changes related to days with no consecutive water (zero-flow days) and the longest zero flow event period; and (iii) the response of tadpoles to zero flow days and longest zero flow event period. Table 7 provides a brief summary of these variables; specific details of the variable definitions are in Ickowicz et al. (2018).

Table 7: Upland riverine ecosystem quantitative modelling variables that experts prioritised in the qualitative model and associated ecological and hydrological variables used in the development of the quantitative impact model (after Ickowicz et al., 2018)

Expert prioritised relationship	Ecological variable (with associated sample units)	Hydrological variable
Response of the upland riparian forest to changes in hydrological regime and groundwater	Annual mean projected foliage cover of species group that includes: Casuarina, yellow box, Blakely's red gum, *Acacia salicina*, *Angophora floribunda*, grey box. Transect of 50 m length and 20 m width that extends from first bench (‘toe’) on both sides of stream	• The mean annual number of events with a peak daily flow exceeding the overbank flow events. • Maximum difference in drawdown under a baseline and under the expected drawdown • The year with the maximum difference in drawdown relative to the baseline
Response of fast-water macroinvertebrates to changes in number of zero-flow days and maximum zero-flow event	Average number of families of aquatic macroinvertebrates in riffle habitat sampled using the NSW AUSRIVAS method for riffles	• The number of zero-flow days per year, averaged over a 30-year period. • The maximum length of spells (in days per year) with zero flow, averaged over a 30-year period.
Response of tadpoles to changes in number of zero-flow days and maximum zero-flow event	Probability of presence of tadpoles from *Limnodynastes* genus (species *dumerilii, salmini, interioris* and *terraereginae*) sampled using standard 30 cm dip net	• The number of zero-flow days per year, averaged over a 30-year period. • The maximum length of spells (in days per year) with zero low, averaged over a 30-year period.

Step 3: Identify risk areas in the regions where quantitative modelling indicated significant changes to landscape group components.

This quantitative modelling approach incorporated expert elicitation in a Bayesian framework to predict changes in ecological system components because of expected changes in hydrology conditions. The method dealt with complexity and limited knowledge that allows for updating with new information, which is an important feature in evidence-based decision making (see for example Hosack et al., 2017).

The modelling of risk to ecosystems at regional scale focuses on recognising which parts of the region are potentially impacted and which parts are unlikely to experience harm. Using our landscape classification as a crucial input, the modelling delineated impacted areas within each region, based on a zone of potential hydrological change. This is the area in the landscape, where hydrological modelling identified an expected change to surface water and groundwater from future resource extraction. Risk levels across a landscape group are a result of aggregating individual risks associated with each ecological variable and categorising the risks into three levels based on their percentile spreads (for details see Herr et al., 2018b).

For the Namoi region, for example, dryland remnant vegetation, human-modified ecosystems, no-floodplain and upland riverine ecosystems and rainforests, will not experience impacts, while floodplain and lowland ecosystems area and streams of floodplain and lowland ecosystems will potentially experience impacts (Herr et al., 2018a). Figure 9 (a) shows the landscape groups that are at risk of impact from hydrological changes as they are situated within the zone of potential hydrological change, and Figure 9 (b) shows the risk level to these landscape groups from the quantitative models. Note that there is a category “Remaining unquantified ‘floodplain and lowland riverine’ classes”. The expert could not develop quantitative models for these classes, because there was no surface water hydrological model available that could predict changes to surface water flows. This was related to the lack of gauging data and groundwater interaction details specific to the lowland drainage channels. Having lowland riverine classes whose risk remains unquantified means there is additional work needed before an assessment and potential mitigation of impacts from hydrological changes is possible (Herr et al., 2018b).

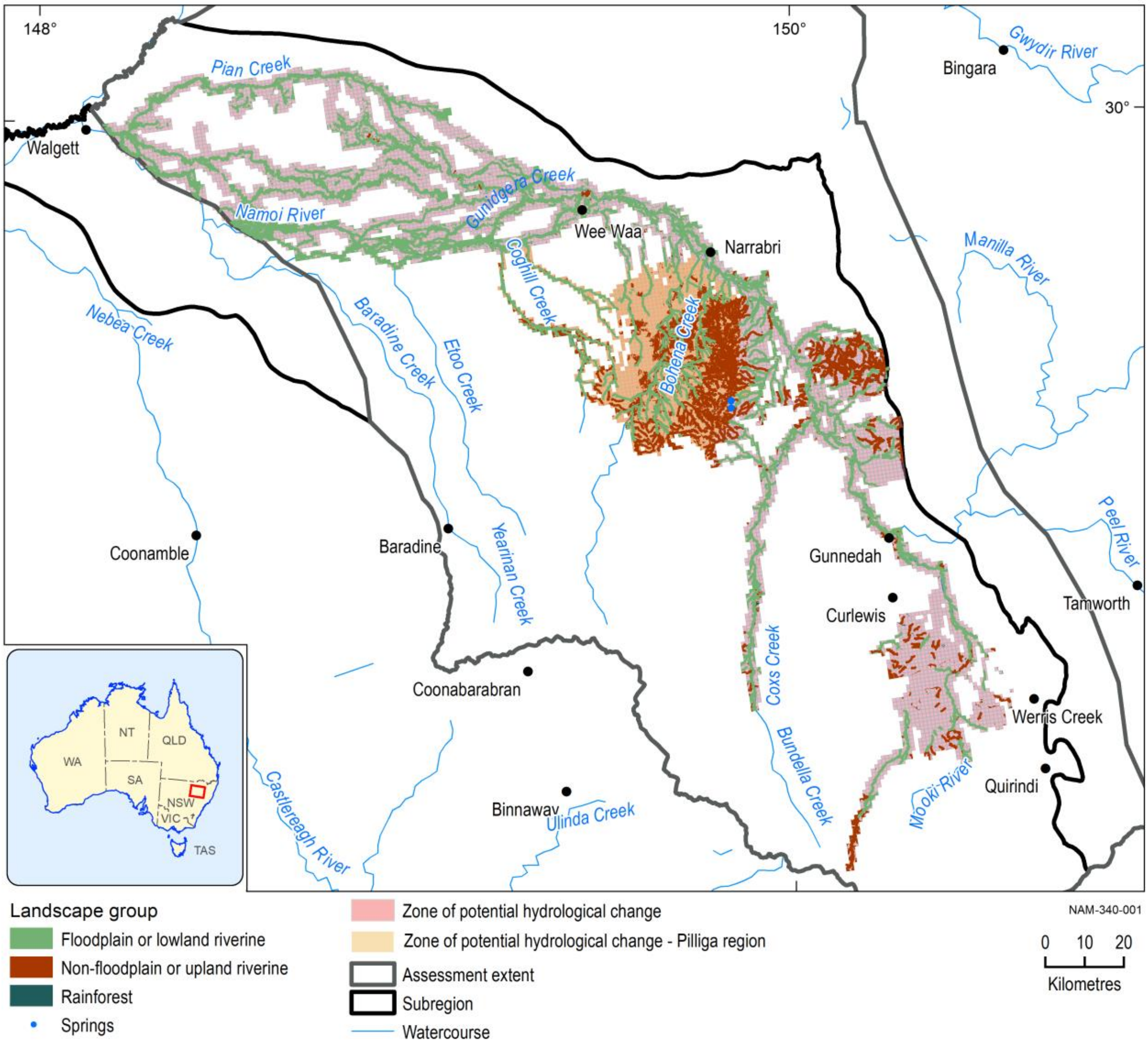

Figure 9a: Landscape classes overlaying areas of potential hydrological change (Herr et al., 2018b)

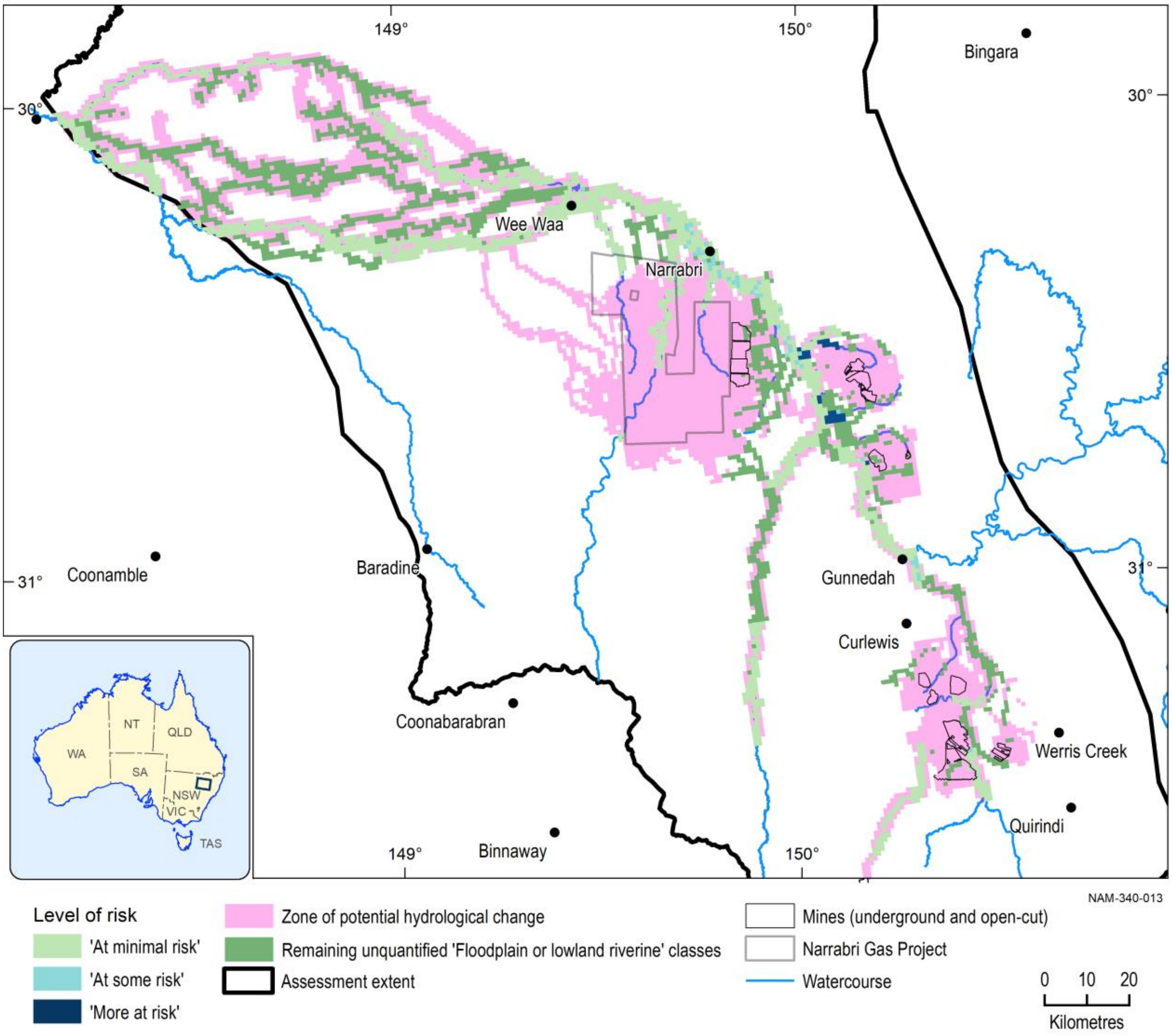

Figure 9b: Hydrological change risk level of lowland landscape class areas (Herr et al., 2018b)

5 Discussion

In Australia, there is no consistent national classification that links ecosystems at landscape level with their underlying hydrological system. While there are many different land classifications that incorporate hydrological aspects, they do not provide linkages between hydrology and landscape elements. None of these enable a broad scale ecological assessment of impacts associated with changes in water flow and availability, and they are not sufficiently generic for the purpose of assessing landscape level water related impacts on ecosystems in a spatially explicit manner (Kilroy et al., 2008; Elmore et al., 2003; Brown et al., 2014; Liermann et al., 2012; Doody et al., 2017; Poff et al., 2010; Aquatic Ecosystems Task Group, 2012; Olden et al., 2012; Gharari et al., 2011). However, the bioregional assessment program needed to assess impacts of coal resource developments on ecological systems via a water pathway. Hence, we developed an ecological landscape classification that would be applicable to the markedly different assessment regions.

We developed this classification based on existing datasets that were readily available in the areas of interest. This is much more resource and time efficient then gathering new data, using for example, remote sensing and taking hydrological measurements (see e.g. Gharari et al., 2011; Leibowitz et al., 2014; Sawicz et al., 2014; Zhang et al., 2016; Addicott et al., 2021; Carlier et al., 2021; Jones et al., 2021). The latter would have also required intensive methodology development, and would, in our opinion, not have provided fit-for-purpose information for the expert elicitation process. The advantage of our approach was that it integrated the relationships between water in the landscape and the landscape classes from the multiple dimensions in the input datasets, which allowed experts to develop causal reasoning. This causal relationship would have been much less clear when using dimensionality reduction and classifications such as proximity analysis because such methods do not infer causality without external information.

Our classification identifies the causal pathways between the water dependency of its components and human activities that result in hydrological changes. Prioritising hydrological features ensures that there is a conceptual linkage between hydrology and landscape classes, as it identifies ecohydrological landscape elements. This was crucial for the experts' understanding of how hydrological changes impact the landscape. No currently existing ecohydrological classification was suitable to do this, either because these were not spatially explicit or they did not cover the landscape completely (Poff et al., 2010; Aquatic Ecosystems Task Group, 2012; Olden et al., 2012). A spatially complete coverage of the landscape is an important prerequisite of the risk analysis because it enables assigning risk levels to the whole landscape, and it allows to identify parts of the landscape where there is insufficient information from the other modelling components. In time critical environmental impact assessments, developing models of different environmental elements often occurs in parallel for those areas where data are available. Where data are unavailable, such modelling is left for future work to improve the risk assessment. In our case, as we had a complete spatial coverage of the landscape, it enables pinpointing which part of the risk modelling inputs needed to prioritise further work. It identified the areas where hydrological modelling needed further refinement because of the lack of gauging stations and knowledge of surface water - groundwater interactions in some of the lowland drainage channels (Figure 9b).

While our spatially explicit landscape classification provided experts with the ability to readily identify cause and effect relationships between landscape elements and landscape hydrology, there are obvious differences between the landscape classifications in the three regions, reflecting their geographical differences (see Figure 5, Figure 7 and Figure 8). It provides the specificity that is required in a regional impact assessment, where the boundaries are based on a combination of geology, water resources and administrative conditions. The regionality also means that there is need for different datasets describing the landscape features that would not be available from a single classification covering the whole of Australia.

Nevertheless, each landscape classification provides a typology with an explicit connection of water to the landscape class. This connection enables a causal link between hydrological change and impact to ecosystems represented by landscape classes. The causal linkage is dependent on (i) a spatially explicit connection between water in the landscape and the landscape classes, (ii) conceptual understanding how changes in water may result in a reaction of specific ecosystem elements in the landscape class and/or landscape group and (iii) a way of modelling quantitative changes in ecosystem elements related to changes in water that incorporates causality. Our ecohydrological classification approach for landscapes provides this spatially explicit connection and has implicit ecohydrological elements that foster the conceptual understanding of the causal linkage. For example, spatially modelling groundwater level drawdown enables a prediction of which springs may be experiencing impacts from water extraction and, with additional modelling, by how much and when. Linking this information with ecological expert inputs, will then allow the identification of impacts on the spring communities and the risk to the communities.

Subsequent ecological modelling using expert elicitation of potential impacts drew heavily on our classification, which is based on a consistent rule-set and fosters conceptual understanding of landscape processes and functions. It provides an essential framework for experts to understand and conceptualise how modelled future hydrological changes from coal resource developments link to potential ecological changes at the landscape level. It is the basis for modelling the ecological risk to the landscape from hydrological changes and it allows the incorporation of different data sources and existing classification schemes. This consistency makes the classification development transparent, repeatable, and adjustable, should new data become available.

5.1 Limitations

While the ecohydrological landscape classification approach provided the basis for the risk assessment outlined above, there are some limitations that require consideration when attempting to develop and apply this ecohydrological landscape classification approach.

An important issue for the landscape classification is formulating a typology that adequately reflects both the functional and structural complexity of the ecosystem. At the same time, it also needs a succinct and consistent representation of the system that is ‘fit for purpose’, which in our context means showing a hydrological connectivity between the landscape classes, and within the general landscape. The systematic classification imposes discrete boundaries among landscape components that may not adequately capture gradients within and across landscape classes. This approach tends to simplify important components of ecotones such as ‘transition’ zones or edges between landscape classes, where ecosystem processes and/or biodiversity are likely to peak and tensions between human induced boundaries occur (Ward et al., 1999; Ryberg et al., 2021). If landscape classes are treated purely as ‘closed’ ecosystems, then the result may be a poor representation of the biotic interactions and energy exchange between adjacent systems, and this could limit a conventional impact and risk analyses. These conceptual challenges may be important considerations for subsequent impact assessments, requiring special attention in assigning risk from human induced changes in hydrology. However, expert modelling of impacts can compensate for this shortfall, when, for example, incorporating riparian areas in riverine and wetland impact model development. In our case, experts intrinsically applied the ecotone concept to riparian areas when discussing and assigning impacts to stream ecosystem variables, thus overcoming the tension of boundaries that the classification imposed (see also Hosack et al., 2018; Ickowicz et al., 2018).

There are also spatial data issues that require additional consideration beyond just simply incorporating existing data. There are several technical issues that constitute important gaps in the landscape classification for the Namoi region, for example. Here, two different approaches to define GDEs were required because one spatial dataset only included terrestrial vegetation and not riverine systems mapped within the stream network (NSW Office of Water, 2015). A second GDE dataset helped overcome this deficiency, and provided the basis to classify the stream network's dependency on groundwater (Bioregional Assessment Programme, 2012).

Wetlands in large areas of Australia are not yet adequately mapped. The separation between groundwater-dependent and surface water-dependent wetlands may not always be accurate. In many areas there is little knowledge of groundwater – surface water interactions. There is also a significant gap in the understanding of water thresholds for ecosystems associated with springs. In part, this results from a lack of bores to provide meaningful groundwater data. Some examples of these data gaps appear in the discussion of the functioning of springs in the Doongmabulla Springs complex in the Galilee region, particularly in identifying the source aquifer (Fensham et al., 2016).

There is extensive work from Queensland that links regional ecosystems vegetation to their groundwater needs, although the mapped areas are still small (Sattler and Williams, 1999; Queensland Government, Queensland, 2016; Queensland Herbarium, 2021). However, in many parts of Australia, GDE mapping and classification approaches are limited, and many areas lack systematic ground-truthing. This is especially true in areas with extensive intact native vegetation remnants, such as the Pilliga Forest of the Namoi region, where large areas of 'Grass woodland GDE' landscape class exist, but the lack of published studies on vegetation–groundwater interactions limits a definition of the nature of this interaction. This is where a risk approach can compensate for the lack of knowledge because an elevated assigned risk can reflect the limits in understanding.

5.2 Conclusions

We showed that our landscape classification approach worked in the three geographically different regions, with widely disparate information sources that fed into a landscape classification. This also makes the approach resource efficient where existing spatial landscape or ecosystem classification schemes, developed for other purposes, can be incorporated into the classification.

The study was able to formulate and implement an attribute-based classification scheme to define and delineate water-dependent features across three large regions. We conclude that this approach allowed us to repurpose several existing schemas into an adaptable and practical typology of a landscape classification. The conceptual framework of landscape ecohydrology forms the basis for this classification, which is used to focus subsequent analysis of potential cumulative impacts on water resources from multiple coal resource developments. The classification enabled the development of specific conceptual and quantitative models that linked changes in hydrology to potential impacts on ecosystems using the landscape classes. The classification provided crucial inputs for a risk analysis of landscape components subjected to hydrological changes.

Applying our approach to different regions showed that it is sufficiently general and flexible to enable the development of ecohydrological classifications in regions in Australia and potentially in other regions around the globe, given a sufficiently mature information base and data availability.

6 References

Abella, S. R., Shelburne, V. B., and MacDonald, N. W.: Multifactor classification of forest landscape ecosystems of Jocassee Gorges, southern Appalachian Mountains, South Carolina, Canadian Journal of Forest Research, 33, 1933-1946, https://doi.org/10.1139/x03-116, 2003.

Addicott, E., Neldner, V. J., and Ryan, T.: Aligning quantitative vegetation classification and landscape scale mapping: updating the classification approach of the Regional Ecosystem classification system used in Queensland, Australian Journal of Botany, 69, 400-413, https://doi.org/10.1071/BT20108, 2021.

Aquatic Ecosystems Task Group: Aquatic Ecosystems Toolkit. Module 1: Aquatic Ecosystems Toolkit Guidance Paper., Australian Government Department of Sustainability, Environment, Water, Population and Communities, Canberra, https://www.awe.gov.au/water/publications/aquatic-ecosystems-toolkit-module-1-guidance-paper, 2012.

Australian Bureau of Agricultural and Resource Economics and Sciences: Catchment Scale Land Use of Australia - 2014, Bioregional Assessment Source Dataset. [dataset], http://data.bioregionalassessments.gov.au/dataset/6f72f73c-8a61-4ae9-b8b5-3f67ec918826, 2014.

Bioregional Assessment Programme: National Groundwater Dependent Ecosystems (GDE) Atlas, Bioregional Assessment Derived Dataset [dataset], http://data.bioregionalassessments.gov.au/dataset/e358e0c8-7b83-4179-b321-3b4b70df857d, 2012.

Bioregional Assessment Programme: Asset database for the Maranoa-Balonne-Condamine subregion on 26 June 2015 [dataset], http://data.bioregionalassessments.gov.au/dataset/35e95025-f962-4425-83c7-767e2d6722e6, 2015.

Bioregional Assessment Programme: Asset database for the Namoi subregion on 18 February 2016, Bioregional Assessment Derived Dataset [dataset], http://data.bioregionalassessments.gov.au/dataset/22061f2c-e86d-4ca8-9860-c349c2513fd8, 2016.

Bioregional Assessment Programme: Landscape classification of the Namoi preliminary assessment extent. Bioregional Assessment Derived Dataset. [dataset], http://data.bioregionalassessments.gov.au/dataset/360c39e5-1225-401d-930b-f5462fdb8005, 2017.

Bioregional Assessments: Bioregional Assessment Programme, https://www.bioregionalassessments.gov.au/bioregional-assessment-program, last access: 26/08/2019, 2018.

Bioregional Assessments: Geological and Bioregional Assessment Program, https://www.bioregionalassessments.gov.au/geological-and-bioregional-assessment-program, last access: 26/08/2019, 2019.

Brown, S. C., Lester, R. E., Versace, V. L., Fawcett, J., and Laurenson, L.: Hydrologic Landscape Regionalisation Using Deductive Classification and Random Forests, Plos One, 9, https://doi.org/10.1371/journal.pone.0112856, 2014.

Bureau of Meteorology: Australian Hydrological Geospatial Fabric ('Geofabric'), version 2.1.1, Canberra, http://www.bom.gov.au/water/geofabric/documents/v2_1/ahgf_dps_surface_cartography_V2_1_release.pdf, 2012.

Carlier, J., Doyle, M., Finn, J. A., Ó hUallacháin, D., and Moran, J.: A landscape classification map of Ireland and its potential use in national land use monitoring, Journal of Environmental Management, 289, 112498, https://doi.org/10.1016/j.jenvman.2021.112498, 2021.

CSIRO: Multi-resolution Valley Bottom Flatness MrVBF at three second resolution CSIRO 20000211 [dataset], http://data.bioregionalassessments.gov.au/dataset/7dfc93bb-62f3-40a1-8d39-0c0f27a83cb3, 2000.

Cullum, C., Brierley, G., Perry, G., and Witkowski, E.: Landscape archetypes for ecological classification and mapping: The virtue of vagueness, Progress in Physical Geography, 41, http://doi.org/10.1177/0309133316671103, 2016a.

Cullum, C., Rogers, K. H., Brierley, G., and Witkowski, E. T. F.: Ecological classification and mapping for landscape management and science, Progress in Physical Geography, 40, 38-65, https://doi.org/10.1177/0309133315611573, 2016b.

Department of Agriculture, W. a. t. E.: National Vegetation Information System (NVIS), https://www.awe.gov.au/agriculture-land/land/native-vegetation/national-vegetation-information-system, last access: 22 Mar 2022, 2021.

Department of Sustainability, Environment, Water, Population and Communities: Murray-Darling Basin aquatic ecosystem classification [dataset], http://data.bioregionalassessments.gov.au/dataset/a854a25c-8820-455c-9462-8bd39ca8b9d6, 2014.

Doody, T. M., Barron, O. V., Dowsley, K., Emelyanoya, I., Fawcett, J., Oyerton, I. C., Pritchard, J. L., Van Dijkf, A. I. J. M., and Warren, G.: Continental mapping of groundwater dependent ecosystems: A methodological framework to integrate diverse data and expert opinion, Journal of Hydrology-Regional Studies, 10, 61-81, https://doi.org/10.1016/j.ejrh.2017.01.003, 2017.

Eigenbrot, F.: Redefining Landscape Structure for Ecosystem Services, Current Landscape Ecology Reports, 1, 80-86, http://doi.org/10.1007/s40823-016-0010-0, 2016.

Elmore, A. J., Mustard, J. F., and Manning, S. J.: Regional patterns of plant community response to changes in water: Owens Valley, California, Ecol Appl, 13, 443-460, https://doi.org/10.1890/1051-0761(2003)013[0443:RPOPCR]2.0.CO;2, 2003.

Evans, T., Tan, K., Magee, J., Karim, F., Sparrow, A., Lewis, S., Marshall, S., Kellett, J., and Galinec, V.: Context statement for the Galilee subregion. Product 1.1 from the Lake Eyre Basin Bioregional Assessment, Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia, http://data.bioregionalassessments.gov.au/product/LEB/GAL/1.1, 2014.

Fensham, R., Silcock, J., Laffineur, B., and MacDermott, H.: Lake Eyre Basin Springs Assessment Project: hydrogeology, cultural history and biological values of springs in the Barcaldine, Springvale and Flinders River supergroups, Galilee Basin springs and Tertiary springs of western Queensland. Report to Office of Water Science, Department of Science, Information Technology and Innovation, Brisbane., https://publications.qld.gov.au/dataset/11c1af89-93b9-497a-b99f-

2ec6c7a8d339/resource/c5d1813b-73a4-4e05-aa86-39a8ed3045fb/download/lebsa-hchb-report-springs-wst-qld.pdf, 2016.

Geoscience Australia: GEODATA TOPO 250K Series 3 [dataset], http://data.bioregionalassessments.gov.au/dataset/a0650f18-518a-4b99-a553-44f82f28bb5f, 2006.

Gharari, S., Hrachowitz, M., Fenicia, F., and Savenije, H. H. G.: Hydrological landscape classification: investigating the performance of HAND based landscape classifications in a central European meso-scale catchment, Hydrol. Earth Syst. Sci., 15, 3275-3291, https://doi.org/10.5194/hess-15-3275-2011, 2011.

Gleeson, T. and Paszkowski, D.: Perceptions of scale in hydrology: what do you mean by regional scale?, Hydrological Sciences Journal, 59, 99-107, https://doi.org/10.1080/02626667.2013.797581, 2014.

Hall, J., Storey, D., Piper, V., Bolton, E., Woodford, A., and Jolly, J.: Ecohydrological conceptualisation for the eastern Pilbara region. A report prepared for BHP Billiton Iron Ore., Subiaco, 240, https://www.bhp.com/-/media/bhp/regulatory-information-media/iron-ore/western-australia-iron-ore/0000/report-appendices/160316_ironore_waio_pilbarastrategicassessment_state_appendix7_appendixd.pdf, 2015.

Hawkins, C. P. and Norris, R. H.: Performance of different landscape classifications for aquatic bioassessments: introduction to the series, Journal of the North American Benthological Society, 19, 367-369, https://www.journals.uchicago.edu/doi/pdfplus/10.1899/0887-3593-19.3.367, 2000.

Hawkins, C. P., Norris, R. H., Gerritsen, J., Hughes, R. M., Jackson, S. K., Johnson, R. K., and Stevenson, R. J.: Evaluation of the use of landscape classifications for the prediction of freshwater biota: synthesis and recommendations, Journal of the North American Benthological Society, 19, 541-556, https://doi.org/10.2307/1468113 2000.

Herr, A., Dambacher, J. M., Pinkard, E., Glen, M., Mohammed, C., and Wardlaw, T.: The uncertain impact of climate change on forest ecosystems How qualitative modelling can guide future research for quantitative model development, Environ Modell Softw, 76, 95-107, https://doi.org/10.1016/j.envsoft.2015.10.023, 2016.

Herr, A., Brandon, C., Beringen, H., Merrin, L. E., Post, D. A., Mitchell, P. J., Crosbie, R., Aryal, S. K., Janarhanan, S., Schmidt, R. K., and Henderson, B. L.: Assessing impacts of coal resource development on water resources in the Namoi subregion: key findings. Product 5: Outcome synthesis for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment, http://data.bioregionalassessments.gov.au/product/NIC/NAM/5, 2018a.

Herr, A., Aryal, S. K., Brandon, C., Crawford, D., Crosbie, R., Davies, P., Dunne, R., Gonzalez, D., Hayes, K. R., Henderson, B. L., Hosack, G., Ickowicz, A., Janarhanan, S., Marvanek, S., Mitchell, P. J., Merrin, L. E., Herron, N. F., O'Grady, A. P., and Post, D. A.: Impact and risk analysis for the Namoi subregion. Product 3-4 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment, https://www.bioregionalassessments.gov.au/assessments/3-4-impact-and-risk-analysis-namoi-subregion, 2018b.

Hobbs, R. J. and McIntyre, S.: Categorizing Australian landscapes as an aid to assessing the generality of landscape management guidelines, Global Ecology and Biogeography, 14, 1-15, http://dx.doi.org/10.1111/j.1466-822X.2004.00130.x, 2005.

Holland, K., Beringen, H., Brandon, C., Crosbie, R., Davies, P., Gonzalez, D., Henderson, B., Janardhanan, S., Lewis, S., Merrin, L., Mitchell, P., Mount, R., O'Grady, A., Peeters, L., Post, D., Schmidt, R., Sudholz, C., and Turnadge, C.: Impact and risk analysis for the Maranoa-Balonne-Condamine subregion. Product 3-4 for the Maranoa-Balonne-Condamine subregion from the Northern Inland Catchments Bioregional Assessment, Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia, http://data.bioregionalassessments.gov.au/product/NIC/MBC/3-4, 2017.

Hosack, G., Ickowicz, A., Hayes, K. R., Dambacher, J. M., Barry, S. A., and Henderson, B. L.: Receptor impact modelling. Submethodology M08 from the Bioregional Assessment Technical Programme, http://data.bioregionalassessments.gov.au/submethodology/M08, 2018.

Hosack, G. R., Hayes, K. R., and Barry, S. C.: Prior elicitation for Bayesian generalised linear models with application to risk control option assessment, Reliab Eng Syst Safe, 167, 351-361, https://doi.org/10.1016/j.ress.2017.06.011, 2017.

Ickowicz, A., Hosack, G., Mitchell, P. J., Dambacher, J. M., Hayes, K. R., O'Grady, A. P., Henderson, B. L., and Herron, N. F.: Receptor impact modelling for the Namoi subregion. Product 2.7 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment, http://data.bioregionalassessments.gov.au/product/NIC/NAM/2.7, 2018.

Jones, C. E. J., Leibowitz, S. G., Sawicz, K. A., Comeleo, R. L., Stratton, L. E., Morefield, P. E., and Weaver, C. P.: Using hydrologic landscape classification and climatic time series to assess hydrologic vulnerability of the western U.S. to climate, Hydrol. Earth Syst. Sci., 25, 3179-3206, https://doi.org/10.5194/hess-25-3179-2021, 2021.

Kilroy, G., Ryan, J., Coxon, C., and Daly, D.: A Framework for the Assessment of Groundwater – Dependent Terrestrial Ecosystems under the WaterFramework Directive, http://erc.epa.ie/safer/resource?id=b5799c70-224b-102c-b381-901ddd016b14, 2008.

Leathwick, J. R., Overton, J. M., and McLeod, M.: An Environmental Domain Classification of New Zealand and Its Use as a Tool for Biodiversity Management, Conservation Biology, 17, 1612-1623, http://dx.doi.org/10.1111/j.1523-1739.2003.00469.x, 2003.

Leibowitz, S. G., Comeleo, R. L., Wigington Jr, P. J., Weaver, C. P., Morefield, P. E., Sproles, E. A., and Ebersole, J. L.: Hydrologic landscape classification evaluates streamflow vulnerability to climate change in Oregon, USA, Hydrol. Earth Syst. Sci., 18, 3367-3392, http://10.5194/hess-18-3367-2014, 2014.

Lewis, S., Evans, T., Pavey, C., Holland, K., Henderson, B., Kilgour, P., Dehelean, A., Karim, F., Viney, N., Post, D., Schmidt, R., Sudholz, C., Brandon, C., Zhang, Y., Lymburner, L., Dunn, B., Mount, R., Gonzalez, D., Peeters, L., O'Grady, A., Dunne, R., Ickowicz, A., Hosack, G., Hayes, K., Dambacher, J., and Barry, S.: Impact and risk analysis for the Galilee subregion. Product 3-4 for the Galilee subregion from the Lake Eyre Basin Bioregional Assessment., Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia, 348, https://www.bioregionalassessments.gov.au/assessments/3-4-impact-and-risk-analysis-galilee-subregion, 2018.

Liermann, C. A. R., Olden, J. D., Beechie, T. J., Kennard, M. J., Skidmore, P. B., Konrad, C. P., and Imaki, H.: Hydrogeomorphic Classification of Washington State Rivers to Support Emerging Environmental Flow Management Strategies, River Res Appl, 28, 1340-1358, http://doi.org/10.1002/rra.1541, 2012.

MacMillan, R., Martin, T., Earle, T., and McNabb, D.: Automated analysis and classification of landforms using high-resolution digital elevation data: applications and issues, Canadian Journal of Remote Sensing, 29, 592-606, https://doi.org/10.5589/m03-031, 2003.

McMahon, G., Gregonis, S. M., Waltman, S. W., Omernik, J. M., Thorson, T. D., Freeouf, J. A., Rorick, A. H., and Keys, J. E.: Developing a spatial framework of common ecological regions for the conterminous United States, Environmental Management, 28, 293-316, http://doi.org/10.1007/s0026702429 2001.

NSW Office of Environment and Heritage: Namoi Valley Flood Plain Atlas 1979, Bioregional Assessment Source Dataset [dataset], http://data.bioregionalassessments.gov.au/dataset/a854a25c-8820-455c-9462-8bd39ca8b9d6, 1979.

NSW Office of Environment and Heritage: Border Rivers Gwydir / Namoi Regional Native Vegetation Map Version 2.0 VIS_ID_2004 [dataset], http://data.bioregionalassessments.gov.au/dataset/b3ca03dc-ed6e-4fdd-82ca-e9406a6ad74a, 2015.

NSW Office of Water: Namoi CMA Groundwater Dependent Ecosystems [dataset], https://data.gov.au/data/dataset/a3e21ec4-ae53-4222-b06c-0dc2ad9838a8, 2015.

NVIS Technological Working Group: Australian Vegetation Attribute Manual: National Vegetation Information System, Version 7.0, Canberra, https://www.environment.gov.au/system/files/resources/292f10e2-8670-49b6-a72d-25e892a92360/files/australian-vegetation-attribute-manual-v70.pdf, 2017.

Office of Groundwater Impact Assessment: Spring vents assessed for the Surat Underground Water Impact Report 2012 [dataset], http://data.bioregionalassessments.gov.au/dataset/6d2b59fc-e312-4c89-9f10-e1f1b20a7a6d, 2015.

Olden, J. D., Kennard, M. J., and Pusey, B. J.: A framework for hydrologic classification with a review of methodologies and applications in ecohydrology, Ecohydrology, 5, 503-518, http://dx.doi.org/10.1002/eco.251, 2012.

Pain, C., Gregory, L., Wilson, P., and McKenzie, N.: The physiographic regions of Australia – Explanatory notes 2011, CSIRO, Canberra, https://publications.csiro.au/rpr/download?pid=csiro:EP113843&dsid=DS4, 2011.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O'Keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E., and Warner, A.: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards, Freshwater Biology, 55, 147-170, https://doi.org/10.1111/j.1365-2427.2009.02204.x, 2010.

Post, D. A., Crosbie, R. S., Viney, N. R., Peeters, L. J., Zhang, Y., Herron, N. F., Janardhanan, S., Wilkins, A., Karim, F., Aryal, S. K., Pena-Arancibia, J., Lewis, S., Evans, T., Vaze, J., Chiew, F. H. S., Marvanek, S., Henderson, B. L., Schmidt, B., and Herr, A.: Impacts of coal resource development in eastern Australia on groundwater and surface water, Journal of Hydrology, 591, https://doi.org/10.1016/j.jhydrol.2020.125281, 2020.

Poulter, B., Ciais, P., Hodson, E., Lischke, H., Maignan, F., Plummer, S., and Zimmermann, N. E.: Plant functional type mapping for earth system models, Geosci. Model Dev., 4, 993-1010, https://doi.org/10.5194/gmd-4-993-2011, 2011.

Pyne, M. I., Carlisle, D. M., Konrad, C. P., and Stein, E. D.: Classification of California streams using combined deductive and inductive approaches: Setting the foundation for analysis of hydrologic alteration, Ecohydrology, 10, https://doi.org/10.1002/eco.1802, 2017.

Queensland Department of Science, Information Technology, Innovation and the Arts: Queensland wetland data version 3 - wetland areas [dataset], http://data.bioregionalassessments.gov.au/dataset/2a187a00-b01e-4097-9ca4-c9683e7f4786, 2012.

Queensland Department of Science, Information Technology, Innovation and the Arts: Queensland groundwater dependent ecosystems [dataset], http://data.bioregionalassessments.gov.au/dataset/10940dfa-d7ef-44fb-8ac2-15d75068fff8, 2013.

Queensland Government, Queensland: Groundwater dependent ecosystem mapping background, https://wetlandinfo.des.qld.gov.au/wetlands/facts-maps/gde-background/, last access: 09 Sep 21, 2016.

Queensland Herbarium: Regional Ecosystem Description Database (REDD). Version 12 (March 2021), Brisbane, https://www.qld.gov.au/environment/plants-animals/plants/ecosystems, 2021.

Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts: Queensland Groundwater Dependent Ecosystems and Shallowest Watertable Aquifer 20150714 [dataset], http://data.bioregionalassessments.gov.au/dataset/3d36e3d4-b16b-43b3-b2eb-c1aea7ef9193, 2015.

Ryberg, T., Davidsen, J., Bernhard, J., and Larsen, M. C.: Ecotones: a Conceptual Contribution to Postdigital Thinking, Postdigital Science and Education, 3, 407-424, https://doi.org/10.1007/s42438-020-00213-5, 2021.

SA Department for Water: South Australian Wetlands – Groundwater Dependent Ecosystems (GDE) Classification [dataset], http://data.bioregionalassessments.gov.au/dataset/fc35d75a-f12e-494b-a7d3-0f27e7159b05, 2010.

Sattler, P. S. and Williams, R. D.: The conservation status of Queensland's bioregional ecosystems, Enivronmental Protection Agency, Brisbane1999.

Sawicz, K. A., Kelleher, C., Wagener, T., Troch, P., Sivapalan, M., and Carrillo, G.: Characterizing hydrologic change through catchment classification, Hydrol. Earth Syst. Sci., 18, 273-285, https://doi.org/10.5194/hess-18-273-2014, 2014.

Snelder, T. H., Cattanéo, F., Suren, A. M., and Biggs, B. J.: Is the River Environment Classification an improved landscape-scale classification of rivers?, Journal of the North American Benthological Society, 23, 580-598, https://doi.org/10.1899/0887-3593(2004)023<0580:ITRECA>2.0.CO;2, 2004.

Thackway, R. and Cresswell, I. D.: An Interim Biogeographic Regionalisation for Australia: A framework for setting priorities in the national reserves system cooperative program, Australian Nature Conservancy Agency, Canberra, 99, https://www.environment.gov.au/system/files/resources/4263c26f-f2a7-4a07-9a29-b1a81ac85acc/files/ibra-framework-setting-priorities-nrs-cooperative-program.pdf, 1995.

Ward, J. V., Tockner, K., and Schiemer, F.: Biodiversity of floodplain river ecosystems: ecotones and connectivity1, Regulated Rivers: Research & Management, 15, 125-139, 10.1002/(sici)1099-1646(199901/06)15:1/3<125::Aid-rrr523>3.0.Co;2-e, 1999.

Welsh, W., Herron, N., Rohead-O'Brien, H., Ransley, T., Aryal, S., Mitchell, P., Buckerfield, S., and Marshall, S.: Context statement for the Maranoa-Balonne-Condamine subregion. Product 1.1 for the Maranoa-Balonne-Condamine from the Northern Inland Catchments Bioregional Assessment, Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia, http://data.bioregionalassessments.gov.au/product/LNIC/MBC/1.1, 2015.

Welsh, W., Hodgkinson, J., Strand, J., Northey, J., Aryal, S., O'Grady, A., Slatter, E., Herron, N., Pinetown, K., Carey, H., Yates, G., Raisbeck-Brown, N., and Lewis, S.: Context statement for the Cooper subregion. Product 1.1 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment. Department of the Environment, Bureau of Meteorology, Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia, http://data.bioregionalassessments.gov.au/product/NIC/NAM/1.1, 2014.

Wiens, J. A. and Milne, B. T.: Scaling of 'landscapes' in landscape ecology, or, landscape ecology from a beetle's perspective, Landscape Ecology, 3, 87-96, https://doi.org/10.1007/BF00131172, 1989.

Wolfe, J. D., Shook, K. R., Spence, C., and Whitfield, C. J.: A watershed classification approach that looks beyond hydrology: application to a semi-arid, agricultural region in Canada, Hydrol. Earth Syst. Sci., 23, 3945-3967, https://10.5194/hess-23-3945-2019, 2019.

Zhang, Z., Zang, R., Wang, G., and Huang, X.: Classification of Landscape Types Based on Land Cover, Successional Stages and Plant Functional Groups in a Species-Rich Forest in Hainan Island, China, Tropical Conservation Science, 9, 135-152, https://doi.org/10.1177/194008291600900107, 2016.

7 Author contributions

AH, LM undertook the original draft preparation. All authors contributed to review and editing, conceptualisation, methodology and investigation.

8 Competing interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

This research was carried out under the auspices of the Bioregional Assessment Programme, a collaboration between the Australian Department of Environment and Energy, CSIRO, Geoscience Australia and the Bureau of Meteorology. The Authors wish to thank Willem Vervoort and two anonymous reviewers for valuable suggestions that provided valuable improvements on the clarity of the manuscript.