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

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Abstract

Describing and classifying a landscape for environmental impact and risk assessment purposes is a non-trivial challenge, as standard landscape classifications that cater for region specific impacts do not exist. Assessing impacts on ecosystems from extraction of water resources across large regions requires linking of landscape features to 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

Introduction

The categorisation of the Earth's surface into geo-ecological landscape classes provides a way to simplify the complexity of 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-

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scale attributes, such as climate, topography, geology, and land cover, that are homogeneous and distinctive compared to other regions, and 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).

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

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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 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. Therefore, a standardised approach to formulating classifications that combine these two aspects, ecosystems and their water sources, is lacking. The 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 resource developments. This new system must incorporate surface water and groundwater regimes into a spatial demarcation of ecosystem boundaries in 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 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 and risks to ecosystems. Importantly, the classification also provides the ability to conceptually describe and causally connect hydrological changes at

Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 12:04:12 PM

These are quite complex statements and I think a more detailed example would be useful. Why are aquatic organisms and environmental flows not useful indicators for "waters and the wider landscape". This might be crystal clear to you, but is not intuitive. This is a major part of your argument.

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 12:07:13 PM

This is again a very dense conceptual statement and it would be worth explaining this in more detail. What do you mean by "surface water and groundwater regimes"? And why do they need to be incorporates into the "spatial demarcation"? How does this relate to catchments/watersheds?

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and testing?

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and test?

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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 risk, even those in a different contextual setting with regards to data sources and existing landscape classifications.

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.

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 groundwater and surface water systems that existing and potential future coal resource developments in the region may impact.

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 1a).

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

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largest remaining area of dry sclerophyll forest west of the Great Diving Range in New South Wales (Welsh et al., 2014).

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 1b).

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 (Figure 1b).

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 part 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 low and unpredictable rainfall (Evans et al., 2014).

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 1c).

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).

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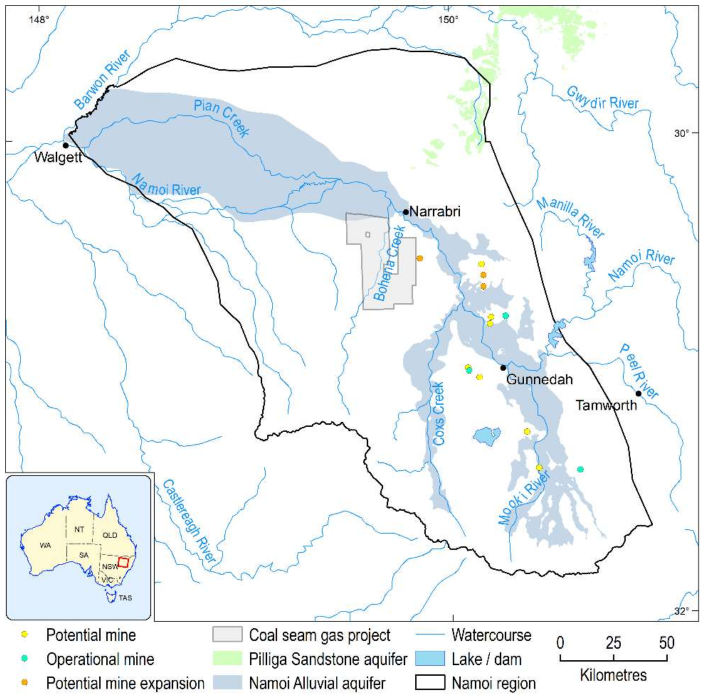
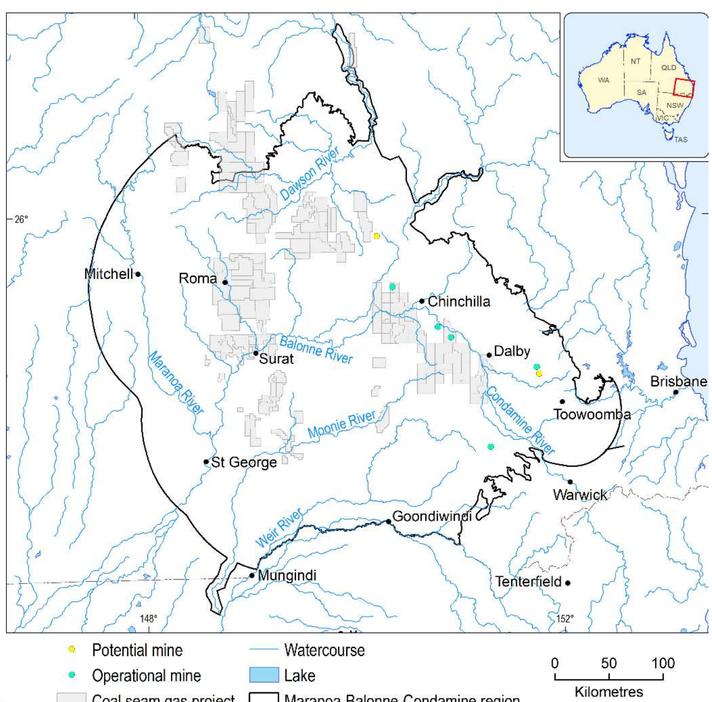


176 (a)



177 (b)

178 **Figure 1. Study areas for (a) the Namoi region (b) the Galilee region and (c) the Maranoa–Balonne–Condamine region,**
179 **showing the potential coal resource development sites**

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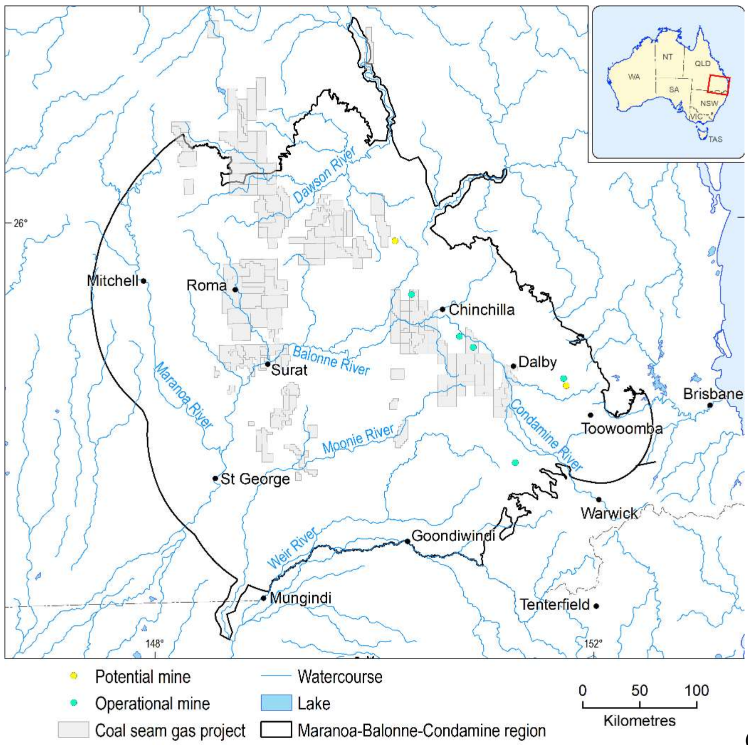

(c)

Figure 1 (cont). Study areas for (c) the Maranoa–Balonne–Condamine region, showing the potential coal resource development sites

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. Existing spatial data for each region forms the basis for categorising the landscape features using a rule-set based on attribute features within the spatial datasets. Depending on their origin and original purpose, the datasets have a regional, state or national coverage. This 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 data sets to achieve a landscape classification for each of our regions. 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).

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Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 12:38:38 PM
Figure 1 b is missing? and Figure 1C is in twice?

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 12:57:32 PM
What is the reason for choosing these three classes? I think this needs to be clarified. Why would these be "distinct" in the landscape and why are they important or relevant?

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

- broad habitat/land use type (remnant/human-modified).
  Note: In the Australian context, remnant vegetation are areas of natural vegetation that did not experience significant human modification.
- wetland (wetland/non-wetland)
- topography (upland/lowland, floodplain/non-floodplain)
- groundwater (groundwater-dependent, Great Artesian Basin (GAB)/non-GAB)/non-groundwater dependent).
  Note: identifies groundwater dependency and classifies this with 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 land forms and use, streams and springs.

For our work, where hydrological connectivity is the main reason for developing a new classification, the most important characteristics are the hydrological features. We developed a hierarchical approach, where hydrological features have priority over other landscape characteristics. This resulted in a spatially complete landscape classification. The method of prioritisation depended on region-specific characteristics and the data availability. An example prioritisation assigned in order of highest to lowest is:

- aquatic ecosystems (e.g. wetlands, streams and lakes)
- remnant vegetation – areas of vegetation that contain relatively intact plant communities
- 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. These landscape groups provided efficiencies in the expert elicitation process, as they combined more similar ecological system components based on our landscape classes while also accounting for region specific differences.

Land form classification

Land form classification relied on the dominant land type of either habitat or land use (remnant/human-modified) 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).

Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 2:31:32 PM
Where does these originate from. Why were these exactly chosen? For example, why just upland/lowland? Basically all these are qualitative choices, probably linked to your final map that you would like. Therefore this should be clarified. Unless these classifications have no influence on the framework development.

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 2:32:28 PM
Can you explain this more? Why specifically is hydrological connectivity the main reason, and how do you define "hydrological connectivity"

Number: 3 Author: rver4657 Subject: Highlight Date: 9/04/2023 2:33:23 PM
This needs some evidence to support why this qualitative choice is important

Number: 4 Author: rver4657 Subject: Highlight Date: 9/04/2023 2:33:52 PM
Can you explain what you mean by "spatially complete"?

Number: 5 Author: rver4657 Subject: Highlight Date: 9/04/2023 2:39:27 PM
I am assuming you will explain this further

Number: 6 Author: rver4657 Subject: Highlight Date: 9/04/2023 2:40:27 PM
What is "dominant": > 50%? And what is the uncertainty around this?

Stream classification

Stream classification in each of the study regions was based on stream position within the catchment, 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).

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).

Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:10:37 PM
I am unsure how this actually worked? did you look at long term data? Or was this simply determined from the existing classifications? What do you exactly mean by "stream position"?

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:11:32 PM
So this is again simply based on the original data.

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Table 1. Land form classification criteria and example datasets

Characteristic	Classification	Example datasets
Habitat/land use	• Non-remnant • Remnant	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

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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)

Results

Below we present the resulting landscape classes for the three regions. For each region, we also combined the landscape classes into groups (landscape groups) to gain efficiencies in a subsequent expert elicitation process. These groups were specific to the region and were based on distinctions in their topography, their water dependency and association with GAB or non-GAB GDEs, floodplain/non-floodplain or upland/lowland environments and remnant/human-modified habitat types. GDEs 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, which enabled conceptualisation of the landscape for modelling purposes. While the approach in defining the landscape classes is based on a

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Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:12:19 PM
I am unclear the methodology. Are we simply talking about GIS overlays? Or is there actually some sort of decision making?

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:16:29 PM
How? Please indicate the rules, as this needs to be reproducible

Number: 3 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:17:05 PM
Please specify, again, reproducibility is important

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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 spatially explicit data.

Landscape classes in the Namoi region

There were 29 landscape classes within six landscape groups in the Namoi region (Figure 2). Of these landscape groups, 'human-modified' (non-remnant) was the largest (59.3%; Table 4), and included land uses such as 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 3a).

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 3b). There were 22 springs identified within the Namoi region, with seven of these associated with the GAB (Figure 3b).

Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:17:53 PM
Please outline this consistent rule set and prioritisation

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:18:34 PM
So this was simply a GIS operation?

Number: 3 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:19:14 PM
In the original data?

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Figure 2. Overview of the Namoi landscape classification schema, including criteria and attributes resulting in six landscape groups

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I can't really see the "criteria", what makes something an "upland" topography compared to a "lowland" topography?

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

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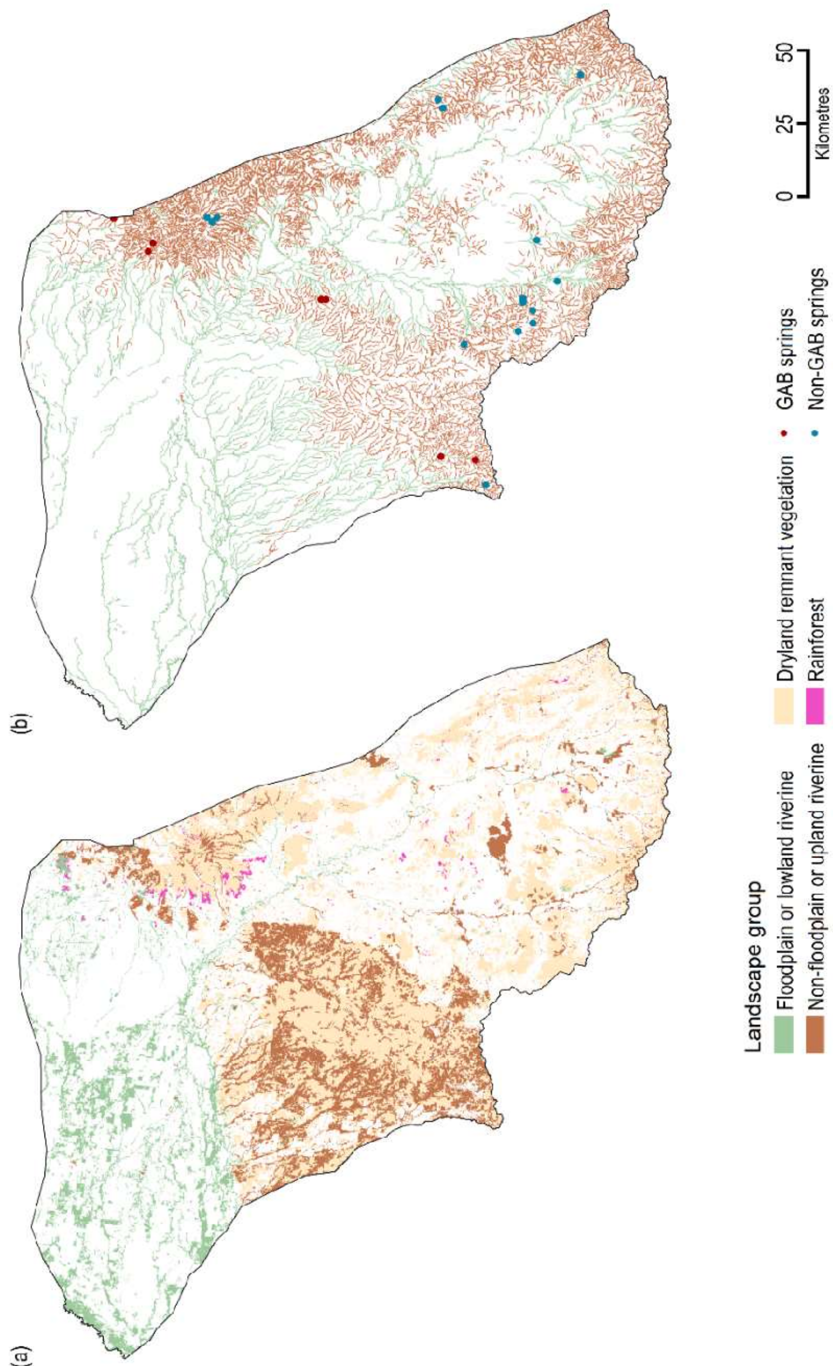

Figure 3. (a) Landscape groups (excluding the 'Human-modified'), and (b) Stream network classified as 'upland' or 'lowland' in the landscape classification and 'Springs' within the Namoi region. GAB = Great Artesian Basin Data: Bureau of Meteorology (2012); Bioregional Assessment Programme (2017)

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Landscape classes in the Galilee region

The Galilee region has 31 landscape classes organised into 11 landscape groups (Figure 4). 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.

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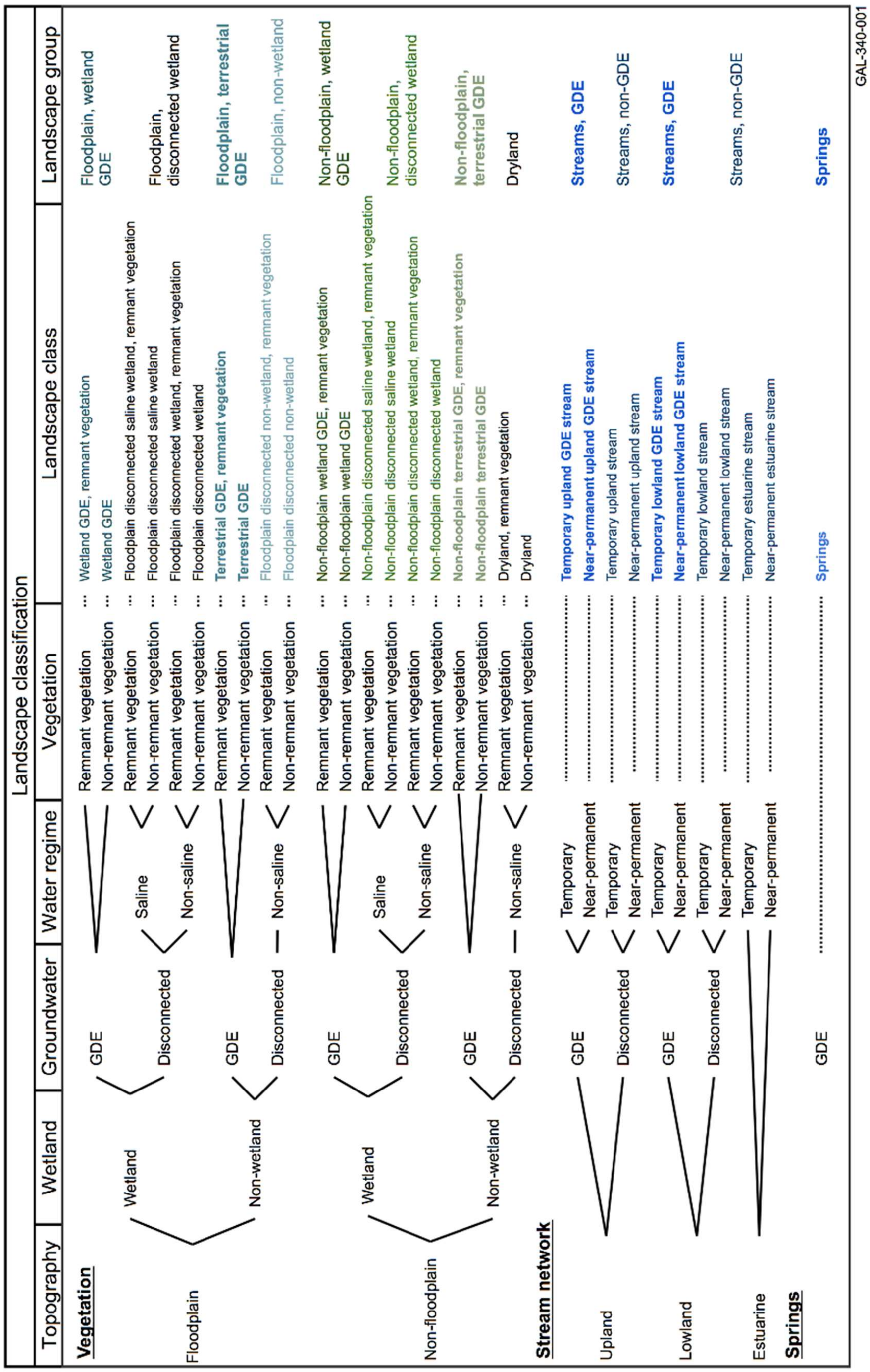

Figure 4. Landscape classification of the Galilee region

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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

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 5). 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 are three landscape groups that cover the stream network. The most dominant landscape group is 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)).

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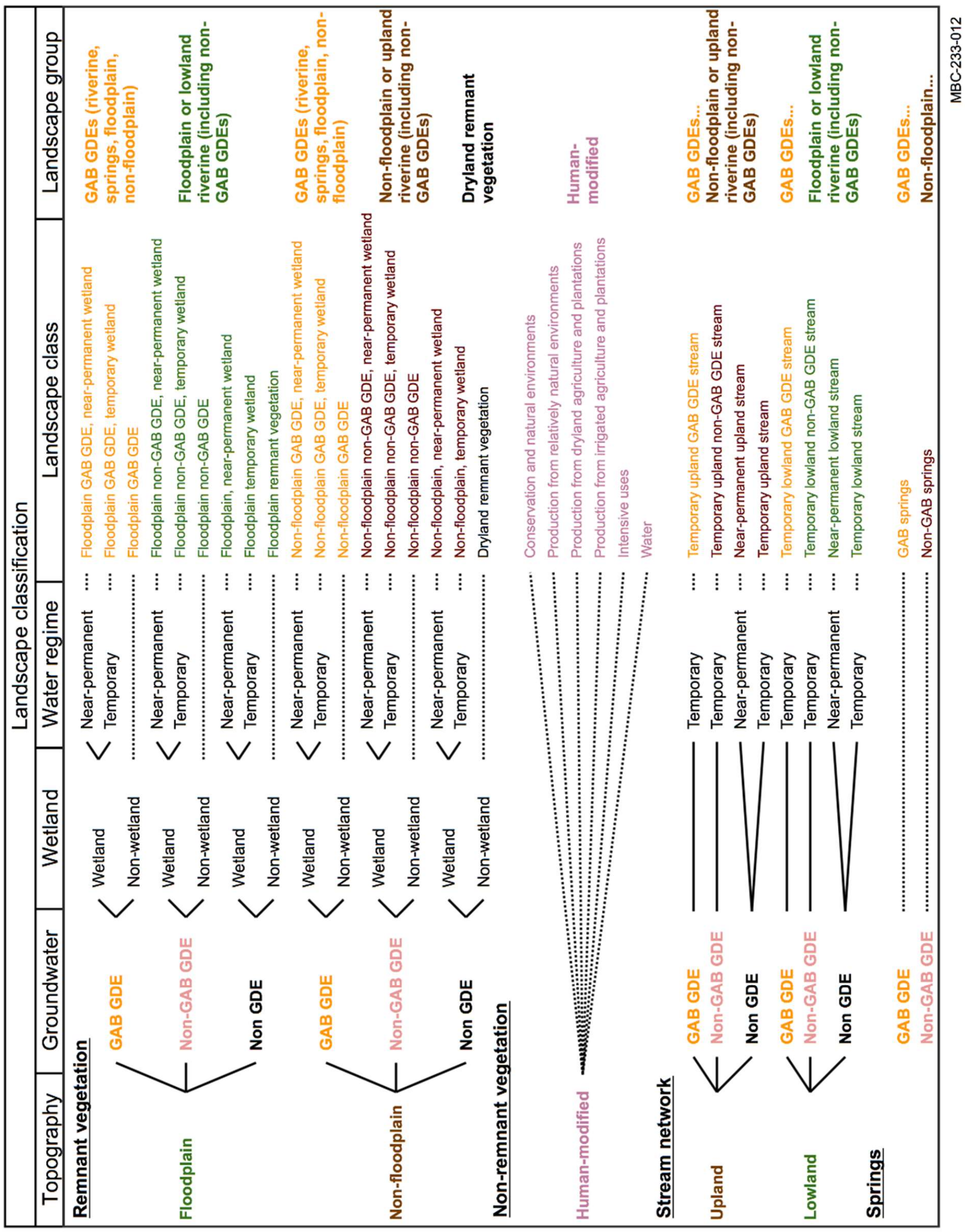

Figure 5. Landscape classification of the Maranoa–Balonne–Condamine region GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem, GAB GDEs… = GAB GDEs (riverine, springs, floodplain, non-floodplain), Non-floodplain… = Non-floodplain or upland riverine (including or non-GAB GDEs)

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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

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 that 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 extraction on ecological systems via a water pathway. Hence, we needed to develop an ecological landscape classification for this purpose that could service the different regions of the assessment.

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 (See Figure 2, Figure 4 and Figure 5) and this is a reflection of the locations and geographical differences of the regions. 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 data sets describing the landscape features that would not be available from a 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 linkage between hydrological change in one part of the

Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:24:56 PM
Can you explain why exactly your classification system does provide this?

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:32:56 PM
It is not clear to me how this impact was included, what specific criteria were used to identify this impact?

Number: 3 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:33:28 PM
how exactly?

Number: 4 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:34:07 PM
Please indicate examples of these differences and how this reflects the region?

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landscape 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. 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 on which landscape elements classified as springs may be experiencing impacts from water extraction and, with additional ecological modelling, by how much and when.

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 allows the incorporation of different data sources and existing classification schemes. This consistency also makes the classification development transparent, repeatable, and adjustable, should new data become available.

In the remainder of this section we show an application of the approach in more detail to substantiate our claim for the general useability of our classification approach in water mitigated regional impact assessment of human developments.

Landscape classification based impact assessment

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. Details of the predicted changes in groundwater and surface water 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). This work included expert assessment of ecological risk to ecosystem components based on conceptual models. Hence, the models needed to identify water mitigated linkages between hydrological changes, ecosystem components and the landscape classes. This occurred in a 3 step process.

In the following we briefly explain the 3 step process to illustrate the utility of our landscape classification approach for assessing the risk to ecosystems in the landscape groups. The process included experts identifying risk to landscape classes using their knowledge on local ecosystems. Specifically, the experts used the broad landscape groups and their underlying hydrogeological features to develop qualitative models initially that then fed into building quantitative models. These models assessed the future hydrological changes and risks to the ecosystems in the landscape groups.

The detailed 3 step process included:

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

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How is this causal linkage tested? It is one thing to link these things, but what is this based on? Or how can this be proven that this actually reflects what is in the landscape and plausible conceptually

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:37:05 PM
Are there published results from this? Where is this modelling?

Number: 3 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:37:30 PM
What demonstrates that this is an "essential" framework

Number: 4 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:51:24 PM
I think a solid concise summary of the main findings of these earlier papers should be included here.

Number: 5 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:52:01 PM
I assume you will explain how they did this?

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Here we use the example of the upland riverine landscape class. 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 positive, negative or neutral influence of one component on another. This understanding also incorporates feedback loops between the ecosystem components in form of digraphs and it enables to direct time intensive quantitative model development to 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).

The hydrological variables, and relationships between ecosystem components that the qualitative modelling process prioritised for upland riverine systems 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). This process helped to focus on those critical ecosystem components that were important quantitative models for an impact and risk assessment of landscape classes. The focus of the quantitative models was on 3 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. Specific details of the variable definitions are in Ickowicz et al. (2018).

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OK, is this because the conceptual model is based on the earlier studies or has this been developed independently?

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 3:53:36 PM
Where is this shown? Or explained?

Number: 3 Author: rver4657 Subject: Highlight Date: 9/04/2023 7:41:44 PM
More detail and a short summary will strengthen the explanation

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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.

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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 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 subregion, 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 6 (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 6 (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).

Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 7:43:19 PM
And the methodology and results of this are where in the paper? Otherwise a summary is needed to help the reader. It also would assist with reproducibility

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 8:04:58 PM
How? Can you please outline this in more detail?

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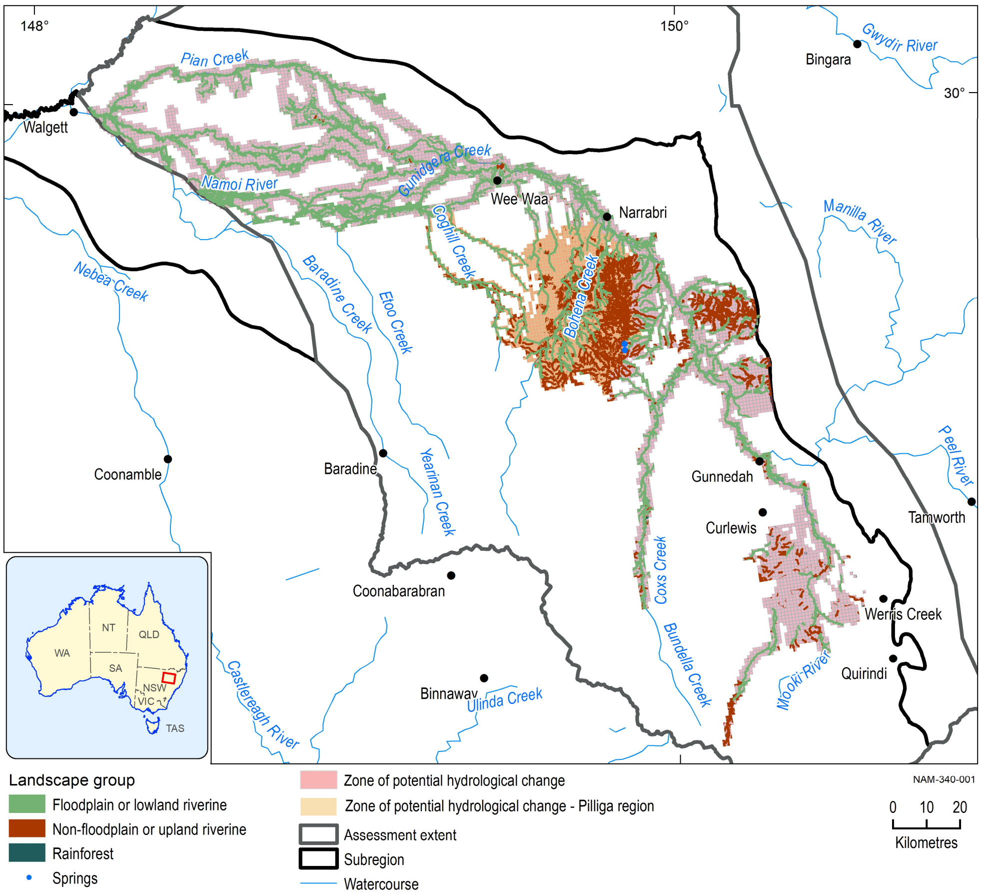

Figure 6a: Landscape classes overlaying areas of potential hydrological change (Herr et al., 2018b)

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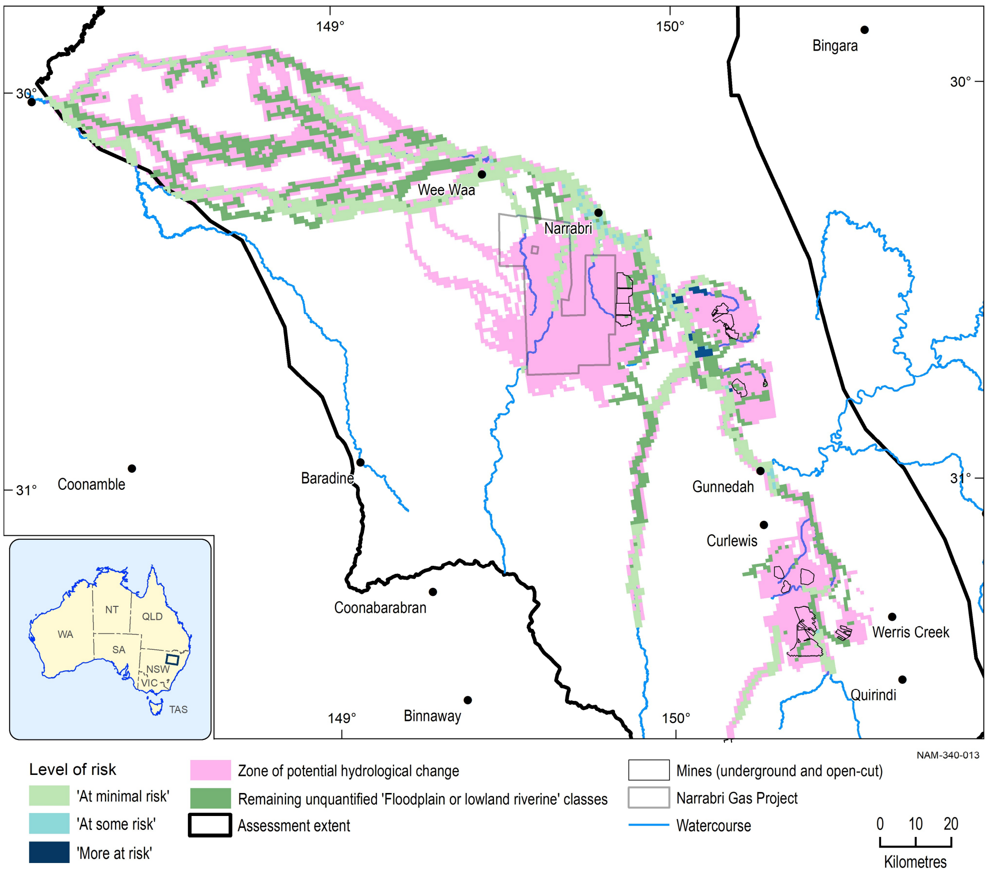

Figure 6b: Hydrological change risk level of lowland landscape class areas (Herr et al., 2018b)

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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, while delivering a succinct and consistent representation of the system that is 'fit for purpose' to assign 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. 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, conceptual modelling of impacts may be able to compensate for this shortfall, when for example, incorporating riparian areas within riverine and wetland model development.

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.

Number: 1 Author: rver4657 Subject: Highlight Date: 9/04/2023 8:07:36 PM
Also, where all the spatial datasets at the same resolution?

Number: 2 Author: rver4657 Subject: Highlight Date: 9/04/2023 8:08:52 PM
This questions the value of the final map? If the orginal data is questionable, how can the combined modelling be correct?

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Conclusions

We showed that our approach works in the three geographically different regions, with widely disparate information sources that feed into the 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 qualitative 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 globally, given a sufficiently mature information base and data availability.

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

Competing interests

The authors declare that they have no conflict of interest.

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