https://doi.org/10.5194/hess-2022-408
Preprint. Discussion started: 21 February 2023

Hydrology and Earth System Sciences
Open Access
Discussions

# 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-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 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 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 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).

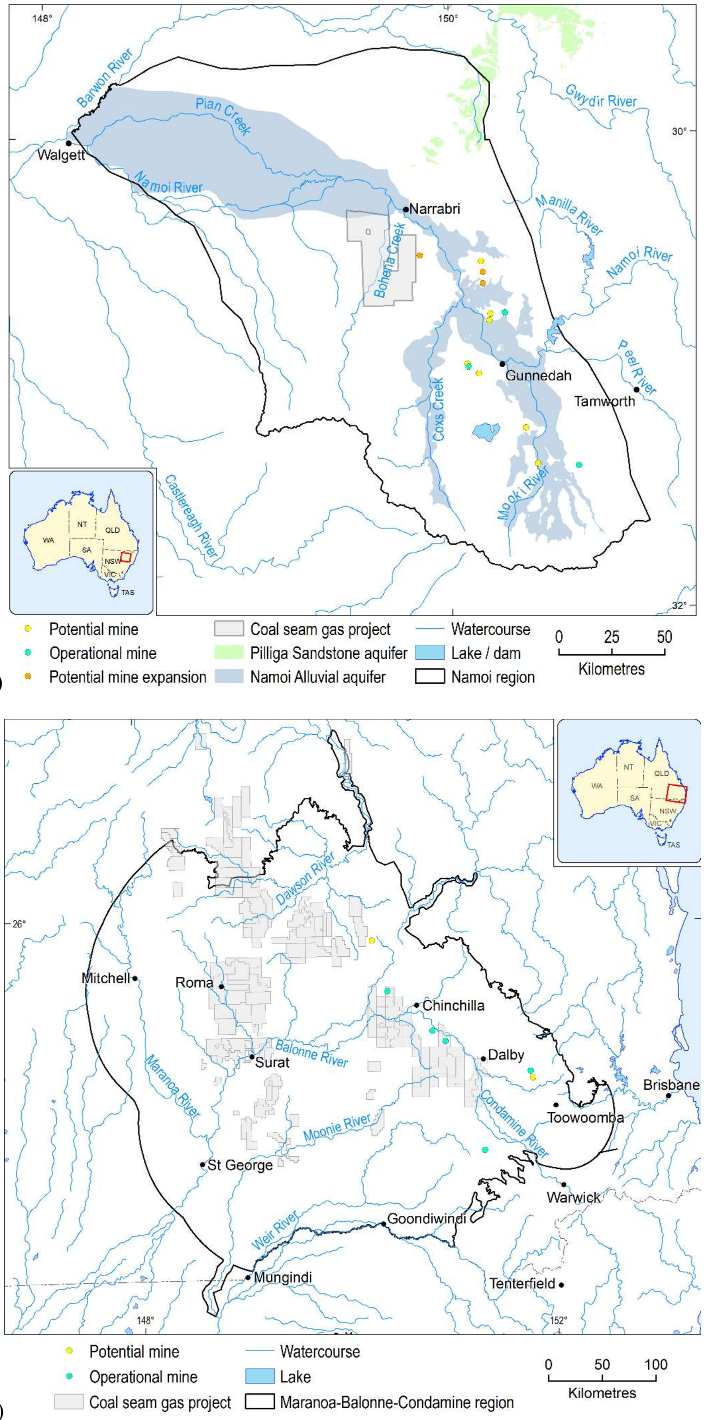
The region covers a range of environments, including mountains of the Great Dividing Range in the east, through to semi-arid and arid areas in the central and western part of the region. The main land use in the region is livestock grazing on native vegetation. There is no intensive agriculture in the 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).



(a)

(b)

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

https://doi.org/10.5194/hess-2022-408
Preprint. Discussion started: 21 February 2023

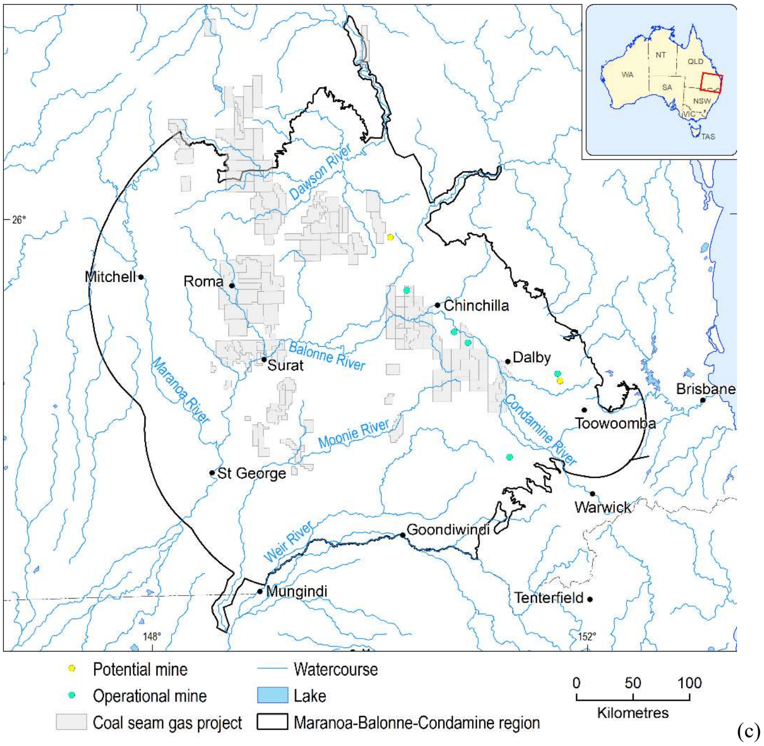


**Figure 1 (cont). Study areas for (c) the Maranoa–Balonne–Condamine region, showing the potential coal resource development sites**

## 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).

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).

### 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).

**Table 1. Land form classification criteria and example datasets**

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

https://doi.org/10.5194/hess-2022-408
Preprint. Discussion started: 21 February 2023

**Table 2. Stream classification criteria and example datasets**

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

**Table 3. Spring classification criteria and example datasets**

| Characteristic | Classification | Example datasets |
|---|---|---|
| Groundwater | • Groundwater dependent (source)<br>• Non-groundwater dependent | Asset database for the Namoi subregion (Bioregional Assessment Programme, 2016) (regional)<br>Asset database for the Maranoa–Balonne–Condamine subregion (Bioregional Assessment Programme, 2015) (regional)<br>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 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).

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275 **Figure 2. Overview of the Namoi landscape classification schema, including criteria and attributes resulting in six**
276 **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 |

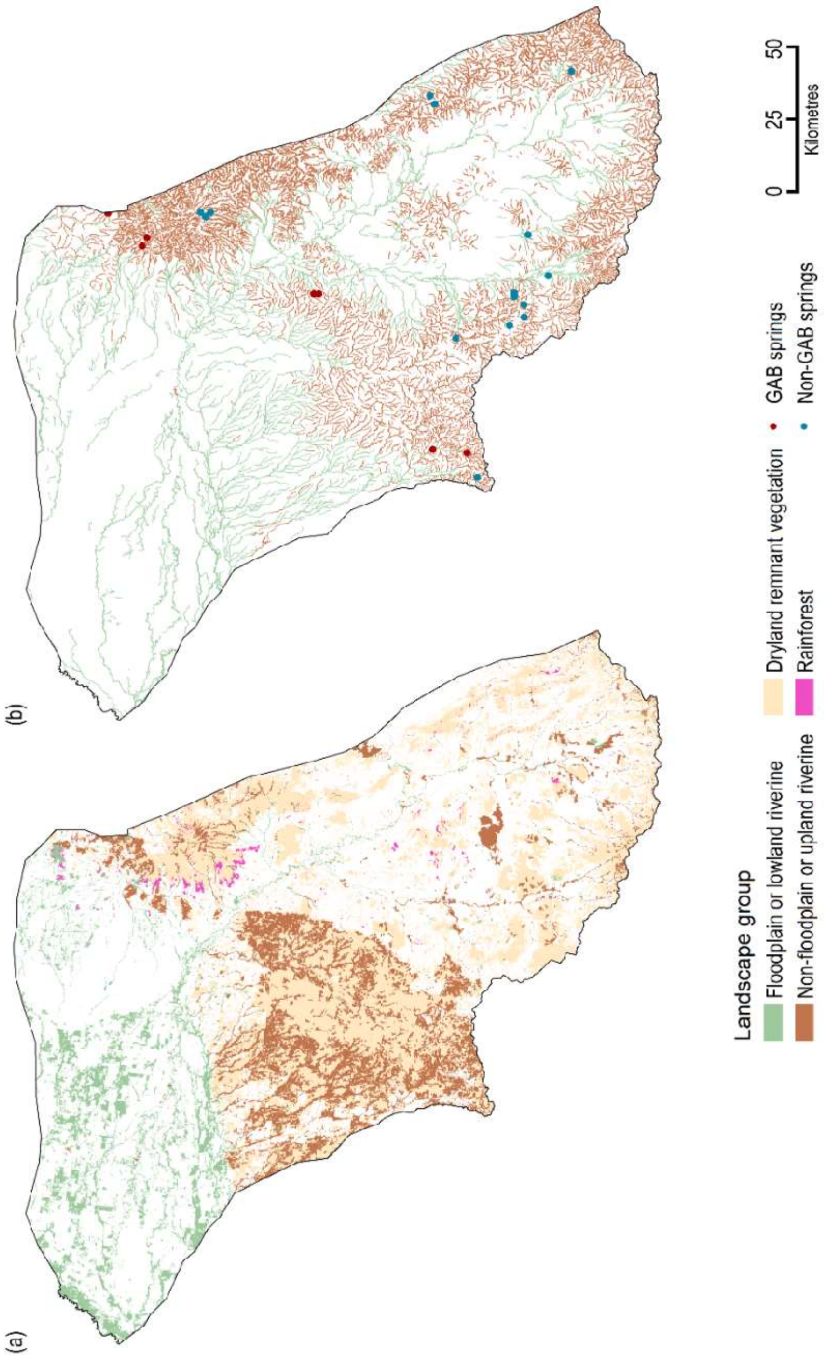

**Figure 3.** (a) Landscape groups (excluding the 'Human-modified'), and (b) Stream network classified as 'upland' or 'lowland' in the landscape classification and 'Springs' within the Namoi region. GAB = Great Artesian Basin Data: Bureau of Meteorology (2012); Bioregional Assessment Programme (2017)

**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.

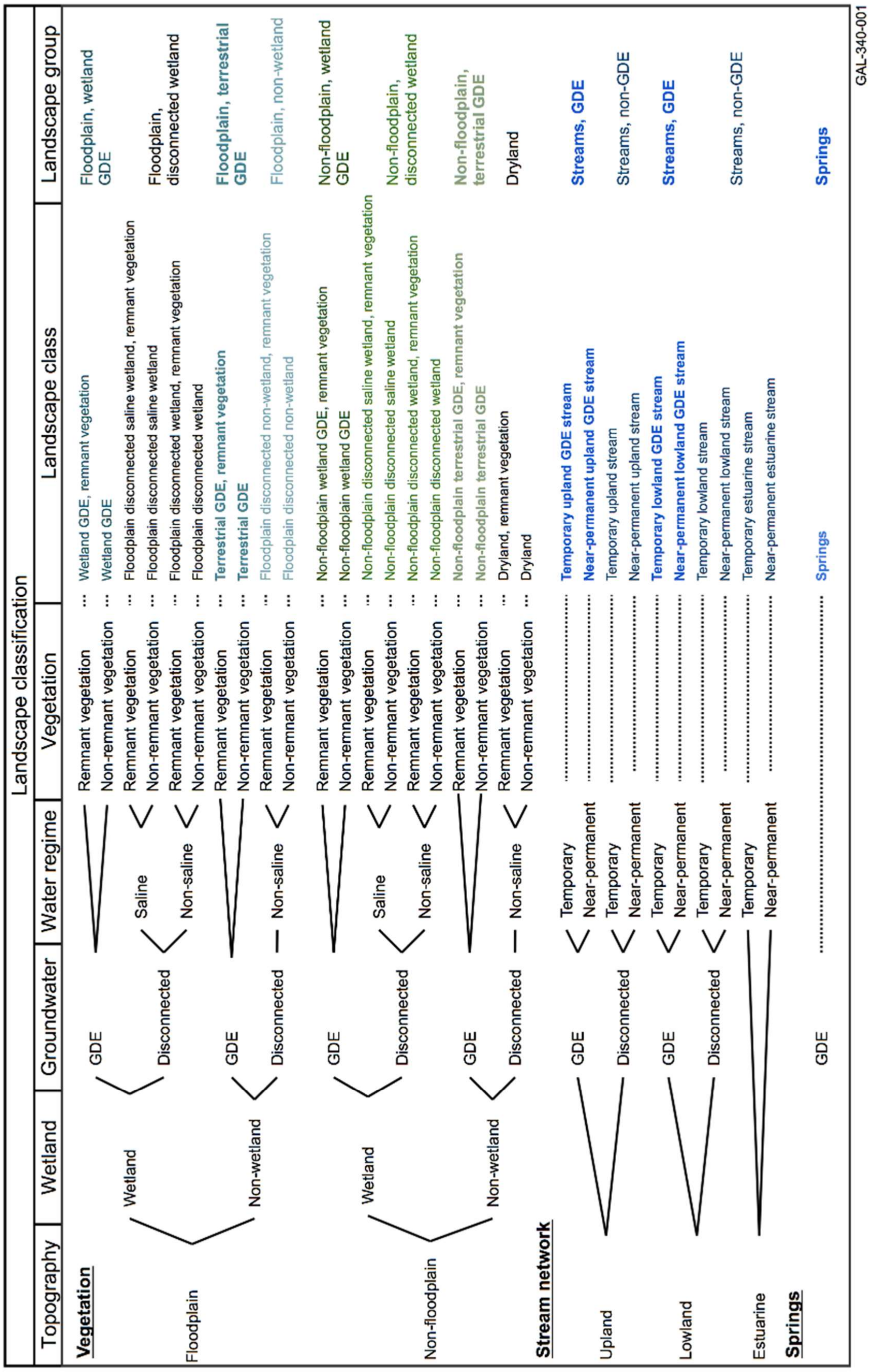

Figure 4. Landscape classification of the Galilee region

**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 |

### 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)).

https://doi.org/10.5194/hess-2022-408
Preprint. Discussion started: 21 February 2023

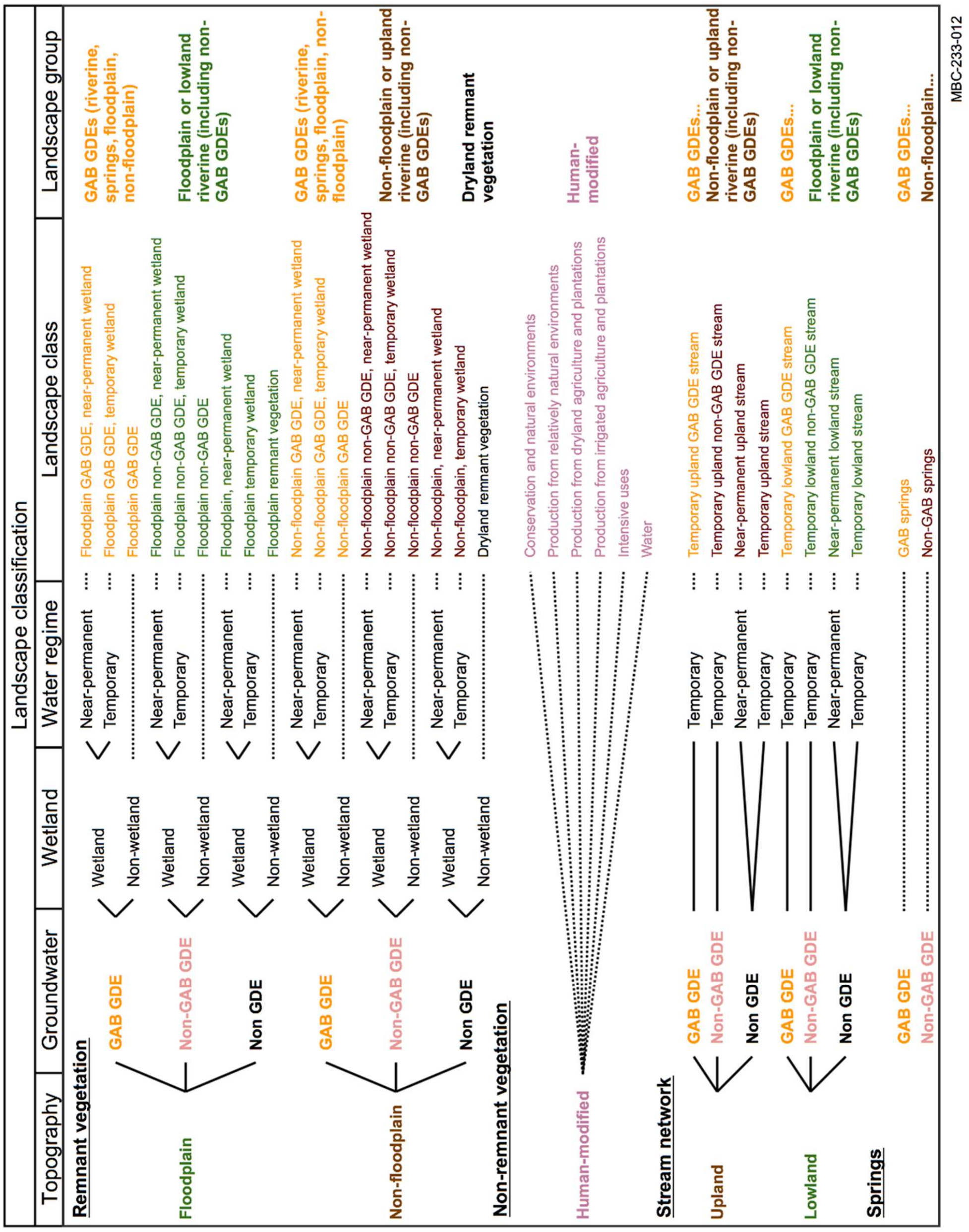

**Figure 5.** Landscape classification of the Maranoa–Balonne–Condamine region GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem, GAB GDEs… = GAB GDEs (riverine, springs, floodplain, non-floodplain), Non-floodplain… = Non-floodplain or upland riverine (including or non-GAB GDEs)

**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 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.

https://doi.org/10.5194/hess-2022-408
Preprint. Discussion started: 21 February 2023

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).

**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.<br>• Maximum difference in drawdown under a baseline and under the expected drawdown<br>• 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.<br>• 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.<br>• 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 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).

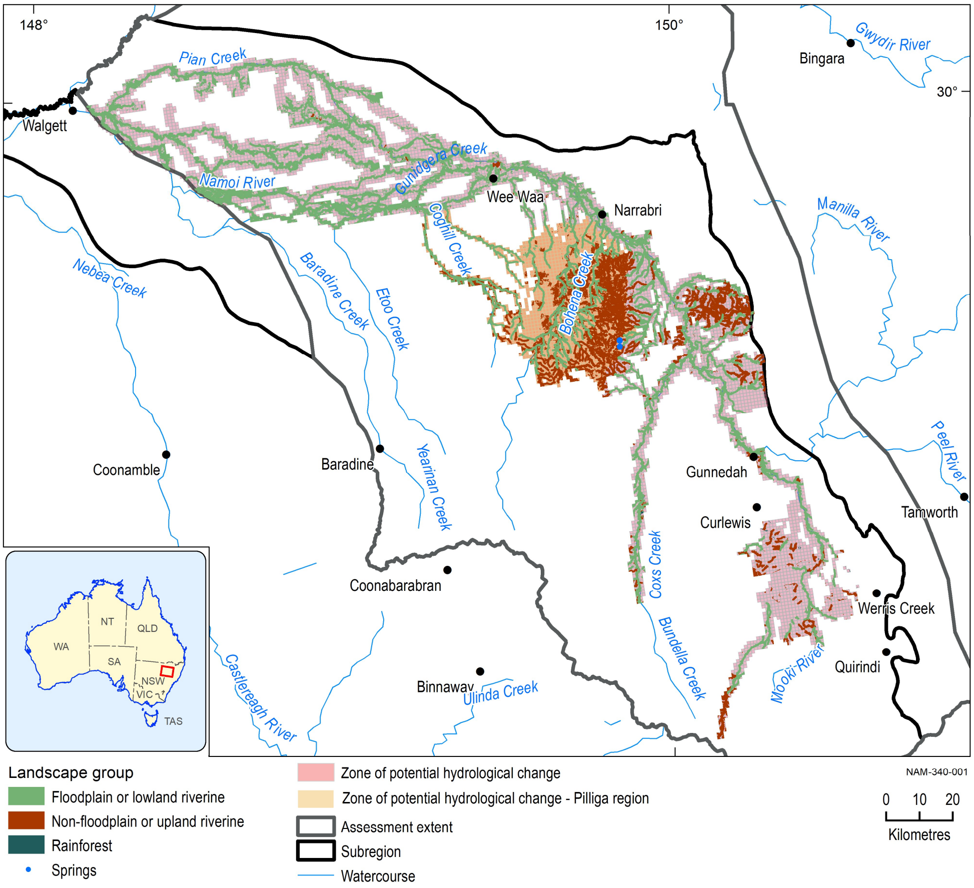

**Figure 6a: Landscape classes overlaying areas of potential hydrological change (Herr et al., 2018b)**

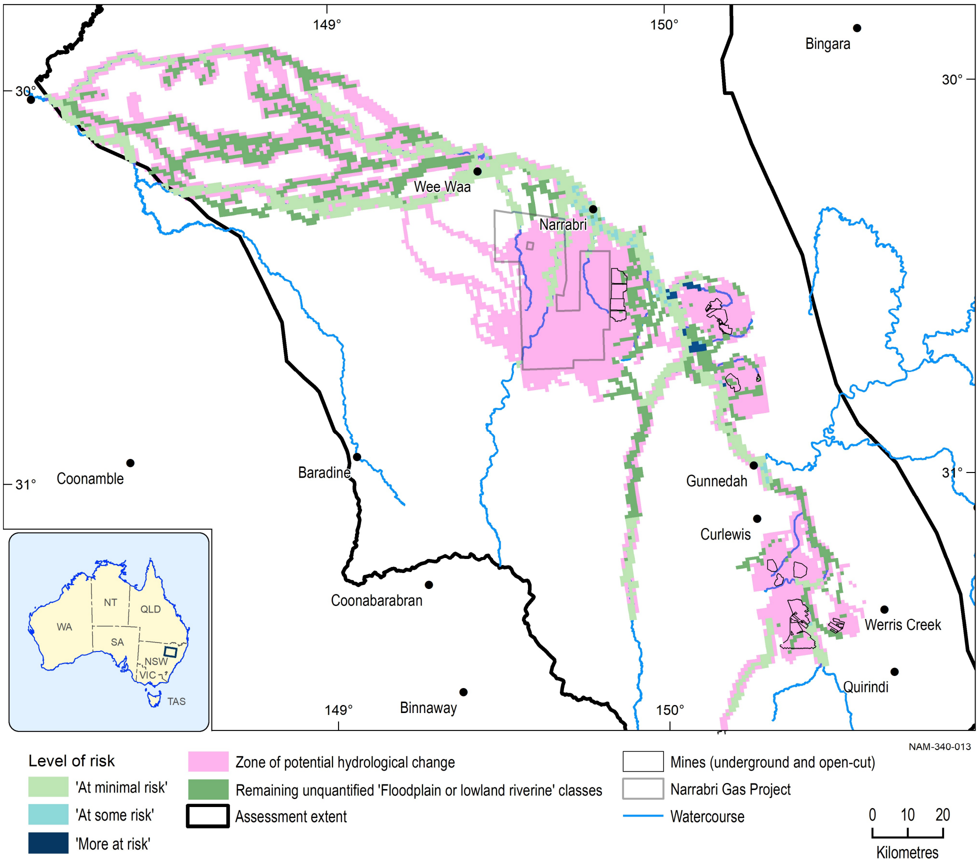

**Figure 6b: Hydrological change risk level of lowland landscape class areas (Herr et al., 2018b)**

**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.

https://doi.org/10.5194/hess-2022-408
Preprint. Discussion started: 21 February 2023

## 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.

## 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, Can J For Res, 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, Prog Phys Geogr, 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, Prog Phys Geogr, 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, Ecological Applications, 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.

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://doi.org/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. Model. Software, 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, https://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. Saf., 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 Research and Applications, 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/descriptions/download, 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.

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.

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.

## Author contributions

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.

## Acknowledgements

This research was carried out under the auspices of the Bioregional Assessment Programme, a collaboration between the Department of Environment and Energy, CSIRO, Geoscience Australia and the Bureau of Meteorology.