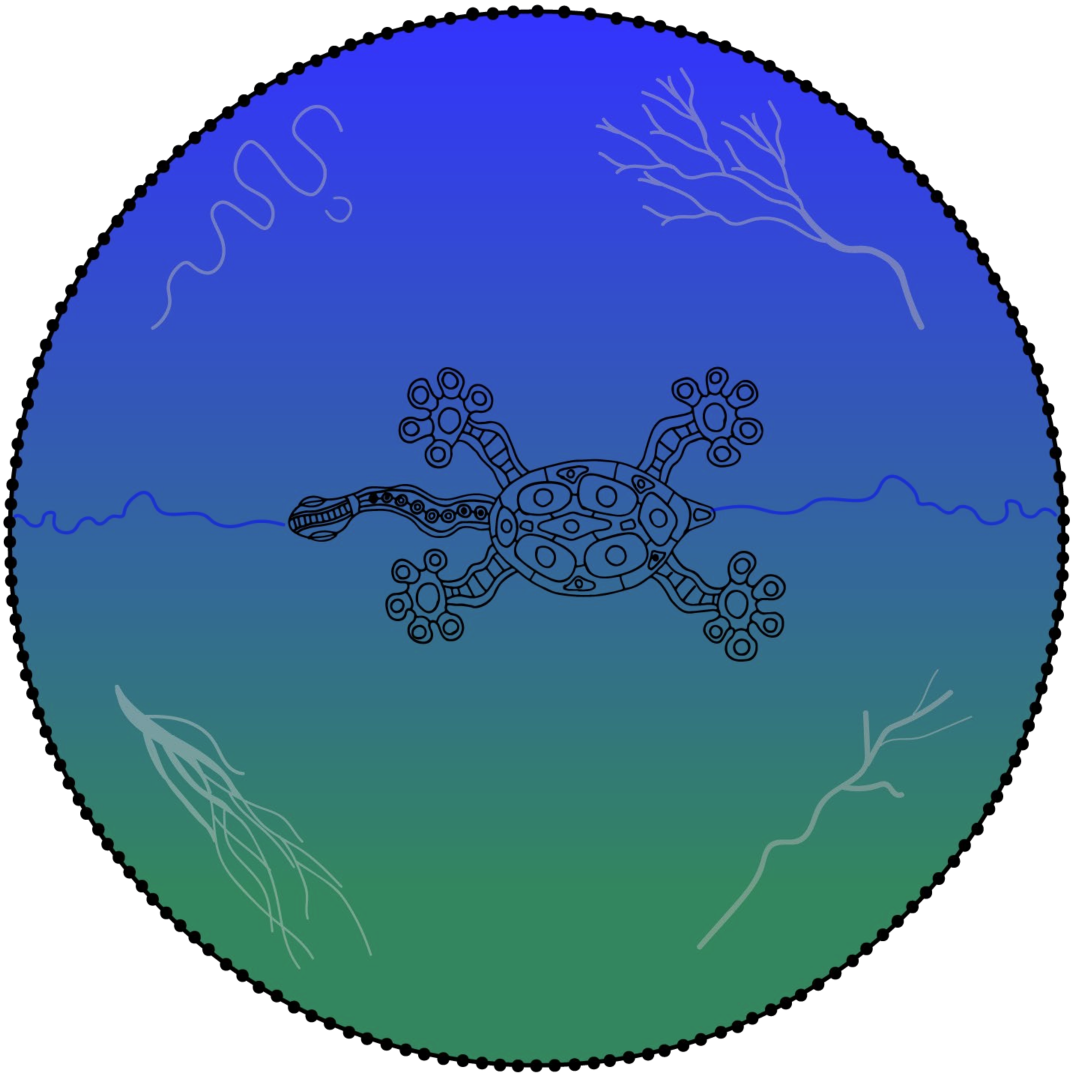

Interim Queensland River Classification Scheme

Module 2 – Literature review of biophysical attributes for river classification: Informing the development of the Interim Queensland River Classification Scheme

Version 1.0

Queensland Government

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The Department of Environment and Science acknowledges Aboriginal peoples and Torres Strait Islander peoples as the Traditional Owners and custodians of the land. We recognise their connection to land, sea and community, and pay our respects to Elders past, present and emerging.
The department is committed to respecting, protecting and promoting human rights, and our obligations under the Human Rights Act 2019.

Citation
Department of Environment and Science 2023. **Interim Queensland River Classification Scheme:** Module 2 – Literature review of biophysical attributes for river classification: Informing the development of the Queensland River Classification Scheme. Brisbane: Department of Environment and Science, Queensland Government.

Acknowledgements

The Interim Queensland River Classification Scheme has been developed by Soil and Catchment Science and Queensland Wetlands Program with input from colleagues at the University of Melbourne, Griffith University, Water Technology, Alluvium Consulting, Department of Environment and Science including Water Planning Ecology and the Herbarium, Department of Resources, Department of Regional Development, Manufacturing and Water and Seqwater. This project was funded by Reef Trust, Department of Climate Change, Energy, the Environment and Water, and the Department of Environment and Science (Office of the Great Barrier Reef, Soil and Catchment Science and Queensland Wetlands Program).

Cover page artwork: long neck freshwater turtle designed by John Locke and image compiled by Trent Munns.

The centre of this artwork is a sacred animal, the long-neck freshwater turtle. The long-neck freshwater turtle exists in two worlds, on land and in water (represented by green and blue colours). The long-neck freshwater turtle connects the two worlds together, as one whole functioning ecosystem. The long-neck freshwater turtle provides important information through its interactions with Country (environment). The sacred animal reminds us of all to protect and care for Country for the future generation.

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1. Introduction, scope and purpose of classification

1.1 Background

The rivers of Queensland have a wide variety of geomorphology, ecology, hydrology and water chemistry. They often connect the land to the sea, extending from headwater streams in upland regions to estuarine coastal sinks, providing water for drinking, cultural purposes, irrigation, recreation and habitat. These rivers also transport water, sediment, nutrients and other chemicals to the Great Barrier Reef and the Gulf of Carpentaria in northern Queensland; Moreton Bay in Southeast Queensland; and to the Murray-Darling Basin in southern Queensland (Queensland Museum, 2022). However, the text-book example of a river running in a single channel to the sea does not encompass all the variability of rivers in Queensland (Figure 1). There are also endorheic rivers, such as those of the Lake Eyre and Bulloo Basins, that do not flow to the coast. These rivers are closed internal drainage basins which retain the water flowing into them and converge into lakes or swamps that eventually evaporate (Queensland Museum, 2022). In Queensland, rivers may be in one or several channels, there may be no floodplain, an extensive floodplain, or an inset floodplain in a much larger channel. Flow may be intermittent, ephemeral, or perennial with differing contributions from groundwater, throughflow and overland flow. Along their paths the channels may pass through temperate, tropical, or arid climatic regions that are characterised by different vegetation communities.

A wide range of classification schemes have been developed for fluvial systems globally (Kondolf et al., 2016; Buffington and Montgomery, 2013; 2022), including schemes that have been adapted or directly applied to some Queensland rivers (e.g. Brierley et al. 2002; Erskine et al. 2005; Spencer et al. 2007; 2009) but they have not been developed specifically for the range and variability in the conditions experienced across the state. They are also inconsistent with the other classification schemes used for aquatic ecosystems in Queensland (DEHP 2017; DES 2020).

Multi-scale, hierarchical and attribute-based classifications schemes already exist for Queensland intertidal and subtidal ecosystems, wetlands and waterholes (DEHP 2017; DES 2023; DES 2020). An extensive literature review of biophysical classification approaches was undertaken for marine and aquatic ecosystems (DES 2019) which concluded that attribute-based classification was the most appropriate method. This conclusion resulted from the recognised advantages in data management, flexibility, transparency and contribution to holistic understanding. While the review did not specifically cover riverine ecosystems, the rationale and benefits of this approach remain equally relevant to river landscapes. This is particularly true in terms of hierarchical frameworks which have the ability to integrate multi-scale factors relevant to riverine systems (Gurnell et al. 2016; Kondolf et al. 2016). The attribute-based approach is also consistent with the Australian National Aquatic Ecosystem Classification Framework (Aquatic Ecosystems Task Group, 2013).

The classification of rivers is the process of simplifying the complexity found in rivers, that often do not have sharp boundaries delineating changes in type. Often descriptors of the parts (components) and processes of the river system are used for classification. Existing approaches include descriptors that can include attributes, metrics and functional typologies and how the functional typologies are derived is often unclear. Attribute-based classification seeks to provide clarity by providing attributes that are transparent and can be divided into meaningful categories. For example, the influence of precipitation on a river system may be described using the attribute of annual average precipitation, subdivided into categories using discrete ranges that encompass the variability in average precipitation across the area of interest.

The classification of the biophysical components of rivers provides a common language of attributes and their categories. It is also an integral part of the Whole-of-System, Values-Based Framework where components are considered alongside processes and values (DES 2022). This means a hierarchical, whole-of-system framework for classifying rivers provides the capacity for enhanced interdisciplinary communication and informs a systematic approach to river management across governing bodies. However, often it is the grouping of attributes using a hierarchical set of rules into a typology that is more useful (AETG, 2013). Typologies can be developed and applied for different purposes such as describing the variability in how rivers contribute nutrients into the water column, or the different ways that river channels are likely to adjust and respond to disturbances.

In the absence of river typologies to inform a biophysical understanding of a channel, there can be a variety of classification outcomes that influence the way that rivers are managed. These can range from applying universal philosophies and practices to all rivers regardless of their differences, to considering that each river is unique. There is a long history of treating rivers as single types, with pervasive perspectives including “rivers should be cleaned out and large wood removed”, “all riverbank erosion is a problem and must be addressed” and “no rivers should have artificial barriers to flow”. For example, in the simplification for large scale regional modelling, riverbanks could be considered to have a uniform height regardless of their position in a catchment or their sediment type. At the other end of the scale of complexity, considering that all rivers are unique means that common principles are not applied, and every management action requires an extensive research effort. Consequently, river classification can provide a valuable tool to inform the understanding of formative biophysical processes, leading to effective management actions.

Figure 1 Queensland has a wide diversity of river types, including (A) single channel and (B) multi-channel systems; (C) rivers with no floodplain, (D) wide floodplains and (E) inset floodplain; and rivers with (F) ephemeral or intermittent, (G) perennial (H) and highly modified flows. All photos by Gary Cranitch © Queensland Museum.

1.2 Purpose and scope of the review

This review complements Module 1 (DES 2023) of the Interim Queensland River Classification Scheme (QRCS). The purpose of this review was to investigate attributes used to classify rivers and typologies of river systems. It is not intended to be a comprehensive literature review of river classification systems to justify and contextualise the attribute-based approach. Kondolf et al. (2016) and Buffington and Montgomery (2022) provide recent benchmark reviews on the state of river classification, as well as a comprehensive list of other review publications that address the topic (e.g., Mosley, 1987; Naiman et al., 1992; Rosgen, 1994; Kondolf, 1995; Tadaki et al., 2014; Kasprak et al. 2016; Gurnell et al., 2016; Pasternack et al. 2018). However, while a brief summary of some of the key findings is presented in Section 3, the intent of this review was to quantitatively and qualitatively explore the range of biophysical attributes/metrics/functional typologies used in existing river classification systems and recommend candidate attributes that may be used to create a classification approach for Queensland rivers consistent with the existing attribute-based Queensland classifications for the intertidal and subtidal ecosystem (DEHP, 2017) and waterholes (DES, 2020).

1.3 Definition of water channel

This review informs the classification of rivers within the state of Queensland. This biophysical classification, and this review, do not need to be limited by the definition of rivers used in a legislative or statutory context. Rivers are referred to by a variety of terms, such as rivers, streams, creeks, drains, waterways, or watercourses, which can cause inconsistencies and confusion. The uncertainty and different interpretations because of these terms means that a different definition has been sought.

The following definition was developed to provide the scope of this classification. It was the result of a literature review followed by refinement by a panel of experts.

A 'water channel' is a wetland channel through which water flows.

- **A channel is a 'morphometric class that is both linear and concave compared with its surrounding elevation.' (Modified from Kopačková et al, 2011)**
- **Water flow may be permanent, intermittent or ephemeral.**
- **Flow may be in one or both directions.**

While a range of terms may be used in practice, and within this document, this definition provides the basis for the classification scheme. Rivers that exist as single features or as multiple interacting features are also within the scope of the review. Floodplains adjacent to rivers and the subsurface features including groundwater are also included.

1.4 Subjectivity in classification

Tadaki et al. (2014) discussed the different biases that can be involved in the classification of river systems.

> "*River classifications intersect with the governing rationalities of a given place and can produce rivers-to-order to support existing power dynamics and environmental discourses*." (Tadaki et al. 2014, p. 363).

Inherently, biophysical classification adopts a 'rational', mechanistic interpretation of river systems defined by biological and physical attributes. A perceived limitation of the adopted attribute-based approach may be its restriction to physical or deterministic variables that can strictly be measured. A classified river network is only one tool in a holistic management framework (e.g. the Whole-of-System, Values-Based Framework (DES 2022)), providing knowledge and insight to support practice. It must be appreciated that classifications are a simplification, static representation of dynamic and continuous systems into relatively objective classes. Further, it is important that classification is only one tool for effective river management and should not constrain management action or intervention and circumvent intuition and critical thinking (Kondolf et al. 2016; Newson 2002).

Subjectivity is a significant issue for river classification, particularly in the segmentation of variables that exist as a continuum into discrete classes. This issue has been a chief criticism of existing classification schemes based on a priori assumptions or expert-driven decision making. An attribute-based classification scheme separates the process of attribute classification (e.g. depth, sediment size) from the development of typologies (i.e. hierarchical combinations of attributes) for a particular purpose (e.g. ecosystem components) (AETG 2012a), and from the mapping of the attributes and types. Separating classifications, typologies and mapping provides greater flexibility to adapt the scheme for multiple purposes. Within this framework, a variety of typologies can be derived to provide participatory engagement and interdisciplinary perspectives, limiting the subjectivity and potential power of any discipline or viewpoint.

In the attribute-based classification systems reviewed here, choices may be constrained by the availability of data and the resources available for their analysis (Tadaki et al. 2014). This is not the case in the QRCS which considers all useful attributes whether data is currently available or not. Thus, attributes may be readily updated as new or improved input datasets become available, without the requirement to alter or adjust the classification scheme.

2. Overview of existing attribute-based classification systems

The Wetland Mapping and Classification Methodology (EPA 2005) and the Interim Australian National Aquatic Ecosystems (ANAE) classification framework (AETG, 2013) were the starting points for reviewing the existing attribute-based classification systems. There were three spatial levels used in the ANAE classification framework to create an attribute hierarchy: (1) regional, (2) landscape and (3) aquatic classes (Figure 2).

The three spatial levels were devised to inform on drivers and processes operating at different spatial scales. Levels 1 and 2 were intended to consider large scale, national regionalisation for landform, including climate, hydrology, and topography. Level 3 was included to separate out the classes of aquatic ecosystems (surface water and subterranean), major aquatic systems (e.g., estuarine, lacustrine, and riverine,), and the attributes used to classify those systems into habitats.

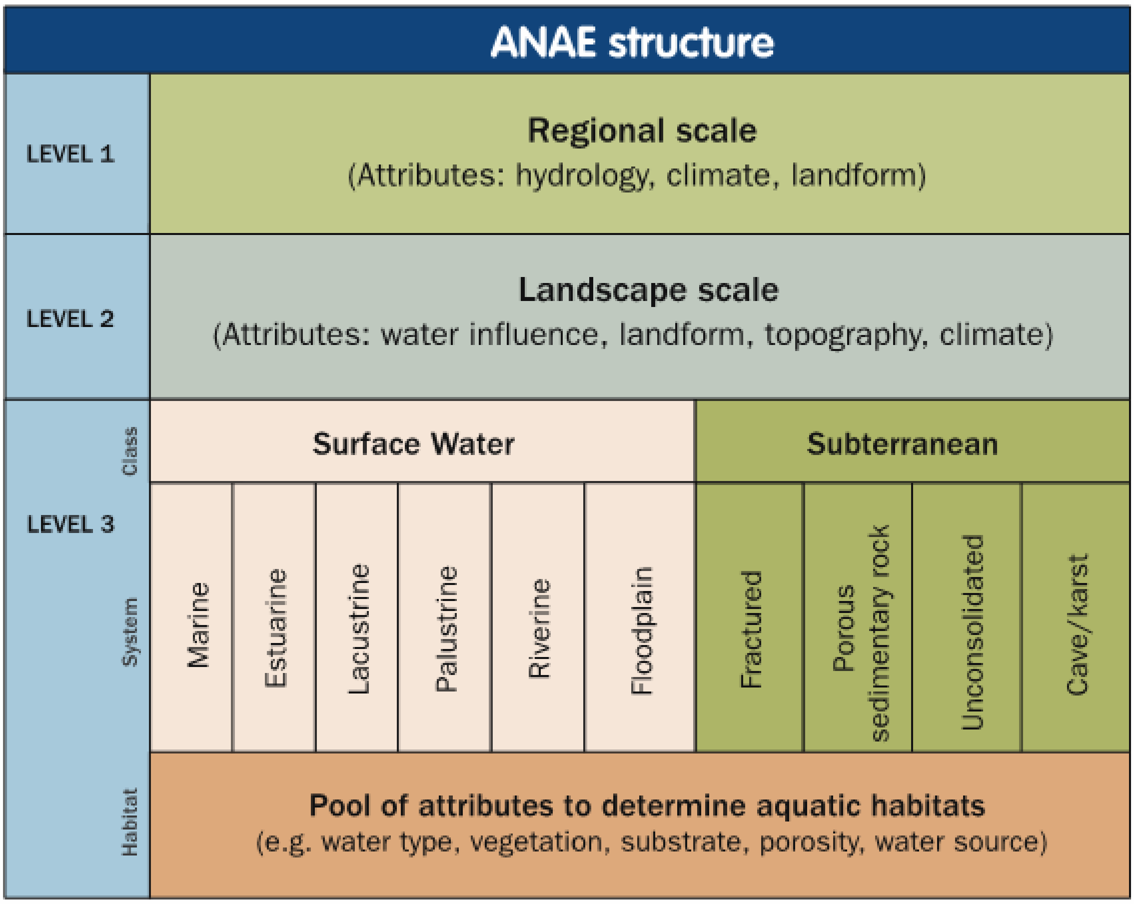


Figure 2 The hierarchical structure of different spatial levels in the ANAE (AETG, 2013)

The Queensland Intertidal and Subtidal Classification scheme (DEHP, 2019) provided a structured framework for the classification of these ecosystems. It allowed for ecosystem-based management to be implemented. The scheme used attributes, categories, thresholds and qualifiers that were applied over five different spatial levels (Figure 3).

Level 1 covered the large-scale drivers and processes at scale appropriate for continental, country or state scales. For example, climate was separated into six principle Köppen classification groups: Desert, Equatorial, Grassland, Subtropical, Temperate, Tropical. In the cases that have required it, the Level 1 attributes have been used hierarchically to set context for the attributes at lower levels. Level 2 considered processes and drivers at a slightly finer scale such as distinguishing between floodplain and non-floodplain areas. In the climate example the six groups are further divided into 27 different Köppen subcategories. The Level 3 aquatic classes, systems, and habitats are more focused on the parts of the landscape dependent on water.

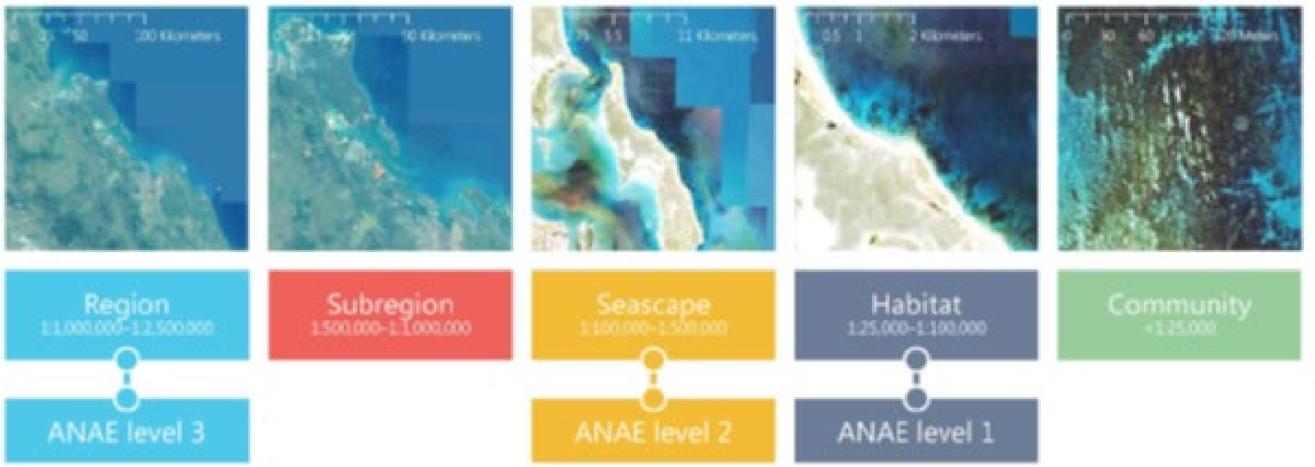


Figure 3 The five levels used in the Queensland Intertidal and Subtidal Classification (DEHP, 2017) shown alongside the original ANAE level (AETG, 2013).

The scheme was based on the following requirements:

- Based on biophysical (biological, physical and chemical) attributes to enable an understanding of ecosystem influences.
- Be consistent, measurable, transparent, repeatable and flexible, including a consistent language and terminology across the state and consistent framework to reduce overlap.
- Ability to integrate with, complement and cross-walk to other state and national mapping, data sets and classification schemes.
- Mappable for managers, researchers, other stakeholders and provides a consistent platform for policy and planning decisions, including offsets.
- Applicable to a range of management issues and scalable for all Queensland, for example for consistent attribute-based data collection, and future monitoring and assessment programs.
- Provide a common framework to incorporate existing data and knowledge for classification, data capture, storage and retrieval, mapping and monitoring, and identify knowledge gaps for future work.

The Queensland Intertidal and Subtidal Classification scheme (DES, 2019) reviewed over 130 aquatic classification schemes for their relevance to the specified requirements, including the attribute-based Groundwater Dependent Ecosystem (GDE) Mapping Method (DSITI, 2015, Glanville et al, 2016). While these schemes were not specific to rivers, a subset of forty schemes were examined in more detail and the purpose, approach, and data inputs/outputs of the schemes were reviewed. The main types of schemes were:

- Whole-of-system (holistic) attribute-based classifications
- Attribute-based classifications for subsets or parts of an ecosystem
- Typology classifications and inventories based on limited attributes or for a limited purpose.

The review concluded that most intertidal and subtidal classification and/or mapping projects are relatively specific. This means they only focus on a narrow range of components of the ecosystem such as sediment, morphology or coral in a restricted geographical area. It was suggested that an attribute-based classification scheme would provide a more holistic and integrated framework that provided a spatial hierarchy and a list of ecosystem components and processes at different levels in the hierarchy. This would then allow the production of typologies to enable more effective management of these systems.

In the Queensland waterhole classification scheme (DES, 2020) four levels were used (Figure 4). Between 1 and 22 initial attributes were assigned to each of the levels (Table 1). After the initial attributes had been assigned then it was possible to describe the relative spatial locations of the mapped attributes using spatial attributes (Table 2). This meant that an extra two attributes were added to the seascape level and three to the habitat level, with no spatial attributes identified at the region or community level.

Climate theme attributes dominated at the region level while water characteristics was the main theme at the community level. To add flexibility to the attributes, so that they could better encompass temporal and anthropogenic variability, the attribute qualifiers of naturalness, trend and period were included. Attributes were also described as enduring or non-enduring. This related to their persistence over time, with enduring ones being easier to map.

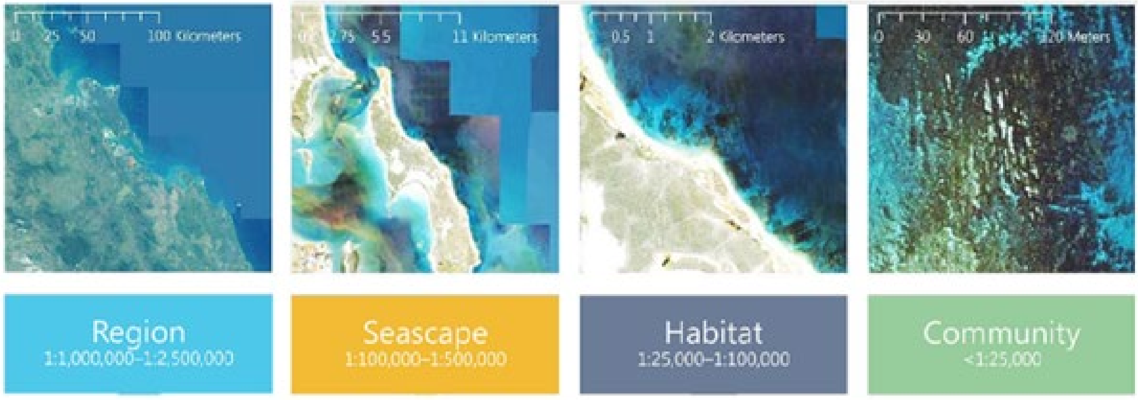


Figure 4 The four levels used in the Queensland waterhole classification (DES, 2020).

Table 1 The initial attributes used to classify waterholes in Queensland at differing spatial levels (DES, 2020)

Region Theme: Attribute	**Landscape/Seascape Theme: Attribute**	**Habitat Theme: Attribute**	**Community Theme: Attribute**
1. *Climate*: Average annual rainfall	1. *Terrain*: Underlying geology	1. *Erosion*: Erosion and deposition features	1. *Waterhole terrain*: Underlying geology
2. *Climate*: Potential evapotranspiration	2. *Water characteristic*: Water source		2. *Waterhole terrain*: Benthic substrate size
3. *Climate*: Phase-offset			3. *Waterhole terrain*: Benthic substrate composition
4. *Climate*: Aridity			4. *Waterhole terrain*: Depression depth 1 attribute
			5. *Waterhole terrain*: Depression depth 2
			6. *Waterhole terrain*: Depression depth 3
			7. *Water characteristic*: Water colour
			8. *Water characteristic*: Water clarity
			9. *Water characteristic*: Salinity
			10. *Water characteristic*: Water pH
			11. *Water characteristic*: Dissolved oxygen
			12. *Water characteristic*: Water hardness
			13. *Water characteristic*: Trophic level
			14. *Water characteristic*: *Water characteristic*: Nutrients
			15. *Water characteristic*: Mixing state
			16. *Water characteristic*: Permanence of water
			17. *Water characteristic*: Timing predictability
			18. *Water characteristic*: Maximum residence time
			19. *Vegetation:* Surrounding vegetation
			20. *Vegetation:* Shading
			21. *Groundwater hydrology:* Aquifer confinement
			22. *Groundwater hydrology:* Waterhole and groundwater spatial connectivity regime

Table 2 The spatially derived attributes used to classify waterholes in Queensland at differing levels (DES 2020)

Region Theme: Attribute	**Landscape/Seascape Theme: Attribute**	**Habitat Theme: Attribute**	**Community Theme: Attribute**
	1. *Degree of isolation*: Proximity to similar waterhole	1. *Water supply*: Water source distance	
	2. *Degree of isolation*: Proximity to any other waterhole	2. *Water supply*: Water permanency in the boarder landform element	
		3. *Water morphology and topology:* Morphological dimensions	

2.1 Summary and recommendations

The existing Queensland attribute-based ecosystem classification schemes have shown the benefits of using a flexible set of attributes that can be applied to create typologies for different purposes. Traditional approaches have been more focused on a single problem, spatial area or component of the ecosystem.

Attributes in the two Queensland based systems have been collated over four or five different spatial scales, rather than the existing three of the ANAE (AETG, 2013). They have been divided into different themes and given qualifiers to describe their temporal variability or trend and amount of anthropogenic modification. The QRCS will adopt a similar system with attributes, spatial attributes and qualifiers and draw on the existing attributes developed for the other schemes, especially at the upper levels.

3. Biophysical river classification

A wide range of attempts to classify rivers have been proposed since the earliest days (e.g. Davis, 1899) and the literature has many examples of different river classification schemes, all of which have their own merits and limitations (e.g. Rosgen, 1994, 1996; Kondolf, 1995; Miller and Ritter, 1996; Brierley and Fryirs, 2000; 2005; Gurnell et al. 2016). Most existing classifications have been designed for a specific purpose at a specific resolution, and while they might perform this role adequately, most could not be regarded as universal or broadly applicable. Across the spectrum of river classifications, the two dominant purposes driving classification are to (1) improve scientific understanding of river function and determine process zones or clusters; or (2) inform decisions and management through (mainly) hydromorphological characterisation. Research driven classifications used to increase the understanding of form and processes of rivers have gradually been superseded by more management-driven systems. These purposes can be further divided into more specific objectives (Table 3). However, the primary motivation for river classification is to simplify the complex interaction of different spatiotemporal attributes nested at different spatial scales.

The approaches to river classification are diverse, with a range of classifications adopted over the last 125 years (Naura et al. 2016). Approaches include classifications based on channel units (Bisson et al. 1982; Wheaton et al., 2015), channel pattern (Strahler 1957; Rosgen et al. 1994) and channel-floodplain interactions (Melton, 1936; Nanson and Croke, 1992), process domains (Schumm 1977; Paustian et al. 1992; Montgomery and Buffington, 1997), evolutionary trajectories (Davis, 1899; Brierley and Fryirs, 2002) and hierarchically nested frameworks (Frissell et al. 1986; Gurnell et al. 2016; Pasternack et al. 2018). Many are not categorically singular in approach, while most river classifications are in some capacity hierarchical and consider the nested spatial distribution of rivers and channels into catchments, networks and reaches that has long been appreciated as an inherent characteristic in fluvial geomorphology (Kondolf et al. 2016). However, management-focused classifications are more likely to be single-scaled, focused on channel reaches relevant to the scale typical of management actions and often align with socio-political boundaries (Kondolf et al. 2016).

Formative processes or genetic controls are also often implicit or directly considered in many river classification schemes, including physiographic environments (Wohl and Merritt, 2005; Spencer et al. 2007; Heasley et al. 2019), sediment load and transport (Schumm 1963; Church, 2002; 2006), and hydrological drivers (Gustard 1992; Lane et al. 2017, 2018; Pasternack et al. 2018). More recently, statistical approaches have sought to objectively identify channel types based on the clustering or diversity of geospatial attributes (Sutfin et al. 2014; Kasprak et al. 2016; Byrne et al. 2020; Henshaw et al. 2020).

Heasley et al. (2019) divide approaches as either bottom-up, from reach-level measurements (response), or top-down, using broader scale controlling descriptors (control). Bottom-up approaches have typically been expensive and time consuming, necessitating large initial input data requirements (formerly reach-scale field datasets) which may underrepresent certain areas and limit their universal applicability. Nonetheless, such approaches are generally preferable as they use actual measurements of the feature of interest rather than inference or prediction as per the latter approach (Heasley et al. 2019).

Most classifications have been inherently regional. Numerous attempts have been made at developing universally accepted geomorphic river classification schemes, with the Rosgen (1994) and the River Styles approach of Brierley and Fryirs (2000; 2005) being recent examples in a line extending back to Davis (1899). Despite the lack of a universally accepted classification framework, the fundamental requirements of an enduring classification scheme,

> *"…should have the ability to encompass broad spatial and temporal scales, to integrate structural and functional characteristics under various in-stream disturbance regimes, to convey information about underlying mechanisms controlling in-stream features, and to accomplish this at low cost and at a high level of understanding among resource managers."* (Naiman et al., 1992, p117).

In addition to this the classification scheme should be as objective as possible and should be repeatable by different operators applying the classification system independently (Kondolf, 1995). The REFORM (REstoring rivers FOR effective catchment Management) framework provides the most recent and likely most robust example of this by using a multi-scale, hierarchical approach for developing process-based understanding of European rivers (Gurnell et al. 2016). Critically, advantages of the framework are that it is open-ended, adaptable, flexible and operates across spatial levels.

The most critical challenge of river classification is that all derived typologies are static descriptions of points on a continuum. Rivers are a process; dynamically-driven hydrogeomorphic systems shaping channel morphology across multiple scales (Byrne et al. 2020). Many biophysical classifications use descriptive channel attributes to produce reach-scale morphological classifications and inform form-process interactions, yet lack a clear articulation of those associated processes (Doyle et al., 1999). Further, classification frameworks have been derived that seek to integrate purely geomorphic form-process associations into eco-hydrologically meaningful form-habitat, function-process frameworks (see Thorp et al., 2006, Schmitt et al., 2007, Leathwick, et. al., 2011). Often, a group of morphological attributes are combined to explain species or species assemblage distribution. So, the classification ends up as a habitat or ecosystem classification rather than a river process classification. It is critical to distinguish whether a river classification is descriptive, or process based, in order to address whether the classification is underpinned by the mechanistic explanations of channel forms (Buffington and Montgomery, 2022).

Table 3 Examples of geomorphic-based river classification objectives. Adapted from Kondolf et al. (2016) with references therein. Additional references are underlined.

Objective	**Scales**					**References**
	Basin	**Valley**	**Network**	**Reach**	**Habitat**	
Describe valley geomorphology, quantify drainage network	●		●			Davis 1899; Strahler 1957; Heasley et al. 2019
Classify and characterize hydrologic regimes	●					Gustard 1992
Provide a theoretic hierarchical framework for river classification	●	●	●	●	●	Hynes 1975; Schumm 1977; Lotspeich 1980; Brussock et al. 1985; Frissell et al. 1986; Kern 1994; Gurnell et al. 2016
Elaborate hierarchical typologies and/or ecoregional studies	●	●	●	●	●	Rohm et al. 1987; Cupp 1989a; Hugues et al. 1993; Omernik 1987; Wasson et al. 1993; Imhof et al. 1996; Allan and Johnson 1997; Heritage et al. 1997; Souchon et al. 2000; Belletti et al. 2017
Characterize valley bottom or floodplain dynamics		●				Galay et al. 1973; Cupp 1989b; Nanson and Croke 1992; Bravard and Peiry 1999; Ferguson and Brierley 1999
Describe (or predict) alluvial channel patterns		●	●			Leopold and Wolman 1957; Galay et al. 1973; Rust 1978; Schumm 1985; Paustian et al. 1984; Van den Berg 1995; Nanson and Knighton 1996; Alabyan and Chalov 1998; Spencer et al. 2005; 2009
Regionalize channel morphology and dynamic	●	●	●	●		Petit 1995; Rosgen 1996
Sectorize streams in reach having homogeneous geomorphic functioning for management purposes	●		●	●		Maire and Wilms 1984; Cupp 1989b; Agence de l'Eau Rhin-Meuse et al. 1991; Orlowski et al. 1995; Van Niekerk et al. 1995;

Objective	Scales					References
	Basin	Valley	Network	Reach	Habitat	
						Bernot et al. 1996; Heritage et al. 1997; Schmitt 2001
Classify streams for management purposes	●			●		NRA 1993; Corbonnois and Zumstein 1994; Rosgen 1994, 1996; Zumstein and Goetghebeur 1994; Bernot and Creuzé des Châtelliers 1998; Doyle et al. 1999; Schmitt 2001; Piégay et al. 2009; Belletti et al. 2013; Gonzalez del Tánago et al. 2016
Classify streams on the basis of their morpho dynamic processes and adjustments	●			●		Kellerhals, et al. 1976; Schumm 1963, 1977; Tricart 1977; Brookes 1987; Whiting and Bradley 1993; Downs 1994, 1995; Montgomery and Buffington 1997; Schmitt 2001; Emery et al. 2003; Orr et al. 2008; Byrne et al. 2020
Classify reference natural states of streams (Leitbild; German approaches)	●			●		Otto and Braukmann 1983; Otto 1991; Müller et al. 1996; Bostelmann et al. 1998a,1998b; Tölk 1998
Identify reaches sensitive to erosion				●		Piégay et al. 1997
Identify reaches producing/storing LWD				●		Piégay et al. 1996
Stratify a River Quality Index	●			●		AQUASCOP 1997; Raven et al. 1997; Malavoi 2000; Schmitt 2001
Identify reaches for rehabilitation purposes	●			●		NRA 1992; Bostelmann et al. 1998a,1998b; Brierley and Fryirs 2000; 2005
Manage biological resources	●	●	●	●	●	Otto and Braukmann 1983; Wright et al. 1984; Cupp 1989a; Biggs et al. 1990; Souchon et al. 2000
Identify aquatic habitats/make biotic typologies (fish, macro-invertebrate, macrophytes)	●		●	●	●	Huet 1949; Pennak 1971; Vannote et al. 1980; Wright et al. 1984; Cupp 1989a; Holmes 1989; Malavoi 1989; Biggs et al. 1990; Hawkins et al. 1993; Robach et al. 1996; Allan and Johnson 1997; Nicolas and Pont 1997; Montgomery et al. 1998; Beechie et al. 2005; Harvey et al. 2008

Integrating process within a classification framework can introduce additional challenges, particularly in terms of supporting objectivity. A foundational geomorphic principle is that form implies process. But differentiating types of rivers based solely on form can lead to problems when using the types for management. Equifinality, for example, is when a form can be the result of many different processes. A deep channel with steep banks could be the result of a high energy stream in a resistant boundary material. It could also be the result of a headcut moving through a system and incising a channel. The future processes in these two different types would be very different and require different management strategies.

Misunderstanding formative processes can lead to the application of inappropriate management approaches and negate some of the key objectives of classification frameworks. Despite being widely adopted by managers due to its relative simplicity, the Rosgen (1994) classification of natural rivers has limitations due to its limited integration of process information (Simon et al. 2007, Lave 2012). To better describe a feature that is variable in both space and time, often a number of snapshots with different forms are used to understand the characteristic behaviour or processes governing that river type. River characterisation and process understanding can be critically informed by historical behaviour and trajectory (Brierley and Fryirs, 2005; Buffington and Montgomery, 2022).

Classification schemes such as Rosgen (1994, 1996) and the River Styles Framework (Brierley and Fryirs, 2000; Brierley et al. 2002) have some subjective parts, often relying on expert judgement backed up with some quantitative data to identify homogeneous reaches at some defined scale or resolution. An approach developed by Parker et.al., (2012) for objectively delineating uniform river reaches provides an approach that addresses how some of the issues with the subjective reach delineation can be overcome. Multivariate statistical techniques are now being increasingly used to derive typologies and remove much of the subjectivity in classification that comes from categorising and populating attributes (e.g. Schmitt et al., 2007, Leathwick, et. al., 2011; Sutfin et al. 2014; Hough-Snee et al. 2015) with varying degrees of success (Kasprak et al. 2016; Byrne et al. 2020).

Effective river management and rehabilitation require a quantitative, process-based understanding of fluvial geomorphology and biophysical interactions within a flexible scheme to address a variety of goals and issues (Kondolf et al. 2016; Buffington and Montgomery, 2022). The most important factors governing the endurance of a classification system is its ease of application but also open-endedness to facilitate the activities of multiple end users and integrate advancements in understandings or technologies (e.g. new high resolution datasets). Flexible classifications can provide valuable tools to provide understanding of river systems within regional frameworks.

3.1 Summary and recommendations

The classification of rivers has diversified from initially trying to understand form and function based on general observations to more data-driven approaches that can be used for river management. In the application of these classifications there is a balance between applying general principles, across different river types, and having specific details/attributes about the region the classification will be applied over.

Rivers exist on a continuum in space and time, classification involves describing particular points along the continuum that can be differentiated from each other using one or more attributes. A purely descriptive classification framework may be limited in its application by solely considering form in the absence of mechanistic drivers. Processes or process inferences are useful for predicting future trajectories that are useful for management, however, these have in the past not been timebound which can restrict their use.

4. Aspects of biophysical river classification

A quantitative review of attributes was made of a subset of biophysical river classification schemes from 30 pieces of literature. These classification schemes were not meant to be an exhaustive review but instead were chosen to encompass a range of time periods, geographic locations and applications. They were intended to highlight the range of ways of classifying and typing biophysical aspects of river systems that have been used, or well cited, both in Australia and internationally (Table 4). The term river system is used to encompass the whole gamut of forms and spatial extents that a river may occupy, or be influenced by, such as surface hydrology, sediment budgets, groundwater and floodplains.

The literature that focused on the river and classified by attributes within the channel was often focused on stream biota (i.e. Frissell *et al.* 1986; Davies, 2000; Parsons et al. 2002; Turak and Koop, 2008). There were also classifications that included river channel and floodplain interactions (e.g. Nanson and Croke 1992; Brierley et al. 2002; Erskine et al. 2005), while several classifications included the groundwater system (e.g. Dahl et al. 2007, Rinaldi et al. 2016). Classification schemes nested hierarchical levels either spatially or by ecosystem components. This meant that some schemes had more than one classification, for example one for the channel and one for the floodplain, resulting in 40 different approaches to segmenting rivers systems. Of these 40 approaches, there were 15 that specifically related to use in Australia (e.g. Jerie, Houshold & Peters, 2003; Bourke and Pickup, 1999).

Classifications were mainly undertaken for river management purposes, with 23 classifications stating informing management practices as the principal objective. Another 15 classifications were undertaken for research-based purposes, while two were created by Jerie, Houshold & Peters (2003) for geoconservation. These latter two classifications were separated from the management category because of the very specific intention. The biophysical emphasis was difficult to separate as many were both geomorphological and biological. Generally, if the purpose was to inform on biological processes, it was tagged as a biological classification. This meant that there were 28 geomorphological classifications and 12 biological ones.

A brief search of vegetation classifications suggested that they tend to be landscape based with some types that relate to waterways but do not necessarily define waterways, for example, the Environmental Vegetation Classification (EVC) used in Victoria (DSE, 2004). The same was true for macroinvertebrate classifications where a restricted instream set of types are used to define habitat conditions (Turak and Koop, 2008).

Table 4 Summary information of river classification schemes selected for detailed investigation.

Reference	Scheme approach	Purpose	Emphasis	No. of attributes	No. types	Spatial area of applicability
Davis (1899)	Classification	Research	Geomorphology	6	3	Region
Melton (1936)	Inventory	Research	Geomorphology	7	7	Region (USA)
Schumm (1963)	Classification	Research	Geomorphology	9	9	Region (Great Plains Rivers USA)
Brice and Blodgett (1978)	Classification	Management	Geomorphology	15	5	Region (USA)

Reference	Scheme approach	Purpose	Emphasis	No. of attributes	No. types	Spatial area of applicability
Frissell et al. (1986)	Typology	Management	Biological	35		Region
Nanson and Croke (1992)	Typology	Research	Geomorphology	6	13	Region
Rosgen (1994)	Typology	Management/fish habitat	Geomorphology	5		Basin
Nanson and Knighton (1996)	Classification	Research: Categorisation of anabranching rivers	Geomorphology	4	6	Region
Bourke and Pickup (1999)	Inventory	Research	Geomorphology	3	3	Region (Arid Central Australia)
AusRIVAS (Davies, 2000; Parsons, 2002)	Classification	Management	Biological	3		Region
	Classification	Management	Biological	5	11	Region
Brierley et al. (2002)	Typology	Management	Geomorphology	7		Region
Snelder and Biggs (2002)	Typology	Management	Geomorphology	6		Region
Jerie, Houshold and Peters (2003)	Classification	Geoconservation	Geomorphology	14	489	Region (Tasmania)
	Typology	Geoconservation	Geomorphology	18	42	Region (Tasmania)
Erskine et al. (2005)	Classification	Management	Geomorphology	8	13	Region (Tropical rivers in Northern Australia)
Dahl et al. (2007)	Typology	Management	Biological (Water framework directive)	4		Region
Fryirs et al. (2007)	Inventory	Research	Geomorphology	5	3	Region
Turak and Koop (2008)	Classification	Management	Biological	21	10	Region (NSW)
	Classification	Management	Biological	3	6	Region (NSW)
	Classification	Management	Biological	3	8	Region (NSW)
	Classification	Management	Biological	3	5	Region (NSW)
NRMSouth (2009)	Typology	Management	Geomorphology	17		Region (Tasmania)
Davies (2012)	Classification	Management	Biological	1	4	Basin (Murray Darling)
Ashworth and Lewin (2012)	Classification	Research: Categorisation of large rivers	Geomorphology	4	6	Region
	Classification	Research: Categorisation of large rivers	Geomorphology	4	5	Region
	Classification	Research: Categorisation of large rivers	Geomorphology	7	4	Region
Buffington and Montgomery (2013)	Review	Research	Geomorphology	8		N/A
DSE (2014)	Typology	Management	Geomorphology	7	25	Region (Victoria)
Gonzalez del Tánago et al. (2016)	Typology	Management	Biological	57		Region
Gurnell et al. (2016)	Typology	Management	Biological	50		Region
Kasprak et al. (2016)	Classification	Research	Geomorphology	6	4	Region
Rinaldi et al. (2016)	Typology	Management	Geomorphology	3	22	Region
	Classification	Management	Geomorphology	9	13	Region
	Classification	Management	Geomorphology	6	9	Region
	Classification	Management	Geomorphology	3	4	Region
Jha and Diplas (2018)	Classification	Research	Geomorphology	11	5	Region
Martínez-Fernández et al. (2019)	Classification	Research	Geomorphology	5		Region

Reference	Scheme approach	Purpose	Emphasis	No. of attributes	No. types	Spatial area of applicability
Solheim et al. (2019)	Typology	Management	Biological	6	20	Region
Henshaw et al. (2020)	Typology	Research	Geomorphology	30	5	Region

4.1 Spatial scales (levels) relevant to river systems

The classifications were reviewed to identify if they were constrained in the spatial scale, termed levels in the ANAE approach (AETG, 2013), over which they could be applied. A number of spatial scales were initially considered: Region; Catchment; Sub-catchment; Reach; Patch. All the classifications were considered appropriate to be applied at the regional level, however, the spatial extent of the region was sometimes constrained such as for tropical rivers (Erskine et al. 2005) or arid central Australia (Bourke and Pickup 1999).

Different spatial hierarchies in the literature were explored to indicate whether the three levels used by the ANAE (AETG, 2013) would be sufficient or if more levels were required. Three types of hierarchy are described ranging from a more ecologically focused approach (Frissell et al. 1986), the River Styles systems (Brierley et al. 2002) that was developed and is frequently used in Australian environments, and the REFORM framework developed to be used across a broad spectrum of rivers in Europe (Gurnell et al. 2016).

The spatial hierarchy used by Frissell *et al.* (1986; Figure 5 and Table 5) appeared to be similar to that used by the attribute based approaches (Section 2). Five different spatial levels or systems were defined: (1) Stream, (2) Segment, (3) Reach, (4) Pool/Riffle, and (5) Microhabitat. Each of these spatial levels was associated with examples of important evolutionary events, developmental processes, and timescales of persistence. The timescales of persistence decrease with spatial level, with the microhabitat sub metre scale persisting for around a year whilst the stream system of around a kilometre in length would have features that persist over around 10^6 years.

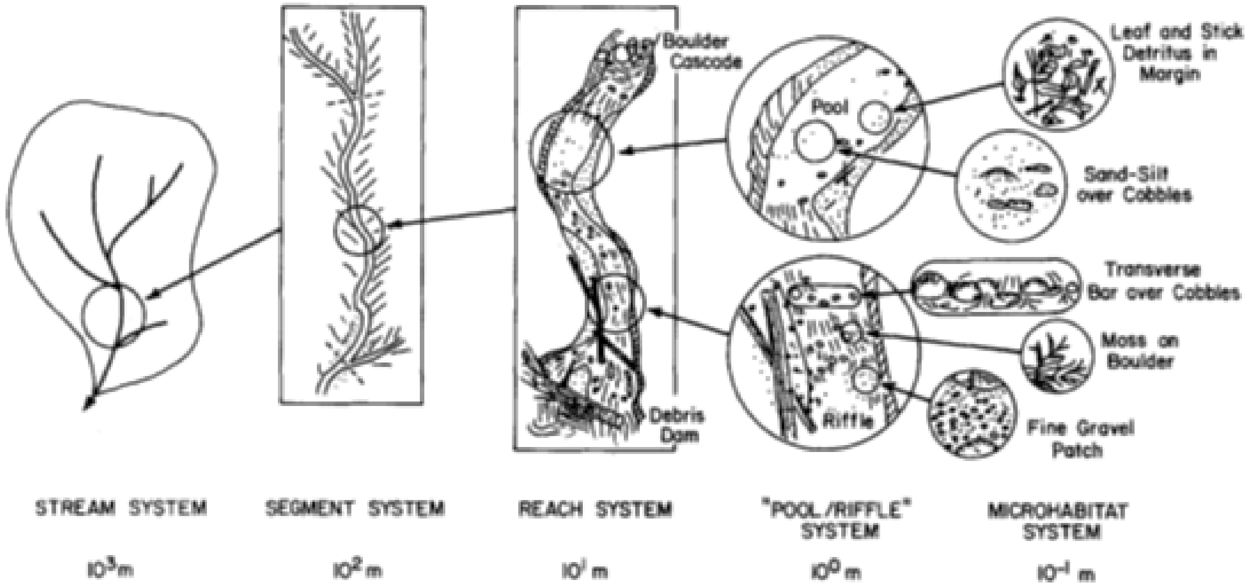
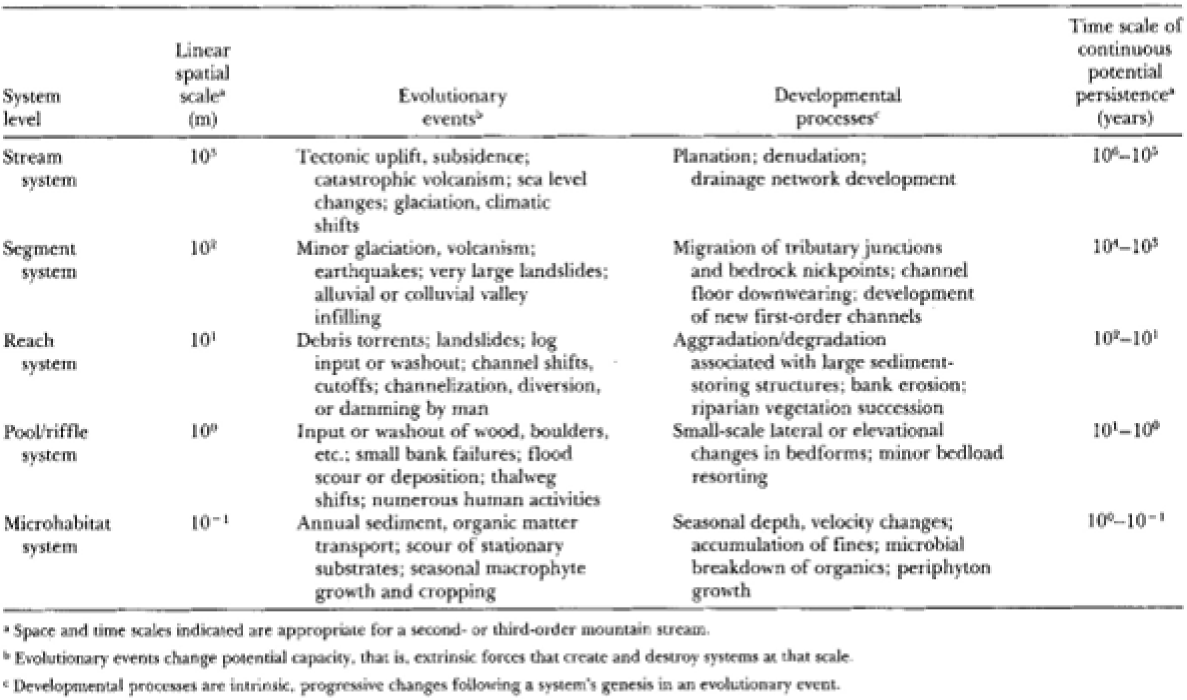


Figure 5 The spatial hierarchy of a second or third Strahler stream order mountain stream (Frissell et al. 1986, p. 203)

Table 5 Spatial and temporal scales for different stream system levels and their controlling events or processes (Frissell et al. 1986, p. 203)



System level	Linear spatial scale[a] (m)	Evolutionary events[b]	Developmental processes[c]	Time scale of continuous potential persistence[a] (years)
Stream system	10^3	Tectonic uplift, subsidence; catastrophic volcanism; sea level changes; glaciation, climatic shifts	Planation; denudation; drainage network development	10^6–10^5
Segment system	10^2	Minor glaciation, volcanism; earthquakes; very large landslides; alluvial or colluvial valley infilling	Migration of tributary junctions and bedrock nickpoints; channel floor downwearing; development of new first-order channels	10^4–10^3
Reach system	10^1	Debris torrents; landslides; log input or washout; channel shifts, cutoffs; channelization, diversion, or damming by man	Aggradation/degradation associated with large sediment-storing structures; bank erosion; riparian vegetation succession	10^2–10^1
Pool/riffle system	10^0	Input or washout of wood, boulders, etc.; small bank failures; flood scour or deposition; thalweg shifts; numerous human activities	Small-scale lateral or elevational changes in bedforms; minor bedload resorting	10^1–10^0
Microhabitat system	10^{-1}	Annual sediment, organic matter transport; scour of stationary substrates; seasonal macrophyte growth and cropping	Seasonal depth, velocity changes; accumulation of fines; microbial breakdown of organics; periphyton growth	10^0–10^{-1}

[a] Space and time scales indicated are appropriate for a second- or third-order mountain stream.

[b] Evolutionary events change potential capacity, that is, extrinsic forces that create and destroy systems at that scale.

[c] Developmental processes are intrinsic, progressive changes following a system's genesis in an evolutionary event.

Brierley et al. 2002 organised the hierarchical levels and reach-level classification of the River Styles Framework primarily based on the degree of valley confinement (Figure 6). Valley-scale features, such as floodplain pockets or channel sinuosity are subsequently used for lower levels. The types were then selected by the grainsize which may vary at the sub-valley – reach scale although the measurement is at a finer scale. The final spatial level is that of the geomorphic unit such as bars, benches and pools.

Gurnell et al. (2016) reviewed 16 multi-scale hierarchical frameworks for rivers in order to recommend a system for the European REFORM programme. The work by Frissell et al. (1986) was considered comprehensive for a multi-scale framework of streams and habitats. After reviewing the existing frameworks, they developed a new one based on eight spatial levels: (1) Region; (2) Catchment; (3) Landscape Unit; (4) River Segment; (5) Reach; (6) Geomorphic Unit; (7) Hydraulic Unit; and (8) River element (Gurnell et al., 2016) (Table 6).

When compared to Frissell et al. (1986) there was more detail at the top levels, describing processes and forms at a regional scale. This fits well with the ANAE (AETG, 2013) approach. Gurnell et al. (2016) were also clear about how they define the levels, including specifying that a reach should have uniform boundary conditions.

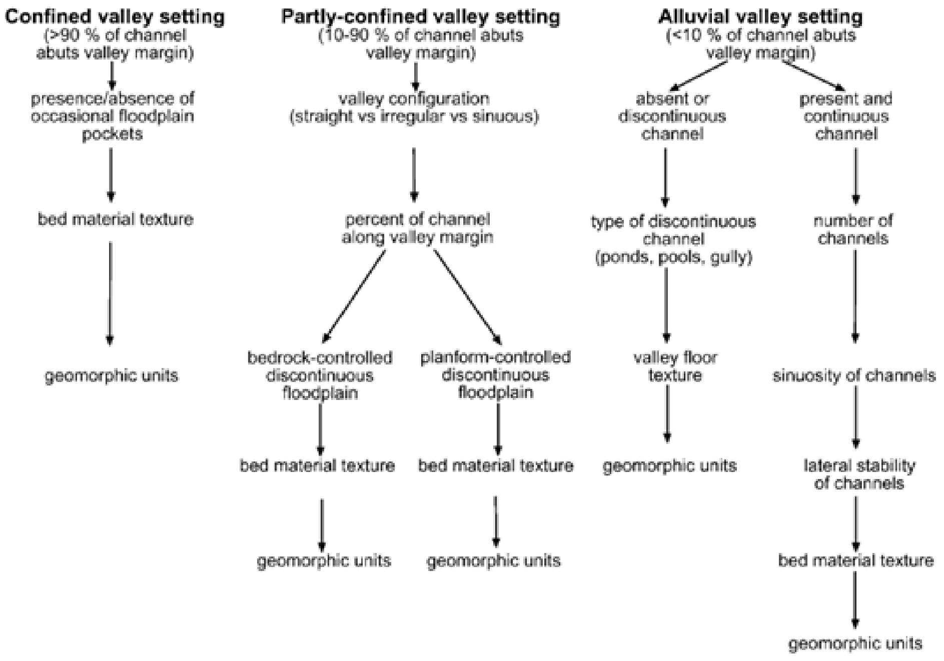


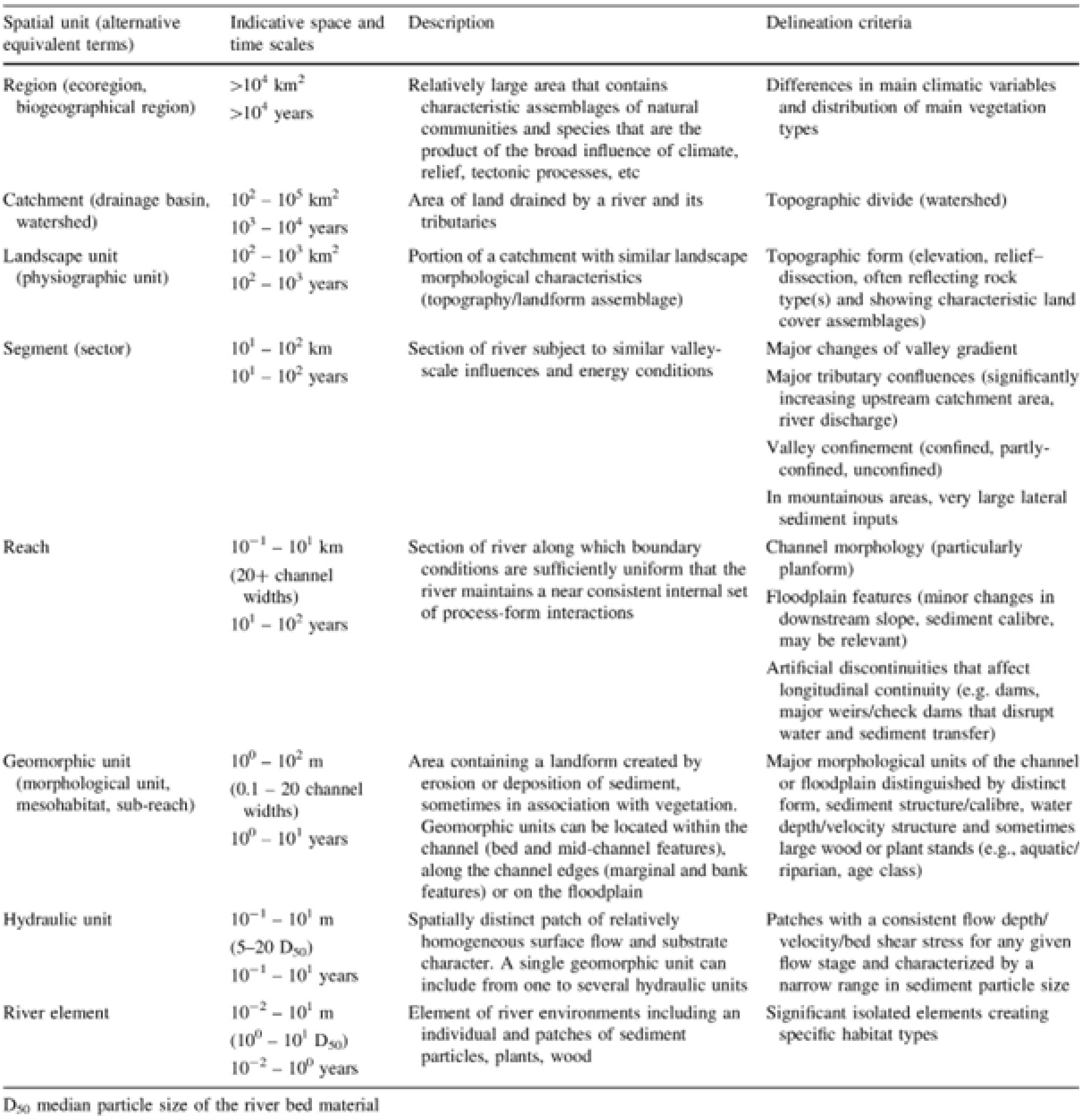
Figure 6 The hierarchical process used to identify river types in the River Styles Framework (Brierley et al. 2002, p. 96)

4.1.1 Summary and recommendations

The review of classification hierarchies suggests that the original three ANAE spatial levels (AETG, 2013) may not be sufficient to describe all the spatial scales that influence and describe riverine ecosystems. The attribute-based approach (AETG, 2013) recommends levels, and attributes appropriate to these levels, but does not suggest how they should be selected in sequence at each level.

The European REFORM framework (Gurnell *et al.,* 2016) builds on the well-received framework by Frissell et al. (1986). The eight levels used will be considered in the Queensland River Classification Scheme (Module 1 DES 2023). The increased complexity of adding new levels should be balanced against any improved ability to describe the processes and forms operating in river systems.

Table 6 Spatial units used with the REFORM framework, alongside indicative temporal and spatial scales and criteria used to define the units (Gurnell et al. 2016 p.10)



Spatial unit (alternative equivalent terms)	Indicative space and time scales	Description	Delineation criteria
Region (ecoregion, biogeographical region)	$>10^4$ km^2 $>10^4$ years	Relatively large area that contains characteristic assemblages of natural communities and species that are the product of the broad influence of climate, relief, tectonic processes, etc	Differences in main climatic variables and distribution of main vegetation types
Catchment (drainage basin, watershed)	$10^2 - 10^5$ km^2 $10^3 - 10^4$ years	Area of land drained by a river and its tributaries	Topographic divide (watershed)
Landscape unit (physiographic unit)	$10^2 - 10^3$ km^2 $10^2 - 10^3$ years	Portion of a catchment with similar landscape morphological characteristics (topography/landform assemblage)	Topographic form (elevation, relief–dissection, often reflecting rock type(s) and showing characteristic land cover assemblages)
Segment (sector)	$10^1 - 10^2$ km $10^1 - 10^2$ years	Section of river subject to similar valley-scale influences and energy conditions	Major changes of valley gradient Major tributary confluences (significantly increasing upstream catchment area, river discharge) Valley confinement (confined, partly-confined, unconfined) In mountainous areas, very large lateral sediment inputs
Reach	$10^{-1} - 10^1$ km (20+ channel widths) $10^1 - 10^2$ years	Section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions	Channel morphology (particularly planform) Floodplain features (minor changes in downstream slope, sediment calibre, may be relevant) Artificial discontinuities that affect longitudinal continuity (e.g. dams, major weirs/check dams that disrupt water and sediment transfer)
Geomorphic unit (morphological unit, mesohabitat, sub-reach)	$10^0 - 10^2$ m (0.1 – 20 channel widths) $10^0 - 10^1$ years	Area containing a landform created by erosion or deposition of sediment, sometimes in association with vegetation. Geomorphic units can be located within the channel (bed and mid-channel features), along the channel edges (marginal and bank features) or on the floodplain	Major morphological units of the channel or floodplain distinguished by distinct form, sediment structure/calibre, water depth/velocity structure and sometimes large wood or plant stands (e.g., aquatic/riparian, age class)
Hydraulic unit	$10^{-1} - 10^1$ m (5–20 D_{50}) $10^{-1} - 10^1$ years	Spatially distinct patch of relatively homogeneous surface flow and substrate character. A single geomorphic unit can include from one to several hydraulic units	Patches with a consistent flow depth/velocity/bed shear stress for any given flow stage and characterized by a narrow range in sediment particle size
River element	$10^{-2} - 10^1$ m ($10^0 - 10^1$ D_{50}) $10^{-2} - 10^0$ years	Element of river environments including an individual and patches of sediment particles, plants, wood	Significant isolated elements creating specific habitat types

D_{50} median particle size of the river bed material

4.2 The number of attributes and types in classification schemes

One of the outcomes of a river classification scheme is a division of rivers into a number of different types (the typology). The types should be relevant and informative to the required use of the classification. For example, if the question is regarding how rivers contribute fine sediment into the water column there should be enough types to separate out significant different types with minimal overlap between them. A compromise needs to be made between showing all the possible effects in all situations and being so granular that significant impacts are missed.

The number of attributes/descriptors used in the classification schemes to define the types is important (Figure 7). Types ranged from being based on single attributes, such as elevation used by Davies et al. (2012) to the 57 used by Gonzalez del Tánago et al. (2016). The average number of attributes used in classification frameworks was 11, while the median was six. In the case of the of the management classifications there was an average of 12 attributes and a median of six.

The number of river types derived from typologies within each classification scheme ranged from the three types defined by Davis (1899) to 489 types defined by Jerie, Household & Peters (2003). The latter had a statistically driven environmental domain analysis that produced these distinct data clusters. The 489 types were, however, then combined to make 90 fluvial mosaics to make them more useful for management. There are also systems (e.g. Brierley et al. 2002; Dahl et al. 2007; NRMSouth 2009; Gonzalez del Tánago et al. 2016) that are open ended so that new types can be added as they are identified.

On average the number of river types defined within a classification was 26 whilst the median number was six. When only the management-focused classifications were selected the average number of river types was 11 and the median was ten. This suggests that around ten types might be useful for similar management applications.

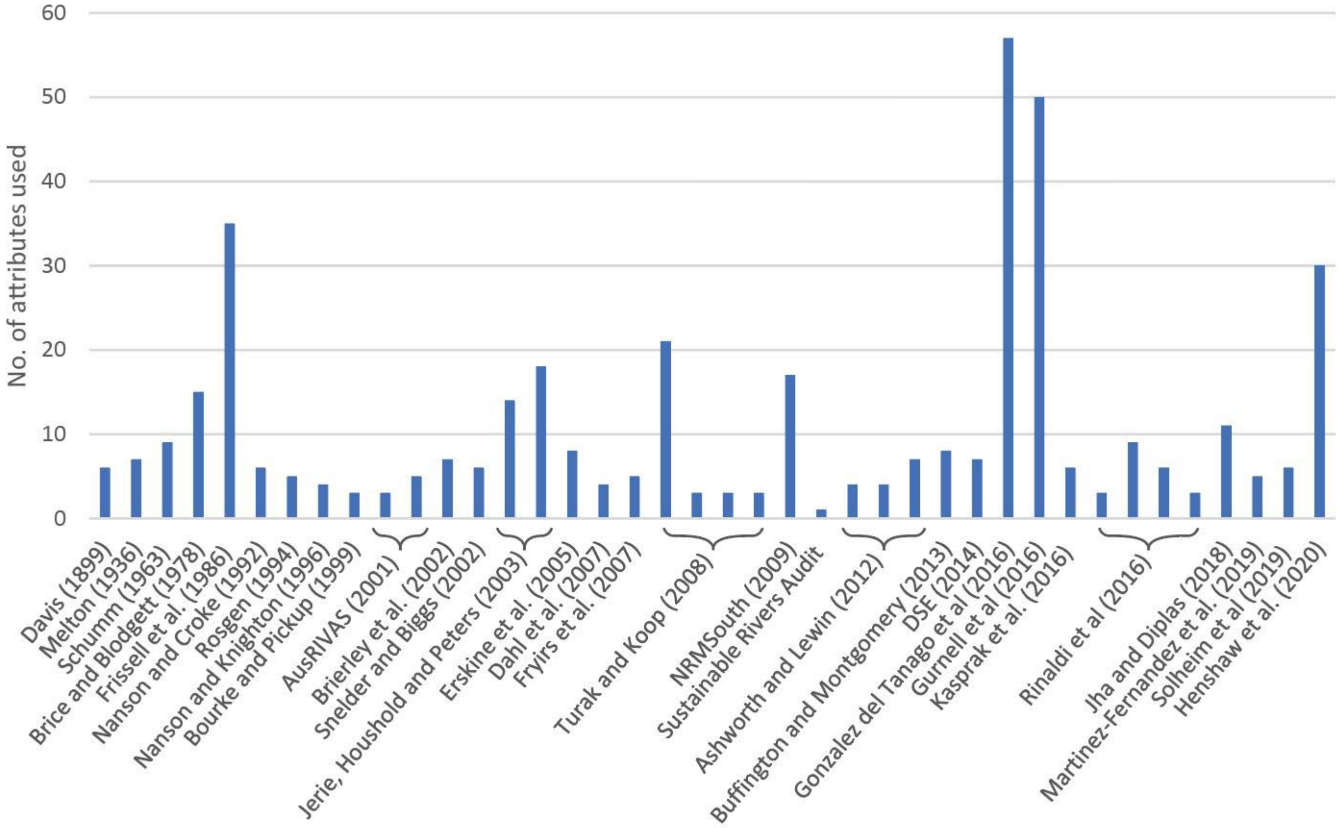


Figure 7 Number of attributes and/or descriptors used in river classification schemes.

4.2.1 Summary and recommendations

There was a large range in the number of types defined by classification systems, however, for management purposes the mean and median were closely grouped to around ten types. This suggests that this number might balance the complexity of the river system against ease of communication and ability to provide management recommendations. In previous classifications this number of types has been generated from on average 12 attributes.

4.3 Attributes, descriptors and types used in other classification frameworks

There were 424 descriptors identified as part of the review that were a range of metrics, attributes and functional typologies. Many of the descriptors used to describe and delineate rivers were different terminology to describe a similar component or process. For example, in-channel bars could be described using the descriptors: presence of bars, position of bars, active lateral bars, active point bars, or depositional features in channel. To better understand the attributes needed in a classification scheme, the 424 descriptors were reduced to 342 by taking out those that appeared identical. These were then consolidated into 46 groups based on similarities in what they were attempting to describe. There were also 15 descriptors that did not readily fit into the groups and were only used in one of the reviewed classifications. These were kept as separate individual descriptors.

The group with the most descriptors was boundary sediment, with 25 different metrics, attributes and functional typologies. These ranged from the presence or absence of different bed and bank sediment sizes, the dominant grainsize class such as sand or gravel, statistical distributions of grainsize (such as D_{50} or the percentage of different grainsize classes), the resistance and mobility of the sediment to flows, the substrate on and underlying the surface, and the amount of anthropogenic material.

The number of different descriptors in a group does not necessarily indicate its relative importance. It may indicate the lack of standardisation in the measurement of the component or processes, or that nuances are important in different applications. For example, if the classification is biologically based, the types of descriptions may differ in their intent compared to a geomorphological focus.

Table 7 Groups used to describe the key groups of descriptors used in biophysical classifications of rivers.

No. descriptors in group	Groups	Theme	Example descriptors
25	Boundary sediment	Substrate (physical)	Bed and bank sediment size
18	Channel mobility (erosion, deposition)	Terrain	Channel narrowing
17	Channel dimensions (based on width)	Terrain	Width:Depth ratio
16	Riparian vegetation	Biota	Tree cover on banks (<50/50-90/>90 % of bankline)
15	Presence of floodplain	Terrain	Presence of floodplain
12	Geomorphic units	Terrain	Presence of geomorphic units typical of channel and floodplain type
12	Channel slope	Terrain	Long profile slope
12	In-channel bars	Terrain	Number/extent/ bare gravel bars and vegetated gravel bars/benches/islands
11	Sediment budgets	Substrate (physical)	Sediment load/budget
11	Stream position in catchment	Terrain	Stream order
10	Channel pattern	Terrain	Channel pattern
10	Planform sinuosity	Terrain	Sinuosity
10	Flow volume descriptors	Hydrology (physical)	Average annual flow
9	Water Chemistry	Hydrology (chemical)	Water chemistry: Alkalinity/Calcium/Colour
8	Floodplain features	Terrain	Floodplain type
8	Channel depth	Terrain	Average bankfull channel depth
8	Baseflow descriptors	Hydrology (physical)	Extent of intermittency (number of days)
7	Flow timing descriptors	Hydrology (physical)	Flow regime type
6	Water depth	Hydrology (physical)	Water depth
6	Groundwater	Hydrology (physical)	% exposed aquifers
6	Catchment size	Terrain	Catchment area
6	Process histories	N/A	Peat process history region
5	Valley topography	Terrain	Channel floor slope
5	Precipitation descriptors	Climate	Average annual precipitation
5	Climate descriptors	Climate	Climate (Warm Extremely Wet/Warm Wet/Warm Dry/Cool Extremely Wet/ Cool Wet/Cool Dry)
4	Floodplain sediment	Substrate (physical)	Grainsize on floodplain
4	Floodplain connection with channel	Hydrology (physical)	% floodplain accessible by flood water
4	Bedrock	Substrate (physical)	Bedrock relief/slope
4	Sediment transport rates	Terrain	Transported sediment size
4	Geology	Geology	Geology (Alluvium/Hard Sedimentary/Soft Sedimentary/Volcanic Basic/Volcanic Acidic/Plutonic)

No. descriptors in group	Groups	Theme	Example descriptors
4	Flow velocity	Hydrology (physical)	Water depth/velocity
4	Soils	Substrate (physical)	% soil permeability class
4	Aquatic plants	Biota	Number of aquatic plant morphotypes
4	Biota	Biota	Common characteristic: taxa collected at most reference sites of that type
4	Large wood	Substrate (physical)	Large wood and fallen trees in channel and riparian corridor
4	Land-use	N/A	% land cover classes
3	Sediment transport processes	Terrain	Dominant mode of sediment transport (bed/Mixed/Suspended)
3	Valley width	Terrain	Average width of erodible corridor
3	Channel cross-sectional shape	Terrain	Cross-sectional form
3	Channel continuity/blocking structures	Substrate (physical)	Number of major blocking and spanning structures (e.g. dams)
3	Channel character at differing flows	N/A	Catchment response
2	Stream power	Hydrology (physical)	Specific Stream power
2	Number of channels	Terrain	Number of low flow channels
2	Channel environment	Climate	Environment (where they are likely to be located)
2	Plant associations: channel	Biota	Dominant riparian plant associations
2	Channel anthropogenic modifications	N/A	Channelised

Attributes can be arranged into themes such as those shown in Table 7. The initial themes used for the development of the QRCS are shown in Table 8. The categories developed from the classification review were separated out into the different themes. The dominant theme was terrain with 13 different groups. While this could be the most useful attribute theme to develop channel typologies, the classification system should have the flexibility in attributes to be applied so that it can develop biophysical typologies for a range or purposes. This means that there are gaps identified from the review that suggest extra attributes may need to be developed, especially in the climate, geology, substrate (chemical), hydrology (chemical) and biota themes.

Table 8 QRCS attribute themes and the number of groups from the classification review within each theme.

Theme	Number of original review groupings
Climate	3
Terrain	13
Geology	1
Substrate (physical)	6
Substrate (chemical)	0
Hydrology (physical)	8
Hydrology (chemical)	1
Biota	4

4.3.1 Summary and recommendations

There were 342 different descriptors identified in the review that described the biophysical components and processes in river systems. These descriptors were a mix of attributes, functional typologies and metrics, many of which were quantifying similar components or processes in slightly different ways. Organising similar descriptors together created 46 descriptive groupings and 15 ungrouped individual descriptors. These 61 descriptors should be used as an initial basis for creating attributes that describe the biophysical aspects of rivers.

Across the eight potential attribute themes there are many descriptor groups in the terrain, substrate and hydrology (physical) themes. In the other themes there are relatively low number of groups and these should be investigated for additional attributes.

5. Conclusions

The review of existing biophysical classification systems shows that rivers have been classified for science and management for at least the last 125 years. The intent, diversity and complexity of classification has increased over time, moving from general descriptions of the landscape and channel to the measurement of many variables in the catchment, channel, groundwater and on the floodplain. The QRCS builds on these existing schemes and creates a framework for classifying rivers that is consistent with and adopts a shared language with the existing Queensland attribute-based aquatic classification schemes. This standard approach to wetland classification in Queensland provides consistency across different (but often connected) aquatic ecosystems, as well as an open-ended and flexible approach in terms of the ability to create typologies for a range of management purposes.

While it is widely acknowledged that process-based classification of rivers enhances the understanding of fluvial systems and their biophysical interactions, the ability of some classification approaches to adequately inform river management and rehabilitation efforts can be hindered by a focus on largely descriptive procedures (Lave, 2012; Buffington and Montgomery, 2013; 2022). The combination of a clear hierarchical framework and comprehensive list of attributes can help inform on processes through the geomorphic consideration of form-process interactions. Many attributes are only relevant when placed within a hierarchical context. However, the development of appropriate temporal qualifiers may be needed to provide context for understanding dynamic processes, river response and future trajectories.

The reviewed classification systems created for management purposes had around 10 different types to describe the range of complexity in river systems and these types were derived from around 12 attributes. The types appear to mainly be based on descriptors in the theme of terrain, substrate (physical) and hydrology (physical). To make the classification effective across a range of applications extra attributes may need to be sought that fit other themes. The hierarchy of spatial levels may also need to be expanded to encompass all the different spatial scales operating in river systems.

6. References

AETG (Aquatic Ecosystems Task Group) 2012, *Aquatic Ecosystems Toolkit. Module 2. Interim Australian National Aquatic Ecosystem Classification Framework*, Australian Government Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Aquatic Ecosystems Task Group, 2013, *Interim Australian National Aquatic Ecosystem Classification (ANAE) Estuarine- Marine Attribute, Workshop Summary Report*, AETG, Auricht Projects.

Ashworth, PJ and Lewin, J 2012. 'How do big rivers come to be different?', *Earth-Science Reviews*, 114(1-2), pp.84-107.

Belletti, B, Rinaldi, M, Bussettini, M, Comiti, F, Gurnell, AM, Mao, L, Nardi, L and Vezza, P 2017, 'Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units', *Geomorphology*, 283, 143-157.

Bisson, PA, Nielsen, JL, Palmason, RA and Grove, LE 1982, 'A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow', in Armantrout, NB (eds) *Proceedings of a Symposium on Acquisition and Utilization of Aquatic Habitat Inventory Information*, Western Division of the American.

Bourke, MC and Pickup, G 1999, 'Fluvial form variability in arid central Australia', in Miller, AJ and Gupta, A (eds) *Varieties of Fluvial Forms,* John Wiley & Sons, Chichester, UK.

Brierley, GJ and Fryirs, K 2000, 'River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment', *Environmental Management* 25(6), New South Wales, Australia, pp 661–679.

Brierley, GJ and Fryirs, K 2005, *Geomorphology and River Management: Applications of the River Styles Framework*, Blackwell, Oxford, UK, 398 pp.

Brierley, G, Fryirs, K, Outhet, D and Massey, C 2002, 'Application of the River Styles framework as a basis for river management in New South Wales', *Applied Geography*, 22(1), Australia pp.91-122.

Brice, JC and Blodgett, JC 1978, *Countermeasures for hydraulic problems at bridges, volume II: case histories for sites 1-283* (No. FHWA-RD-78-163), United States Federal Highway Administration, Office of Research and Development.

Buffington, JM and Montgomery, DR 2013, 'Geomorphic classification of rivers' in Shroder, J and Wohl, E (eds) *Treatise on Geomorphology; Fluvial Geomorphology*, Vol. 9. San Diego, CA: Academic Press, pp.730-767.

Buffington, JM and Montgomery, DR 2022, ‘Geomorphic classification of rivers: An updated review’, *Treatise on Geomorphology*, 2nd edition, Vol. 6.2, pp. 1143-1190, https://doi.org/10.1016/B978-0-12-818234-5.00077-8

Byrne, CF, Pasternack, GB, Guillon, H, Lane, BA, and Sandoval-Solis, S 2020, ‘Reach-scale bankfull channel types can exist independently of catchment hydrology’, *Earth Surface Processes and Landforms*, 45(9), pp. 2179-2200.

Church, M 2002, ‘Geomorphic thresholds in riverine landscapes’, *Freshwater Biology* 47, pp. 541–557.

Church, M 2006, ‘Bed material transport and the morphology of alluvial rivers’, *Annual Review of Earth and Planetary Sciences* 34, pp. 325–354.

Dahl, M, Nilsson, B, Langhoff, JH and Refsgaard, JC 2007, ‘Review of classification systems and new multi-scale typology of groundwater–surface water interaction’, *Journal of Hydrology*, 344(1-2), pp.1-16.

Davies, PE 2000, ‘Development of a national river bioassessment system (AUSRIVAS) in Australia’, in *Assessing the biological quality of fresh waters: RIVPACS and other techniques*, proceedings of an International Workshop held in Oxford, UK, on 16-18 September 1997, pp. 113-124.

Davies PE, Stewardson MJ, Hillman TJ, Roberts JR and Thoms MC 2012, *Sustainable Rivers Audit 2: The ecological health of rivers in the Murray–Darling Basin at the end of the Millennium Drought (2008–2010),* Volume 1, Murray–Darling Basin Authority, Canberra, ACT, Australia.

Davis, WM 1899, ‘The geographical cycle’, *Geographical Journal* 14, pp. 481–504.

Gonzalez del Tánago, M, Gurnell, AM, Belletti, B and de Jalón, DG 2016, ‘Indicators of river system hydromorphological character and dynamics: understanding current conditions and guiding sustainable river management’, *Aquatic sciences*, 78(1), pp.35-55.

Department of Environment and Heritage Protection 2017, *Queensland Intertidal and Subtidal ecosystem classification scheme Version 1.0: Module 1—Introduction and implementation of intertidal and subtidal ecosystem classification*, Queensland Wetlands Program, DEHP, Queensland Government, Brisbane.

Department of Environment and Science 2019, *Queensland Intertidal and Subtidal Ecosystem Classification Scheme Version 1.0: Module 2 Literature review of intertidal and subtidal classification frameworks and systems: Informing the development of the Queensland Intertidal and Subtidal Ecosystem Classification Scheme*, Queensland Wetlands Program, DES, Queensland Government, Brisbane.

Department of Environment and Science 2020, *The Queensland Waterhole Classification Scheme*, Queensland Wetlands Program, DES, Queensland Government, Brisbane.

Department of Environment and Science 2022, *Whole-of-System, Values-Based Framework*, Wetland*Info*, accessed December 2022.

Department of Environment and Science 2023. Interim Queensland River Classification Scheme: Module 1 – Introduction to the River Classification Scheme. Brisbane: Department of Environment and Science, Queensland Government

Department of Sustainability and Environment 2004, *EVC/Bioregion Benchmarks for Vegetation Quality Assessment*, DSE, Melbourne, Victoria.

Department of Sustainability and Environment 2014, *ISC Physical Form sub Index - Index of Stream Condition* (ISC3), DSE, Melbourne, Victoria.

Department of Science, Information Technology and Innovation 2015a, *Groundwater Dependent Ecosystem Mapping Method: A method for providing baseline mapping of groundwater dependent ecosystems in Queensland*, DSITI, Brisbane, Queensland.

Doyle, MW, Miller, DE and Harbor, JM 1999, ‘Should river restoration be based on classification schemes or process models? Insights from the history of geomorphology’, in Walton, R and Nece, RE (eds), *Proceedings of the ASCE International Conference on Water Resources Engineering*, Seattle, Reston, VA, American Society of Civil Engineers.

Environmental Protection Agency 2005, *Wetland Mapping and Classification Methodology – Overall Framework – A Method to Provide Baseline Mapping and Classification for Wetlands in Queensland*, Version 1.2, Queensland Government, Brisbane. ISBN 0 9757 344 6 6

Erskine, WD, Saynor, MJ, Erskine, L, Evans, KG and Moliere, DR 2005, ‘A preliminary typology of Australian tropical rivers and implications for fish community ecology’, *Marine and Freshwater Research*, 56(3), pp.253-267.

Frissell, CA, Liss, WJ, Warren, CE and Hurley, MD 1986, ‘A hierarchical framework for stream habitat classification: viewing streams in a watershed context’, *Environmental management*, 10(2), pp.199-214.

Fryirs, KA, Brierley, GJ, Preston, NJ and Kasai, M 2007, ‘Buffers, barriers and blankets: the (dis) connectivity of catchment-scale sediment cascades’, *Catena*, 70(1), pp.49-67.

Glanville, K, Ryan, T, Tomlinson, M, Muriuki, G, Ronan, M and Pollett, A 2016, 'A Method for Catchment Scale Mapping of Groundwater-Dependent Ecosystems to Support Natural Resource Management (Queensland, Australia)', *Environmental Management*, vol. 57, no. 2, pp. 432-49.

Gurnell, AM, Rinaldi, M, Belletti, B, Bizzi, S, Blamauer, B, Braca, G, Buijse, AD, Bussettini, M, Camenen, B, Comiti, F and Demarchi, L 2016, ‘A multi-scale hierarchical framework for developing understanding of river behaviour to support river management’, *Aquatic Sciences*, 78(1), pp.1-16.

Gustard, A 1992, ‘Analysis of river regimes’, in Calow, P and Petts, GE (eds), *The Rivers Handbook. Hydrological and Ecological Principles*, vol. 1, pp. 29–47. Oxford: Blackwell

Heasley, EL, Millington, JD, Clifford, NJ and Chadwick, MA 2019, ‘A waterbody typology derived from catchment controls using self-organising maps’, *Water*, 12(1), p.78.

Henshaw, AJ, Sekarsari, PW, Zolezzi, G and Gurnell, AM 2020, ‘Google Earth as a data source for investigating river forms and processes: Discriminating river types using form-based process indicators’, *Earth Surface Processes and Landforms*, 45(2), pp. 331-344.

Hough-Snee, N, Roper, BB, Wheaton, J and Lokteff, RL 2015, ‘Riparian vegetation communities of the American Pacific Northwest are tied to multi-scale environmental filters’, *River Research and Applications*, 31, pp. 1151–1165.

Jerie, K, Houshold, I and Peters, D 2003, *Tasmania’s river geomorphology: stream character and regional analysis*, Volume 1, Department of Primary Industries, Water and Environment. Hobart, Tasmania, Australia.

Jha, R and Diplas, P 2018, ‘Elevation: a consistent and physically-based framework for classifying streams’, *Journal of Hydraulic Research*, 56(3), pp. 299-312.

Kasprak, A, Hough-Snee, N, Beechie, T, Bouwes, N, Brierley, G, Camp, R, Fryirs, K, Imaki, H, Jensen, M, O’Brien, G and Rosgen, D 2016, ‘The blurred line between form and process: a comparison of stream channel classification frameworks’, *PloS One*, 11(3), p.e0150293.

Kondolf, GM 1995, ‘Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations’, *Aquatic Conservation* 5, pp. 127–141.

Kondolf, GM, Montgomery, DR, Piégay, H and Schmitt, L 2003, ‘Geomorphic Classification of Rivers and Streams’, in Kondolf, GM and Piégay, H (eds) *Tools in Fluvial Geomorphology*, pp. 171-204, Chichester, UK: John Wiley & Sons

Kondolf, GM, Montgomery, DR, Piégay, H and Schmitt, L 2016, ‘Geomorphic Classification of Rivers and Streams’, in Kondolf, GM and Piégay, H (eds) *Tools in Fluvial Geomorphology*, 2nd edition pp. 133-158, Chichester, UK: John Wiley & Sons

Kopačková, V, Rapprich, V, Šebesta, J and Zelenkov, K 2011, ‘Slope dependent morphometric analysis as a tool contributing to reconstruction of volcano evolution’, *Earth and environmental sciences*, pp.219-240.

Lane, BA, Pasternack, GB, Dahlke, HE and Sandoval-Solis, S 2017, ‘The role of topographic variability in river channel classification’, *Progress in Physical Geography* 41 (5), pp. 570–600.

Lane, BA, Pasternack, GB and Sandoval-Solis, S 2018, ‘Integrated analysis of flow, form, and function for river management and design testing’, *Ecohydrology*, 11(5), e1969.

Lave, R 2012, ‘Bridging political ecology and STS: A field analysis of the Rosgen Wars’, *Annals of the Association of American Geographers*, 102(2), pp.366-382.

Leathwick, JR, Snelder, T, Chadderton, WL, Elith, J, Julian, K and Ferrier, S 2011, ‘Use of generalised dissimilarity modelling to improve the biological discrimination of river and stream classifications’, *Freshwater Biology* 56, pp. 21–38.

Martínez-Fernández, V, Gonzalez del Tánago, M and de Jalón, DG 2019, ‘Selecting geomorphic variables for automatic river segmentation: Trade-offs between information gained and effort required’, *Geomorphology*, 329, pp. 248-258.

Melton, FA 1936, ‘An empirical classification of flood-plain streams’, *Geographical Review*, 26(4), pp.593-609.

Miller, JR and Ritter, JB 1996, ‘An examination of the Rosgen classification of natural rivers’, *Catena* 27, 295–299.

Montgomery, DR and Buffington, JM 1997, ‘Channel-reach morphology in mountain drainage basins’, *Geological Society of America Bulletin* 109, pp. 596–611.

Mosley, MP 1987, ‘The classification and characterization of rivers’, in Richards, KS (ed), *River Channels, Environment and Process*, Blackwell, Oxford, pp. 295–320

Naiman, RJ, Lonzarich, DG, Beechie, TJ and Ralph, SC 1992, ‘General principles of classification and the assessment of conservation potential in rivers’, in Boon, PJ, Calow, P and Petts, GE (eds), *River Conservation and Management*, Chichester, John Wiley & Sons, pp. 93–124.

Nanson, GC and Croke, JC 1992, 'A genetic classification of floodplains', *Geomorphology*, 4(6), pp.459-486.

Nanson, GC and Knighton, AD 1996, 'Anabranching rivers: their cause, character and classification', *Earth surface processes and landforms,* 21(3), pp.217-239.

Newson, M 2002, 'Geomorphological Concepts and Tools for Sustainable River Ecosystem Management', *Aquatic Conservation Marine and Freshwater Ecosystems*, 12, pp. 365-379.

National Committee on Soil and Terrain 2009, *Australian Soil and Land Survey Field Handbook*, 3rd edition, National Committee on Soil and Terrain, CSIRO. p. 246

Natural Resource Managers South 2009, *The Tasmanian River Condition Index Reference Manual*, NRM South, Hobart, Tasmania.

Naura, M, Clark, MJ, Sear, DA, Atkinson, PM, Hornby, DD, Kemp, P, England, J, Peirson, G, Bromley, C, and Carter, MG 2016, 'Mapping habitat indices across river networks using spatial statistical modelling of River Habitat Survey data', *Ecological Indicators* 66, pp. 20–29.

Parker, C, Clifford, NJ and Thorne, CR 2012, 'Automatic delineation of functional river reach boundaries for river research and applications', *River Research and Applications*, 28(10), pp.1708-1725.

Parsons, M, Thoms, M and Norris, R 2002, 'Australian river assessment system: AusRivAS physical assessment protocol', *Monitoring river health initiative technical report*, 22.

Pasternack, GB, Baig, D, Weber, MD, and Brown, RA 2018, 'Hierarchically nested river landform sequences. Part 1: Theory', *Earth Surface Processes and Landforms*, 43(12), pp. 2510-2518.

Paustian, SJ, Anderson, K, Blanchet, D, Brady, S, Cropley, M, Edgington, J, Fryxell, J, Johnejack, G, Delliher, D, Kuehn, M, Maki, S, Olson, R, Seesz, J and Wolanek, M 1992, *A channel type user guide for the Tongass National Forest, southeast Alaska*, USDA Forest Service, Alaska Region, Technical Paper R10-TP-26, 179 pp.

Queensland Museum 2022, *Wetlands of Queensland*, Queensland Museum Network, Brisbane.

Rinaldi, M, Gurnell, AM, Gonzalez Del Tánago, M, Bussettini, M and Hendriks, D 2016, 'Classification of river morphology and hydrology to support management and restoration', *Aquatic Sciences*, 78(1), pp.17-3.

Roper, BB, Buffington, JM, Archer, E, Moyer, C and Ward, M 2008, 'The role of observer variation in determining Rosgen stream types in northeastern Oregon mountain streams', *Journal of the American Water Resources Association*, 44(2), pp. 417-427.

Rosgen, DL 1994, 'A classification of natural rivers', *Catena*, 22(3), pp.169-199.

Rosgen, DL 1996, *Applied River Morphology*, Pagosa Springs, CO, Wildland Hydrology, p. 390

Schmitt, L, Maire, G, Nobelis, P and Humbert, J 2007, 'Quantitative morphodynamic typology of rivers: A methodological study based on the French Upper Rhine basin', *Earth Surface Processes and Landforms* 32, pp. 1726–1747.

Schumm, SA 1963, 'Sinuosity of alluvial rivers on the Great Plains', *Geological Society of America Bulletin*, 74(9), pp.1089-1100.

Schumm, SA 1977, *The Fluvial System*, Blackburn Press, Caldwell, NJ, p. 338

Simon, A, Doyle, M, Kondolf, M, Shields Jr, FD, Rhoads, B and McPhillips, M 2007, 'Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel response 1', *JAWRA Journal of the American Water Resources Association*, 43(5), pp.1117-1131.

Snelder, TH and Biggs, BJ 2002, 'Multiscale river environment classification for water resources management 1', *JAWRA Journal of the American Water Resources Association*, 38(5), pp.1225-1239.

Spencer, JR, Brooks AP and Knight, J 2007, 'Towards an objective approach for a regional - continental scale geomorphic river classification', in Wilson, AL, Dehaan, RL, Watts, RJ, Page, KJ, Bowmer, KH, and Curtis, A (eds) *Proceedings of the 5th Australian Stream Management Conference, Australian rivers: making a difference*. pp. 372-377, Charles Sturt University, Thurgoona, New South Wales.

Spencer, JR, Brooks AP and Stein, J 2009, *Biophysical classification: classifying riverscapes across northern Australia, TRaCK Project 3.2 Final Report*, Tropical Rivers and Coastal Knowledge, Australian Government.

Solheim, AL, Globevnik, L, Austnes, K, Kristensen, P, Moe, SJ, Persson, J, Phillips, G, Poikane, S, van de Bund, W and Birk, S 2019, 'A new broad typology for rivers and lakes in Europe: Development and application for large-scale environmental assessments', *Science of the Total Environment*, 697, p.134043.

Strahler, AN 1957, 'Quantitative analysis of watershed geomorphology', *Transactions of the American Geophysical Union* 38, pp. 913–920.

Sutfin, NA, Shaw, J, Wohl, EE and Cooper, D 2014, ‘A geomorphic classification of ephemeral channels in a mountainous, arid region, southwestern Arizona, USA’, *Geomorphology* 221, pp. 164–175.

Tadaki, M, Brierley, G and Cullum, C 2014, ‘River classification: theory, practice, politics’, *Wiley Interdisciplinary Reviews: Water*, 1(4), pp.349-367.

Thorp, JH, Thoms, MC and Delong, MD 2006, ‘The riverine ecosystem synthesis: biocomplexity in river networks across space and time’, *River Research and Applications* 22, pp. 123–147.

Turak, E and Koop, K 2008, ‘Multi-attribute ecological river typology for assessing ecological condition and conservation planning’, *Hydrobiologia*, 603(1), pp.83-104.

Wheaton, JM, Fryirs, KA, Brierley, G, Bangen, SG, Bouwes, N and O’Brien, G 2015, ‘Geomorphic mapping and taxonomy of fluvial landforms’, *Geomorphology* 248, pp. 273–295.

Wohl, E, Merritt, D 2005, ‘Prediction of mountain stream morphology’, *Water Resources Research* 41, W08419.