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A MULTI-SCALE HIERARCHICAL FRAMEWORK FOR DEVELOPING UNDERSTANDING OF RIVER BEHAVIOUR TO SUPPORT RIVER MANAGEMENT.

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ABSTRACT

This paper introduces this special issue of Aquatic Sciences. It outlines a multi-scale, hierarchical framework for developing process-based understanding of catchment to reach hydromorphology that can aid design and delivery of sustainable river management solutions. The framework was developed within the REFORM (REstoring rivers FOR effective catchment Management) project, funded by the European Union's FP7 Programme. Specific aspects of this 'REFORM framework' and some applications are presented in other papers in this special issue.

The REFORM framework is founded on previous hierarchical frameworks, sixteen examples of which are reviewed. However, the REFORM framework has some particular properties that reflect the European context for which it was developed.

The framework delineates regional landscapes into nested spatial units at catchment, landscape unit, segment, reach, geomorphic unit and finer scales. Reaches, regardless of their 'naturalness', are assigned to a river type based on valley confinement, planform and bed material.

Indicators are quantified at each spatial scale to feed three groups of assessments. First, contemporary indicators at reach and geomorphic unit scales investigate present processes, forms and human pressures within each reach. These feed assessments of present reach hydromorphological function / alteration, including whether the reach is functioning appropriately for its type; riparian corridor function and alteration; and hydromorphological adjustment. Second, indicators at catchment to segment scales investigate water and sediment production and delivery to reaches and how these are affected by human pressures now and in the past. These are used to construct an inventory of changes over space and time. Third, historical reach and geomorphic unit scale indicators are used to construct the trajectory of reach-scale changes. Contemporary reach-scale assessments, space-time inventory, and trajectory of changes are then combined to establish how river reaches of different type, subject to different human pressures, and located in different environmental contexts behave in response to changes at all considered spatial scales. These support forecasts of the likely responses of reaches to future scenarios (e.g. changes in climate, land cover, channel interventions).

KEYWORDS

REFORM framework, Space scale, Time scale, Hydromorphology, River management, River rehabilitation.

AN INTRODUCTION TO HIERACHICAL FRAMEWORKS FOR ASSESSING THE HYDROMORPHOLOGY OF RIVER SYSTEMS

This paper introduces this special issue of Aquatic Sciences by outlining the multi-scale, hierarchical framework that has been developed for improving hydromorphological understanding and informing management of rivers, particularly in a European context. Here the term hydromorphology, which is used widely within Europe, refers to the suite of hydrological and geomorphological processes and forms that occur within catchments and their river systems. This paper provides the rationale behind the development of the framework and briefly overviews its structure and key features including the way that it supports understanding of the hydromorphological behaviour of river reaches in response to temporal changes at catchment to reach scales. It also refers to other papers within this special issue that provide more details on particular aspects of the framework or that illustrate the framework's application.

River management often focuses on individual reaches of river networks, aiming to improve their ability to support human needs and those of the river ecosystem. However, the form, sedimentary and vegetation structure, dynamism and behaviour of river reaches depends not only upon natural processes and human interventions within the reach but also within the wider catchment. Furthermore, the response of river reaches to changes in processes and human pressures across the catchment is often delayed. This is because it takes time for the effects of changes (e.g. land cover change, dam construction) to propagate from their initial location across catchments and through river networks to individual river reaches. Thus, understanding of reach scale hydromorphology requires knowledge of processes and human pressures at not only the reach scale but at larger spatial scales including the catchment scale. Since human interventions or pressures at one location and time may induce responses at one or more other locations and times, such knowledge needs to relate to both current and past pressures and processes. Without such a spatial and temporal understanding, management interventions cannot be fully informed and so may not be sustainable and may potentially require significant ongoing maintenance.

In response to this complexity, researchers have developed many spatially-hierarchical frameworks to support better understanding of the functioning of river catchments, networks and corridors. These have been developed with a variety of scientific and management purposes in mind. Several authors have reviewed this topic (e.g. Naiman et al., 1992; Kondolf et al., 2003) and a selection of sixteen examples of hierarchical frameworks, some specifically focussed on hydromorphology, some with a broader ecological focus, are briefly described in Table 1. These examples illustrate a range of different frameworks for developing understanding or assessing river systems by organizing and interpreting information across a hierarchy of spatial scales. Many frameworks incorporate formal classifications of spatial units such as river reaches or segments (i.e. the units are assigned to distinct categories or classes based on specific attributes). Where frameworks incorporate such classifications, they are briefly described in Table 1. The following generalisations can be drawn from the example frameworks listed in Table 1:

1. Despite its early publication date, the work of Frissell et al. (1986) continues to present the most comprehensive conceptual multi-scale framework for investigating streams and habitats. The spatial units are delineated so that units at smaller spatial scales nest within those at larger spatial scales. The framework incorporates hydromorphological processes and forms and vegetation at all spatial scales in relation to their influence on habitat. Time scales of persistence or adjustment are associated with spatial units at each scale. Indicators of form and process are suggested for spatial units at each scale. The role of the indicators is explained in terms of developing understanding of the functioning of spatial units and the process linkages among units and scales. Although no formal classifications of spatial units are proposed, the way in which indicators could contribute to classification is discussed. All of the methods described in Table 1 consider a hierarchy of spatial units, but the degree to which they develop the other aspects of the conceptual approach proposed by Frissell et al. (1986) varies widely.

2. Many of the frameworks focus entirely on hydromorphological processes and forms that are either directly measured or inferred. This is because interactions between processes and forms control the dynamic morphology or behaviour of rivers and their mosaics of habitats. Hydromorphological processes drive longitudinal and lateral connectivity within river networks and corridors, the assemblage and turnover of physical habitats, and the sedimentary and vegetation structures associated with those habitats.

3. Some frameworks are conceptual, providing a way of thinking about or structuring analyses of river systems, and interpreting their processes, morphology and function (e.g. Frissell et al., 1986; Habersack, 2000; Fausch et al., 2002; Thorp et al., 2006; Beechie et al., 2010; McCluney et al., 2014). Some frameworks are more quantitative, generating one or more indices or classifications of spatial units that support assessment of river systems (e.g. Rosgen, 1994; González del Tánago and García de Jalón, 2004; Merovich et al., 2013; Rinaldi et al., 2013, 2015a). However, some frameworks follow an intermediate course, generating relatively open-ended indices or classes that can be interpreted flexibly (e.g. Brierley and Fryirs, 2005).

4. Time scales and temporal changes are not included in all frameworks, particularly where the framework is proposed as an input to further assessment or analysis (e.g. Snelder and Biggs, 2002, González del Tánago and García de Jalón, 2004). A time scale is included as a dimension of each spatial scale in some approaches (e.g. Habersack, 2000; Dollar et al., 2007), whereas others incorporate historical analyses that track human interventions or changes in units through time at some spatial scales (e.g. Rosgen, 1994; Montgomery and MacDonald, 2002; Brierley and Fryirs, 2005; Beechie et al., 2010; Rinaldi et al., 2013a, 2015). In some cases, theoretical or historical analyses or consideration of specific future scenarios are used to develop space-time understanding that can support management decision-making (e.g. Montgomery and Buffington, 1997, 1998; Montgomery and MacDonald, 2002; Benda et al., 2004; Brierley and Fryirs, 2005; McCluney et al., 2014).

5. Although all frameworks incorporate characteristics that are used to delineate spatial units and may indicate how those units function, many provide specific, well-defined indicators of processes, forms or of the condition of spatial units (e.g. Rosgen, 1994; Montgomery et al., 1997, 1998; Montgomery and MacDonald, 2002; Benda et al., 2004; Brierley and Fryirs, 2005; Merovich et al., 2013; Rinaldi et al., 2013, 2015a). Furthermore, some of the frameworks include indicators of human pressures and their impacts (e.g. Merovich et al., 2013; McCluney et al., 2014; Rinaldi et al., 2013, 2015a).

6. Finally, although most frameworks could be described as incorporating processes to some degree, some methods are particularly process-based, even when processes are inferred from forms and associations rather than being quantified by direct measurements. Frameworks that consider temporal dynamics and trajectories of historical change (see point 4, above) are particularly effective in developing understanding of processes and the impacts of changed processes cascading through time and across spatial scales.

Although the list of frameworks presented in Table 1 is far from comprehensive, it illustrates that different types of hierarchical framework have been proposed. These previous frameworks have provided a foundation for developing the multi-scale, hierarchical framework for the hydromorphological assessment of European rivers that is described in this paper. This REFORM framework was developed within the REFORM project, which is funded by the European Commission with the aim of supporting sustainable river management and restoration. It has been developed to fit into the context of the European Union's Water Framework Directive (WFD; European Commission, 2000), which constitutes the principal legal instrument for managing and restoring aquatic ecosystems within member states of the European Union, and so it is intended for application by river managers. The following sections of this paper introduce the REFORM framework and describe its key properties; briefly describe the application of the framework; and then introduce this special issue by referring to other papers that provide further details on particular aspects of the framework and its application.

THE REFORM FRAMEWORK

The REFORM framework is informed by many previous frameworks (Table 1). Those of Frissell et al. (1986), Montgomery and Buffington (1997, 1998), Habersack (2000), Brierley and Fryirs (2005) and Rinaldi et al. (2013) have been particularly influential. Nevertheless, the REFORM framework has several properties that *in combination* differentiate it from its predecessors and suit it to application by river managers working in the environmental contexts for which it has been developed.

1. Because the aim of the research was to develop a tool for use by river managers, the framework has been kept as simple to apply as was felt possible. It is a hydromorphological framework which includes relevant information on vegetation.

2. Reflecting the long history of human interventions on European rivers, the framework incorporates human pressures as well as natural processes and forms at all included spatial scales and gives them equal weighting.

3. The framework is open-ended to the extent that European member states can incorporate their own data sets, methods and modelling tools, although specific methods have been proposed and fully-described for consideration by member states. This open-ended nature ensures the framework's relevance to all member states, and thus maximizes the potential for its process-based 'way of thinking' to be widely adopted. It also ensures that elements of the framework methodology can be adapted to local circumstances, reflecting the enormous variety of river environments and data sets found within Europe.

4. The framework includes spatial units at region, catchment, landscape unit, segment, reach, geomorphic unit, hydraulic unit and river element (i.e. patch of sediment, plant stand etc.) scales. However, the core scales are those ranging from catchment to geomorphic unit. Each spatial unit has an indicative temporal scale of persistence / adjustment, but the main temporal element of the framework is a historical analysis of available data sets. A definition of each spatial scale and associated indicative space and time scales are provided in Table 2.

5. The key scale of the framework is the river reach, since this is the scale at which rivers are most often assessed, managed and rehabilitated. A central and unique feature of the REFORM framework is that all reaches are classified into 'river types' using clearly-defined, simple criteria. All other elements of the framework are directed at understanding the naturalness or artificiality of these reaches and their types, the processes to which they are subjected, and their morphodynamic behaviour. This involves assessment of (i) the cascade of processes affecting reaches from catchment to reach scales, (ii) the degree to which reaches display characteristics at reach and finer scales that are indicative of 'natural' function according to their type or of 'artificiality', and (iii) the ways in which reach morphology has changed or behaved through time in response to changes in processes and direct human interventions at catchment to reach scales. To fit with the long history of human pressures on European rivers, and thus the fact that there is no time in the past for which detailed information is available that can be considered to represent pristine conditions, the character of the river in the past is not considered as a 'reference condition' that refers to a 'pristine state'. Instead, the entire space-time analysis assesses the degree to which the morphodynamic behaviour of some river reaches suggest that they are functioning or have functioned in a relatively natural way. This analysis provides process-form information that can inform management of more impacted reaches of otherwise similar type.

6. Recommendations are made on how to delineate spatial units and how processes, forms and human pressures can be represented by indicators. Tables 2 and 3, respectively, provide brief summaries of the properties used for delineation, and the purpose and types of indicators that are estimated. The reach type is the key indicator.

7. Indicators support the assessment of human pressures, processes, and morphological responses at each spatial scale. They also support the assessment of the past and present behaviour of river reaches and their riparian zones in terms of changes in their form and function in response to changes in processes and human pressures from catchment to reach scales.

8. Space-time understanding of catchments and their river systems is developed from the indicators and provides a basis for estimating potential reach-scale adjustments to future changes across the spatial units (e.g. climate change, land cover change, introduction or removal of channel reinforcement or structures). Such analyses also help to identify whether or not the river type initially defined by simple rules corresponds to the river type that might function most effectively at a given location or whether a different type is more appropriate, so informing the design of any proposed restoration.

Application of the REFORM framework requires a significant data resource. Measurements at the hydraulic unit and river element scales are not widely available. However, collection of such data by purpose-designed field survey contributes to monitoring specific reaches where detail is needed to track changes, particularly following management interventions. Information at all of the other spatial scales can be obtained from national surveys and analyses such as physical habitat surveys, riparian habitat surveys, morphological surveys and hydrological regime assessments (Belletti et al., 2015a); climate, river flow and groundwater data sets; and national scale mapping of, for example, geology, soils and vegetation. Furthermore, many relevant data sets are available at a European scale (Table 4, see also the paper by Bizzi et al., 2015 in this special issue). While contemporary and recent data sets are usually easy to obtain, historical information may be more restricted (for a recent review see Grabowski et al., 2014).

Reflecting the purpose of the application, data availability, and the combination of cost, time and effort that is available, the REFORM framework can be applied in different ways. For catchment assessment and management purposes, the aim should be to sub-divide the entire catchment into a complete set of catchment to reach scale units, and, at a minimum, to include geomorphic units as attributes of each reach. In this way, the assemblage of reach types and their properties can be placed within a catchment and river network context. However, in large catchments, it may not be possible to compile information on a complete set of units for the entire catchment. Under these circumstances, it is necessary to sub-divide the catchment to the scale of its major landscape units, and then isolate representative sub-catchments within each landscape unit where segments and reaches along the main channel and major tributaries can be analysed. In this way, an analysis of the properties of different reach types can be investigated within sub-catchments that are representative of the catchment's landscape units. If the purpose is to focus on a particular reach or segment, perhaps in the context of designing an intervention or rehabilitation, the assessment still needs to focus on spatial units that contain and are immediately upstream of the reach or segment under consideration so that the processes affecting the reach can be investigated.

OVERVIEW OF THE APPLICATION OF THE REFORM FRAMEWORK

Application of the framework involves three main stages:

(i) *Delineation* of the spatial units;

(ii) Assembly of available data sets to *Characterise* the spatial units so that *Indicators* of processes, forms and human pressures can be extracted for units across the spatial scales to represent their present and past state;

(iii) *Assessment* of the present and past character of river reaches (a) to understand how they are affected by processes and human pressures from catchment to segment scales; (b) to understand how these affect river behaviour by driving trajectories of change at the reach scale; and (c) to use the knowledge gained to assess the likely impact of future scenarios on catchment to segment processes and reach scale responses.

Stage (i) Delineation

The boundaries of each spatial unit are delineated using the criteria listed in Table 2, so that each unit at any particular spatial scale is located entirely within a single unit at the next scale. If delineation of geomorphic units, hydraulic units and river elements is required, it must be obtained from field survey. However, sufficient information on geomorphic units is usually available to include them as reach scale indicators during stage (ii). Delineation of other spatial units can be achieved using existing information.

Stage (ii) Characterisation and Indicators

Once the spatial units are delineated, their properties are characterised using existing data sets. Characterisation involves identifying existing data sets that contain relevant information from which the recommended set of indicators can be extracted. The characterisation process allows incorporation of many local data sets of different types that can help to define a required set of indicators of processes, forms, and human pressures. Some example indicators are listed in Table 3. Further details of the recommended indicators are provided elsewhere in this special issue (González del Tánago et al., 2015a).

Indicators have been devised to represent processes of water and sediment production and delivery at catchment to reach scales, and also human pressures and interventions that may affect water and sediment production and longitudinal continuity through the river system. Indicators also represent the extent and structure of riparian and aquatic vegetation at segment to reach scales and the degree to which these appear to have been impacted by human pressures. At the reach and geomorphic unit scales, indicators refer to flow energy, channel and floodplain dimensions and types, the assemblage of geomorphic units that is present, and the degree to which there are constraints on the lateral continuity of inundation, erosion and deposition of sediment and large wood.

The key scale is the reach scale and the key indicator at this scale is the river type. Twenty-three river types are defined using three criteria: (1) valley confinement: confined, partly confined, unconfined; (2) planform: straight, sinuous, meandering, braiding, anabranching (defined using specific ranges of values of sinuosity, braiding and anabranching indices); (3) bed material: bedrock, colluvial, boulder, cobble, gravel, sand, silt, clay. River types range from 'confined bedrock' to 'unconfined, sand-silt, anabranching', with reaches with an artificial bed allocated to an 'artificial' type. Information is provided on the typical gradient, stability, size and variability in bed material, and geomorphic units that may be expected if these types are functioning in a natural way. In addition, the river types are associated with floodplain types and the typical floodplain geomorphic units that may be observed if the floodplain is a product of the long term dynamics of the river type. The twenty-three river types were developed from previous geomorphological research (e.g. Schumm, 1985; Knighton and Nanson, 1993; Rosgen, 1994; Nanson and Knighton, 1996; Montgomery and Buffington, 1997; Church, 2006; Fuller et al., 2013; Nanson, 2013) with additional information on geomorphic units in confined and bedrock river reaches obtained from Grant et al. (1990) and Halwas and Church (2002). The ten floodplain types with which the river types are associated, are based on those suggested by Nanson and Croke (1992). This brief summary of the river and floodplain types is fully elaborated elsewhere in this special issue (Rinaldi et al., 2015b).

Most of the indicators (e.g. Table 3) have the potential to change through time, so both their contemporary and past values are estimated wherever possible. Historical analysis of indicators extends back as far as reliable sources of information are available, typically up to 100 years. Ideally, indicators should be evaluated for several time periods in the past to allow a trajectory of change to be tracked. Of course, this may not be feasible, and a longer historical time scale and higher temporal resolution may be achieved for some indicators (e.g. planform) but not for others (e.g. bed elevation).

Stage (iii) Assessments

The indicators that are extracted from the set of past and present characteristics of each spatial unit are integrated to develop an understanding of how and why river reaches have their current properties and also whether these have changed over time and what may have caused such changes. This is tackled in a sequence of four steps that are fully described in the paper by González del Tánago et al. (2015a) which also appears in this special issue. These are briefly outlined below.

First, the current state of individual reaches is assessed. Four main assessments are made:

> *Hydromorphological function:* Starting from the reach type indicator, assessment is based on whether the assemblage of geomorphic units within the channel and floodplain indicate that the reach is functioning as would be expected, and whether the stream power appears to be sufficient to maintain functioning.
>
> *Hydromorphological alteration:* Given the indicators of human pressures, the degree of disruption of longitudinal and lateral continuity and restriction of bed or bank dynamics within the reach is assessed.

Riparian corridor function / artificiality: This is assessed using indicators of the size, vegetation age structure, and sources and presence of large wood within the riparian corridor of the reach.

Hydromorphological adjustment: The degree and way in which the reach appears to be adjusting or behaving at present is assessed using indicators of the presence, extent and spatial pattern of relevant geomorphic units, and the sedimentary structure of bed and banks.

Second, past and present indicators at catchment, landscape unit and segment scales are used to estimate past and present water production and delivery, and river flow regime; and also sediment production and delivery from the catchment and through the river network. Comparison of present and past values of these indicators, preferably including several time periods in the past, helps to quantify the degree to which flow and sediment processes have changed through time and the likely causes of the changes (e.g. land cover changes, dam construction, channel reinforcement etc.). Based upon this information, a space-time inventory of changes is constructed, focusing particularly on human alterations that have impacted on flow and sediment processes delivered to river reaches.

Third, reach scale historical indicators are coupled with the contemporary reach scale indicators to reconstruct, as far as is possible, the nature of morphological changes within a reach and the timing of those changes to indicate the changing behaviour of the reach. For example, based on an analysis of historical maps and air photographs, an individual reach may show a trajectory of channel narrowing, widening, lateral migration, or a change in river type through time, or the reach may switch from one adjustment type to another. Vertical changes (e.g. bed incision or aggradation) can also be reconstructed from cross section or longitudinal profile information as well as from the evolution of the stage-discharge relationship at gauging stations (specific-gauge analysis). The causes of any identified changes can then be interpreted from knowledge obtained about changes in flow and sediment processes across the catchment and river network during the second step. Along a river, different river reaches may show different degrees and types of morphological adjustment or different behavioural responses to specific changes in the processes delivered to them. Such differences in adjustment may relate to the reach river type and to human interventions within the reach.

Fourth, potential responses at the reach scale to future scenarios of change can be considered, usually focussing on reaches of different river type within particular segments or landscape units, and using information on the way reaches of this type have adjusted in the past. By basing the assessment of causes and responses to changes in the past on a defined set of indicators, those same indicators and their likely responses to specific future scenarios can be interpreted at all spatial scales, providing a basis for forecasting how reaches of different type may respond to particular types of intervention or process change. Furthermore, where reaches are heavily modified by human interventions, historical analyses of all reaches and consideration of future scenarios may contribute to identifying a more appropriate reach type that could guide rehabilitation or restoration designs. Future trajectories are usually based on a small number of scenarios relevant to the river in question, with the aim of informing management recommendations. Two core scenarios are the likely trajectories of adjustment behaviour under (i) the present climate and (ii) likely climate changes (e.g. over the next 50 years) but with no significant change in catchment management. Other scenarios can reflect proposed or likely future changes in river management, land cover, the implementation of particular projects etc.

ELABORATING AND APPLYING THE REFORM FRAMEWORK

This paper has presented a brief overview of the REFORM framework that has been developed for application by river managers within Europe. It is both flexible and it incorporates many aspects of previous hierarchical frameworks. Therefore, the framework should be applicable to landscapes beyond Europe that have a similar, long history of human pressures, and where a framework for application by river managers is required. Further details of important aspects of the REFORM framework are presented in two other papers in this special issue. The indicators are justified and described and their application is illustrated by González del Tánago et al. (2015a). The paper by Rinaldi et al. (2015b) fully explores three particularly important indicators: the river, floodplain and flow regime types. It also presents a typology of groundwater-surface water interactions that can be linked to the river and floodplain types.

Remotely sensed data sources provide an increasingly important source of information on river catchments, and so the paper by Bizzi et al. (2015) review of this topic to aid users of the REFORM framework to gain information on whatever level of complexity they feel is appropriate. Furthermore, modelling can help to characterise river segments and reaches and can also be used to investigate future scenarios. The paper by Camenen et al. (2015) considers different approaches to modelling the sediment budget of a long segment of a large river, the River Loire, France. Ziliani and Surian (2015) also employ modelling at the segment scale to illustrate how this aids understanding of a trajectory of changes and possible future channel evolution within reaches of the lower course of the Tagliamento River, Italy.

Finally, because of the open-ended nature of the REFORM framework, and the way it can be used to incorporate different local data sets and models to address different management issues, three papers illustrate management-specific applications. These papers illustrate how the framework has helped to diagnose management problems resulting from fine sediment delivery and transfer in a low gradient, temperate, agricultural catchment in southern England (Grabowski and Gurnell, 2015); problems induced by past gravel mining and other disturbances in an Italian river (Belletti et al., 2015b); and problems induced by flow regulation in two rivers in Spain (González del Tánago et al., 2015b).

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Table 1. Examples of spatially-hierarchical frameworks to support better understanding of the functioning of river catchments, corridors and networks.

Source	Aims	Spatial Scales	Historical Analysis, Time Scales	Process / Form / Intervention Indicators	Classifications[1]	Scenarios
Frissell et al. (1986)	Classification of streams and habitats to support monitoring, determine local impacts of land use practices, generalise from site data, assess basin-wide, cumulative impacts of human activities.	WATERSHED SYSTEM STREAM SYSTEM SEGMENT SYSTEM REACH SYSTEM 'POOL-RIFFLE' SYSTEM MICROHABITAT SYSTEM	Time scale of potential continuous persistence for each spatial scale.	Characteristic variables proposed, many of which are sufficiently specific to be indicators. WATERSHED: geology, topography, soils, climate, biota, culture. STREAM SYSTEM: long profile slope, shape, network structure. SEGMENT: channel floor lithology, down-valley slope, position in network, valley side slope, potential climax vegetation, soils REACH: bedrock relief, down-valley slope, morphogenetic form or process, channel pattern, local side slopes, floodplain, bank composition, riparian vegetation POOL-RIFFLE: bed topography, water surface slope, morphogenetic form or process, immovable substrates, bank configuration. MICROHABITAT: under- and over-lying substrate, water depth, velocity, overhanging cover.	No specific classifications proposed but open-ended criteria (see indicators) are provided for delineating and characterising stream, segment, reach, 'pool-riffle', microhabitat types to underpin classification of Watersheds, Streams, Segments, Reaches, 'Pool-riffles', Microhabitats to indicate how smaller units of particular types contribute to larger units in a nested way, with temporal dynamics appropriate to the spatial scale.	Not explicitly considered, but relevant topics discussed.
Rosgen (1994)	Classification system for natural rivers suitable for engineering, fish habitat enhancement and water resource management applications.	LEVEL I: GEOMORPHIC CHARACTERISATION (approximates segment scale) LEVEL II: MORPHOLOGICAL DESCRIPTION (approximates reach to geomorphic unit scale)	Stream type changes through time are established from historical maps and aerial photographs.	Stream type is the only true indicator, although it is defined by value ranges of indicative stream properties, and is the output of a classification procedure (see classification). Processes and sensitivity are inferred from stream types (sensitivity to disturbance, recovery potential, sediment supply, stream bank erosion potential, vegetation influence).	STREAM TYPES are defined by value ranges of stream characteristics: 9 LEVEL I TYPES: slope, valley-channel cross section (entrenchment, w/d), channel planform (sinuosity). 42 LEVEL II TYPES: subdivision of level I types using channel material types and channel slope ranges.	Not explicitly considered, but some discussion of relevant themes.
Montgomery and Buffington (1997, 1998)	Geomorphological channel classifications and their use for systematizing channel morphology and physical processes for assessing physical channel condition and response potential.	REGION (geomorphic province) CATCHMENT (climate, geology, land use) VALLEY SEGMENT CHANNEL REACH CHANNEL UNIT	Examples of historical change presented, but process change scenarios considered rather than a formal historical analyses.	LOCAL: valley bottom slope, confinement, entrenchment, riparian vegetation; overbank deposits; active channel – pattern; bank condition; bars, pools, bed material.	3 VALLEY SEGMENT TYPES: Colluvial, Bedrock, Alluvial 9 CHANNEL TYPES: Colluvial, Bedrock, Cascade, Step-pool, Plane-bed, Pool-riffle, Dune-ripple, Forced step-pool, Forced pool-riffle.	Changes in riparian vegetation and delivery of large wood, discharge, and sediment (including passage of sediment waves).

Source	Aims	Spatial Scales	Historical Analysis, Time Scales	Process / Form / Intervention Indicators	Classifications	Scenarios
Habersack (2000)	River-scaling approach to the assessment of abiotic and biotic components of rivers.	REGION-CONTINENT CATCHMENT SECTION LOCAL POINT	Provides typical timescales for adjustments in abiotic and biotic processes and patterns. Infers / models causes and effects through downscaling and upscaling analyses.	REGION-CONTINENT: geology, tectonics, hydrology. CATCHMENT: size, network, erosion potential. SECTION: slope, planform, sediment regime. LOCAL: bed and bank forms and inferred processes. POINT: substrate calibre, variability, sorting, flow velocity, shear stress etc..	No specific classifications but open-ended criteria are provided for the physical characterisation of each spatial scale unit and for the interpretation of linkages by downscaling and upscaling.	Not explicitly considered.
Fausch et al. (2002)	Conceptual framework for studying and managing lotic fishes and their habitats in the context of riverscapes, which explicitly embraces the continuous, hierarchical, and heterogeneous nature of these linear aquatic habitats.	BASIN SEGMENT REACH CHANNEL UNIT MICRO-HABITAT	No explicit historical component, although spatio-temporal changes are discussed.	Broad recommendations reflecting 5 principles: 1. Choose appropriate scales, think / work at multiple scales. 2. Processes interact across scales - embrace this complexity. 3. Unique features (e.g. discrete habitat features or rare events) can have over-riding effects. 4. Unintended consequences of habitat degradation occur in all directions. 5. Match observations and predictions to scales at which managers may effect change.	No explicit classifications.	Scenarios not explicitly considered as part of the framework, but discussion of emerging challenges encompasses potential future changes.
Montgomery and MacDonald (2002)	Conceptual framework for diagnosing channel condition, evaluating channel response, and developing channel monitoring programs.	REGION (biogeographic context), CATCHMENT LOCAL (valley and channel).	CATCHMENT: changes in water, sediment, riparian vegetation, wood inputs. LOCAL: changes in riparian vegetation, channel dimensions, pattern, features, bed material.	CATCHMENT: proximity to water, sediment, wood sources. LOCAL: valley bottom: slope, confinement, entrenchment, riparian vegetation, overbank deposits; active channel: pattern, bank condition, bars, pools, bed material.	5 CHANNEL TYPES: Cascade, Step-pool, Plane-bed, Pool-riffle, Dune-ripple (differences in energy dissipation and relative transport capacity).	Chronic increases in: supply of coarse sediment, supply of fine sediment, peak flow magnitude-frequency.

Source	Aims	Spatial Scales	Historical Analysis, Time Scales	Process / Form / Intervention Indicators	Classifications	Scenarios
Snelder and Biggs (2002)	River environment classification aims to provide a multi-scale spatial framework for river management	MACRO MESO MICRO	No historical component.	In application to New Zealand CLIMATE: mean annual precipitation, temperature, potential evapotranspiration. SOURCE OF FLOW: rainfall volume in elevation categories, lake influence index. GEOLOGY: proportions of each geological category in reach catchment area. LANDCOVER: proportion of each land cover category in reach catchment area. NETWORK POSITION: stream order. VALLEY LANDFORM: slope.	REACHES ARE CLASSIFIED based on a spatial hierarchy of controlling factors: MACRO-MESO Watershed controls on water and sediment supply. Climate, Source of Flow, Geology, Land cover. MICRO Local scale interactions between watershed controls and topographic factors. Network position, Valley landform.	Not considered.
Benda et al. (2004)	Geomorphic framework to develop testable predictions about how the spatial arrangement of tributaries in a river network interacts with stochastic watershed processes to influence spatio-temporal patterns of habitat heterogeneity.	BASIN SUB-BASIN NETWORK CONFLUENCE	No historical component, although theoretical temporal changes are fundamental to the framework.	Seven structural indicators of river networks: BASIN: 1. size, 2. shape. SUB BASIN: 3. network configuration, 4. size difference between tributary and main stem. NETWORK: 5. drainage density; 6. confluence density. CONFLUENCE: 7. network geometry (confluence angle, distance between tributaries).	Classification is not part of this framework.	Consider theoretically how stochastic watershed disturbances (e.g. floods, fire, storms) impose temporal heterogeneity on confluence effects in a predictable fashion that reflects controls exerted by the network structure.
González del Tánago and García de Jalón (2004)	Hierarchical classification system for application to Spanish rivers.	ECOREGION WATERSHED SEGMENT REACH	No historical component.	No explicitly stated indicators.	SPATIAL UNITS CLASSIFIED AT ALL FOUR CONSIDERED SCALES using pre-existing methods, in some cases adapted or combined.	Not considered.
Brierley and Fryirs (2000, 2005)	The River Styles Framework provides a coherent, catchment-wide template for river management.	CATCHMENT LANDSCAPE UNIT REACH GEOMORPHIC UNITS HYDRAULIC UNITS	An evolutionary sequence is constructed for each river (reach) style using field evidence and information from historical sources. This is interpreted using historical evidence of catchment to reach scale changes in geomorphic linkages and human interventions.	Process controls are inferred from downstream sequences of river (reach) styles in the context of catchment area, valley width and slope, unit stream power for specific flood events, and an assessment of whether each is sediment supply or transport limited.	No explicit classifications provided. A river styles tree is developed for a catchment where each reach style is related to its valley setting, planform, bed material texture and geomorphic units.	Guidance is provided for assessing reach reference conditions, current condition, sensitivity and recovery potential. These are used to assess the impact of various scenarios on river style and condition change.

Source	Aims	Spatial Scales	Historical Analysis, Time Scales	Process / Form / Intervention Indicators	Classifications	Scenarios
Thorp et al. (2006)	The Riverine Ecosystem Synthesis is a framework for understanding both broad, often discontinuous patterns along longitudinal and lateral dimensions of river networks and local ecological patterns across various temporal and smaller spatial scales.	CATCHMENT / ECOREGION RIVER NETWORK FUNCTIONAL PROCESS ZONE HYDROGEOMORPHIC PATCH TYPES ABIOTIC AND BIOTIC (MICROHABITAT) PATCHES	No explicit historical component. Time scale is restricted to ecological time frames relevant to community regulation and ecosystem processes.	No explicit process indicators but the following are provided: (i) a list of mechanisms influencing different abiotic and biotic patch types. (ii) a list of tenets / hypotheses relating species diversity, density, distribution; community composition; and biocomplexity to the types, mosaics, dynamics and controlling processes of functional processes zones and their contained patches.	No explicit classifications but conceptualises some downstream patterning in the character of functional process and their contained hydrogeomorphic patches and abiotic / biotic sub-patches through river networks.	None explicitly considered although relevant topics are discussed.
Dollar et al. (2007)	A framework for the interdisciplinary study and management of river ecosystems which incorporates parallel hierarchies in the geomorphology, hydrology and ecology of a river with different organizational elements and levels of organization for each.	Geomorphological spatial hierarchy: GEOMORPHIC PROVINCE, DRAINAGE BASIN, MACRO-REACH, CHANNEL TYPE, PARTICLE Ecological spatial hierarchy: LANDSCAPE, ECOSYSTEM, COMMUNITY, SPECIES, ORGANISM Hydrological hierarchy: OCCURRENCE, VOLUME, DISCHARGE, VELOCITY, TURBULENCE	No explicit historical component. However, timescales of persistence / stability / adjustment are proposed for each hierarchical element.	Processes at relevant timescales are proposed for each spatial scale. In a South African application of the hydrology-geomorphology subsystems: GEOMORPHIC PROVINCE / BASIN: tectonic, climate change, base level change, weathering and erosion. MACRO-REACH: climate variability, weathering and erosion. CHANNEL TYPE: sediment transport, deposition, vegetation stabilisation. GEOMRPHIC UNIT: flow-sediment-vegetation feedbacks, sediment transport, deposition, entrainment.	No explicit classifications	Multi-level flow chain models are constructed to assess the outcomes of specific changes in, for example, the flow regime.
Beechie et al. (2010)	An open-ended approach to process-based restoration acknowledging that ecosystem conditions at any site are governed by hierarchical regional, watershed, and reach-scale processes controlling hydrologic and sediment regimes; floodplain and aquatic habitat dynamics; and riparian and aquatic biota.	REGION / LANDSCAPE WATERSHED REACH	Compares historical and present land use at watershed scale, habitat conditions and biota at reach scale in order to guide appropriate restoration actions.	Incorporates indicators of driving processes: REGION / LANDSCAPE: tectonics, erosion. CATCHMENT: runoff processes, erosion - sediment supply, discharge. REACH: riparian processes, channel-floodplain interactions.	No explicit classifications	Presents restoration principles rather than scenario responses: 1. Target root causes of habitat and ecosystem change. 2. Tailor restoration actions to local potential. 3. Match scale of restoration to scale of physical and biological processes. 4. Be explicit about expected outcomes and recovery time.

Source	Aims	Spatial Scales	Historical Analysis, Time Scales	Process / Form / Intervention Indicators	Classifications	Scenarios
Merovich et al. (2013)	Multiscale approach for establishing stream conservation priorities in active coal-mining regions, based on relating landscape variables to water chemistry and ecological condition at the segment scale.	WATERSHED (COMMUNITY) SUB-WATERSHED (NEIGHBOURHOOD) SEGMENT WATERSHED (HOUSE)	No historical analysis.	Uses combined ICI results for watershed – sub-watershed - segment classifications to identify and prioritise stream restoration and protection priorities at the segment scale. ICI results incorporate landscape indicators of human interventions (mining, land cover) and natural processes (drainage area, geology, topography).	CLASSIFIES SEGMENTS according to their conditions (Integrated Condition Index, ICI) based on a statistical analysis of segment water quality and ecological conditions and their landscape properties. Segment level conditions (ICI) are amalgamated through a weighted procedure, to sub-watershed (neighbourhood) and watershed (community) scales.	Not explicitly considered.
McCluney et al. (2014)	To understand the strong influences that upstream and watershed processes can have, including human modifications, this research conceptualises rivers as 'macrosystems' of repeating, interacting habitat patches, distributed throughout watersheds and along hydrologic flow paths, where ecological responses of whole basins reflect cumulative and emergent properties and processes operating across scales.	REGION BASIN SUB-BASIN / VALLEY SEGMENT REACH POOL-RIFFLE MICROHABITAT	No formal historical analysis but human interventions (land cover, dams etc.) are explicitly included, and temporal asynchronies are acknowledged.	Macrosystem 'sensitivity', 'resistance' and 'resilience' are explored through an analysis of networks of reaches within which changes induced, for example, by human interventions can be explored.	No explicit classifications.	The conceptual framework lends itself to the consideration of the impact of different scenarios.
Rinaldi et al. (2013, 2015a)	A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at integrating objectives of ecological quality and flood risk mitigation.	CATCHMENT PHYSIOGRAPHIC UNIT SEGMENT REACH GEOMORPHIC UNIT	Historical analysis is used to reconstruct the trajectories of channel evolution, and to establish human interventions (gravel extraction, dam construction, realignment etc) and human-induced changes in processes (e.g. flow, sediment discharge).	The index of reach hydromorphological condition (Rinaldi et al., 2013) integrates scores on 28 indicators of reach functionality, artificiality and channel adjustments. Additional indicators are used to evaluate channel dynamics.	16 RIVER REACH TYPES defined according to their level of confinement, planform, and bed configuration. Hydromorphological condition is assessed by quantifying catchment to reach scale indicators of functionality, artificiality (and relevant historical changes) and channel adjustments.	A series of possible intervention scenarios can be formulated, and a general decision-making framework is provided on how to identify the best scenario.

[1] 'classification' refers to the assignment of spatial units (e.g. reaches, segments) to distinct categories or classes based on specific attributes

Table 2. Spatial units included within the REFORM framework: descriptions, indicative time and space scales, delineation criteria

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

Table 3. Examples of indicators and the processes they indicate at catchment to reach scales of the REFORM framework (for further details see González del Tánago et al. (2015a))

SCALE	KEY PROCESSES	EXAMPLE INDICATORS
Catchment	Water production	Average annual precipitation, Average annual water yield
Landscape Unit	Runoff production / retention	% Exposed aquifers, % Soil permeability class, % land cover classes
	Fine and coarse sediment production	Annual soil erosion, Coarse sediment source areas
River Segment	Valley features	Valley confinement and gradient, River confinement
	Flow regime and extremes	Flow regime type, Average annual flow, Base flow index, Median, 2 year and 10 year floods
	Sediment delivery and transport regime	Eroded soil delivery , Segment sediment budget
	Disruption of longitudinal continuity	Number of major blocking and spanning structures (e.g. dams, drop structures, weirs, bridges)
	Riparian corridor size, functions, succession, wood delivery	Average riparian corridor width, Continuity of riparian vegetation along river edge, Age structure of riparian vegetation
Reach	Stream power	Specific stream power at contemporary bankfull width
	Flooding extent	% Floodplain accessible by flood water
	Channel type and dimensions	Channel type, Floodplain type, Average bankfull channel width, depth and slope, Bed and bank sediment size, Presence of geomorphic units typical of channel and floodplain type
	Contemporary evidence of channel adjustments	Eroding, laterally aggrading banks, Channel widening, narrowing, bed incision, bed aggradation, Vegetation encroachment
	Historical evidence of channel adjustments.	Changes in channel width, Sinuosity, braiding, anabranching indices, Rate of lateral channel movement
	Constraints on channel adjustments, water, sediment, wood continuity	Average width of erodible corridor, Longitudinal continuity, Lateral continuity
	Vegetation dynamics (riparian, aquatic vegetation and wood)	% Riparian corridor under riparian vegetation, Riparian vegetation age structure, Large wood and fallen trees in channel and riparian corridor, Abundance of riparian tree and large wood associated geomorphic units, Aquatic plant extent, Abundance of aquatic plant associated geomorphic

Table 4. Pan European data sources that are mainly freely available and can support delineation and characterisation of spatial units

Data set / source	Description	Web link	Information Type
Synthesis of several primary data sources	Biogeographic Regions and Subregions	www.globalbioclimatics.org http://www.eea.europa.eu/data-and-maps/figures/biogeographical-regions-europe-2001	Maps of Regions
ASTER GDEM	30 m resolution , 7-14 m vertical accuracy	http://asterweb.jpl.nasa.gov/gdem.asp	Topographic
EU-DEM	Pan-EU DEM at 25 m based on ASTER GDEM m (higher quality than any other publicly available DEM at EU scale)	http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/geodata/digital_elevation_model	Topographic
NASA SRTM3 DEM	90m resolution, 10 m vertical accuracy	http://www2.jpl.nasa.gov/srtm/ http://glovis.usgs.gov/	Topographic
JRC CID Portal	High resolution (1,2,5,10 m) satellite imagery, spatial coverage and dates vary	http://cidportal.jrc.ec.europa.eu/imagearchive/main/	Channel planform, vegetation/land use
Image 2000 Satellite Imagery	12.5 m resolution (panchromatic), 25 m (multispectral)	http://image2000.jrc.ec.europa.eu/index.cfm/page/image2000_overview	Channel planform, vegetation/land use
LandSat (4,5,7,8) Satellite Imagery	30 m resolution (15m from 1999), 1982-present	http://earthexplorer.usgs.gov/ http://glovis.usgs.gov/	Channel planform, vegetation/land use
ASTER Satellite Imagery	30m resolution	http://asterweb.jpl.nasa.gov/index.asp	Channel planform, vegetation/land use
Declassified Satellite Imagery (Corona, KH-7, KH-9)	1'-50' resolution, 1960-1980, spatial coverage varies	http://earthexplorer.usgs.gov/	Channel planform, vegetation/land use
European Water Archive	Flow data (daily/monthly) from 3800 gauging stations, 441 are near-natural catchments	http://www.bafg.de/GRDC/EN/04_spcldtbss/42_EWA/ewa.html	Hydrology
CCM2 Database	Pan-European database of river networks and catchments	http://ccm.jrc.ec.europa.eu/php/index.php?action=view&id=23	Inferred channel network from DEM, catchment boundaries and characteristics
Ecrins - European catchments and rivers network system	Improved river network based on CCM2, FEC – functional elemental catchments based on Strahler number	http://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network	Inferred channel network from DEM, catchment boundaries, lakes
Corine Land Cover	Land cover data (1990, 2000, 2006), resolution = 100 m	http://www.eea.europa.eu/data-and-maps	Land use / cover
One Geology Europe	Surficial geology coverage for Europe, resolution varies	http://www.onegeology.org/	Geology