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REFORM

REstoring rivers FOR effective catchment Management

Deliverable	D2.1 Part 1
Title	A hierarchical multi-scale framework and indicators of hydromorphological processes and forms*

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Summary

Background and Introduction to Deliverable 2.1.

Work Package 2 of REFORM focuses on hydromorphological and ecological processes and interactions within river systems with a particular emphasis on naturally functioning systems. It provides a context for research on the impacts of hydromorphological changes in Work Package 3 and for assessments of the effects of river restoration in Work Package 4.

Deliverable 2.1 of Work Package 2 proposes a hierarchical framework to support river managers in exploring the causes of hydromorphological management problems and devising sustainable solutions. The deliverable has four parts. Part 1 (this volume) provides a full description of the hierarchical framework and describes ways in which each element of it can be applied to European rivers and their catchments. Part 2 includes thematic annexes which provide more detailed information on some specific aspects of the framework described in Part 1. Part 3 includes catchment case studies which present the application of the entire framework described in Part 1 to a set of European catchments located in different biogeographical zones. Part 4 includes catchment case studies which present a partial application of the framework described in Part 1 to a further set of European catchments.

Summary of Deliverable 2.1 Part 1.

Research Objective.

The research objective for Deliverable 2.1 is to develop a process-based, multi-scale, hierarchical framework to support river managers in assessing the hydromorphological character of rivers, exploring the causes of hydromorphological problems, and devising sustainable management solutions.

The rationale for developing the framework lies in the fact that the hydromorphological character of river reaches depends not only upon interventions and processes within the reach but also within the upstream and sometimes the downstream catchment. In addition, the character of river reaches often responds in a delayed way to processes and interventions within the catchment. As a result, understanding hydromorphology at the reach scale requires understanding of both current and past processes and interventions not only within the reach but also at larger spatial scales.

A multi-scale approach to investigating hydromorphology inevitably focuses on geomorphological characteristics and the hydrological and geomorphological processes that influence the character and dynamics of river channels and their floodplains across time and space. However, these characteristics and processes are also crucial for river ecology. Hydromorphological processes drive longitudinal and lateral connectivity within river networks and corridors, the assemblage and turnover of in-channel and floodplain habitats, and the sedimentary and vegetation structures associated with those habitats. As a result, a process-based, multi-scale understanding of hydromorphology is essential for identifying degraded segments and reaches of river and for developing sustainable restoration approaches that are in sympathy with hydromorphological functioning from catchment to reach scales.

Methods and Results.

Founded on frameworks proposed in the scientific literature, the REFORM framework is open-ended and user-oriented, allowing users to incorporate any suitable information and tools that may be locally available, but at the same time indicating the minimum level of information required across time and space scales, and some of the simple tools and Pan-European data sets that are available to provide this information when suitable local or national data sets and tools are not available.

This report (D2.1 Part 1) describes the phases that are required to implement the framework including: (i) the delineation of spatial units at region to geomorphic unit scales; (ii) the ways in which those units and their temporal dynamics can be characterised, including the application and interpretation of a river typology; (iii) the extraction of indicators of present and past condition based on the characterisations, from which; (v) changing condition and past and future trajectories of change can be assessed and interpreted.

This report (D2.1 Part 1) is supported by fuller methodological details of some aspects of the framework in Part 2 and example applications of the framework in parts 3 and 4.

In implementing the framework, the central importance of (i) 'getting to know your catchment' is strongly emphasised throughout, as are (ii) the benefits of gathering data in the field rather than over-relying on remotely-sensed information, and (iii) the importance of involving a fluvial geomorphologist in the investigating team. Although the development of catchment to geomorphic unit understanding is best based on local knowledge from the catchment in question, the ways in which broader scientific knowledge and models can be incorporated into the analysis are also discussed and illustrated.

Conclusions and Recommendations.

In assessing hydromorphology, to date there has been too strong a reliance on the reach scale, on the river channel and its current condition, and on focusing on specific river reaches in order to assess rivers, diagnose river problems and design intervention, rehabilitation and restoration measures.

For sustainable solutions to river management problems, it is crucial to develop understanding of the functioning of the reach in the context of the character and changes in the spatial units (segment, landscape unit, catchment, biogeographical region) within which the reach is located. It is also crucial to understand that the character of reaches depends heavily on the nature of the riparian zone and, where present, the floodplain, and also the degree to which the river is able to interact with its riparian zone and floodplain. By incorporating information of these types, the present and past character of the reach can be interpreted in the context of present and past changes that have occurred at the reach and all larger spatial scales, and that have cascaded down from the catchment to influence the reach. It also allows interpretation of how changes in the floodplain and riparian zone interact with changes within the river channel. The ways in which reaches of different type within a catchment have responded to changes / interventions in the past provides crucial information for forecasting how reaches may change in the future, whether the catchment continues to be used and to function as at present or to be subjected to different scenarios of change. The REFORM framework allows users to incorporate all of these multi-scale spatial and temporal aspects into river assessment and management.

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Glossary

This glossary defines some of the terms that are used widely in this report. The given definitions relate specifically to the way in which these terms are used in this report.

Term	Description
Aggradation	Raising the surface of the land (e.g. the bed of a stream or river) by deposition of sediment. Stream bed aggradation results from an increase in delivery of sediment from the catchment or from erosion of upstream river channels or from the upstream progression of sedimentation as a result of change in base level downstream (e.g.upstream of a dam).
Anabranching	A river with more than one channel separated by vegetated islands.
Aquatic vegetation (emergent)	Vegetation composed of plant species that are adapted to living in water environments. These species can only grow in water or in soil that is permanently saturated with water. Several groups of aquatic plants (often called hydrophytes or macrophytes) can be defined, such as emergent, floating leaved, free-floating, submerged. Of these, emergent plants are of particular geomorphological significance because their canopies project through the entire water profile and so interact strongly with river flows and transported sediment.
Armouring	Where the river bed surface is comprised of coarser particles than the underlying river bed layers as a result of removal (mobilisation and transport) of the finer particles from the bed surface layer.
Bank material	The sediments of which the river banks are composed.
Bankfull (channel and discharge)	The bankfull level of a river channel cross- section is the level at which water starts to spill out of the channel (on one or both banks) onto the surrounding floodplain. The bankfull discharge is the discharge or river flow that fills the river channel up to the bankfull level.
Baseflow	The background flow in a river (from groundwater or soil moisture) that is not storm runoff.
Bed material	The sediments of which the river bed is composed.
Bed shear stress	The stress imposed on the bed of the river by the flow.
Biogeographic region	Relatively large area that contains characteristic assemblages of natural communities and species that are the product of broad influences of climate, relief, tectonic processes, etc.
Braiding	A river with more than one channel separated by bars of bare sediment.
Burial (of river bed)	Burial is a special type of bed aggradation, where finer sediments (e.g.silt and sand) are deposited in a sufficiently thick layer to bury a coarser (e.g. gravel) river bed.
Catchment	Area of land drained by a river and its tributaries.
Clogging (of river bed)	The infiltration of fine sediment particles into the gaps between the larger sediment particles of a river bed. The process eventually leads to clogging of the gaps in the river bed through which water would otherwise flow, and as a consequence, the reduction of oxygen penetration into the bed.

Term	Description
Condition (geomorphic, biotic)	Condition refers to the degree to which a channel or river bed is maintaining the properties that it would be expected to show if it were functioning in a natural way. Geomorphic condition relates to the presence of geomorphic units, channel forms, sedimentary structures that would be expected for the river type if it were functioning in a natural way. Biotic condition relates to the presence of communities of species in appropriate abundances and age structures for the river type if it were functioning in a natural way.
Confinement (of a river)	The degree to which the lateral movement of a river channel is confined by the presence of valley sides or terraces. A confinement index can be calculated as the ratio of alluvial plain width to channel width.
Confluence	Junction of two rivers
Connectivity	Shorthand for 'hydrological connectivity' . It expresses the degree to which water within the river channel can flow freely from upstream to downstream (longitudinal connectivity), between the river channel and floodplain (lateral connectivity), between the river channel and underlying alluvial sediments and rocks (vertical connectivity).
Debris flow	Water-lubricated / saturated masses of soil, rock, wood and vegetation that flow rapidly down valley sides and steep river channels, gathering material as they flow, and accumulating on valley floors and in downstream river channels.
Degradation (of a river)	Occurs when human actions lead to the (geomorphic or biotic) condition of a river falling below that of a naturally functioning river of similar type.
Disconnectivity (of a river)	Disconnectivity occurs when barriers disrupt longitudinal connectivity (e.g. installation of dams and weirs), lateral connectivity (e.g. incision of the river bed or embankment construction) or vertical connectivity (e.g. clogging of the river bed).
Ecology	The scientific study of interactions between organisms and their environment.
Entrenchment (of a river)	The ratio between channel width and alluvial plain width.
Erodible corridor	The floodplain or, where a true floodplain is absent, the extent of erodible sediment adjacent to a river, that is not protected from erosion by flood or transport infrastructure embankments, or bank reinforcement. Bedrock river channels generally have no erodible corridor.
Floodplain	An area of low-lying, relatively flat ground adjacent to a river, formed by the river, and thus formed of river sediments and subject to flooding.
Flow duration	Flow duration is the proportion of time during which a river achieves a particular flow magnitude. A flow duration curve shows the percentage of time that different magnitudes of river flow are equalled or exceeded.
Flow regime	The typical pattern of changes in water flow through the course of the year.
Fluvial geomorphology	The scientific study of river and floodplain landforms and the fluvial processes of water and sediment movement that shape them.

Term	Description
Geomorphic unit	Area containing a landform created by erosion and/or deposition inside (instream geomorphic unit) or outside (floodplain geomorphic unit) the river channel. Geomorphic units can be sedimentary units located within the channel (bed and mid-channel features), along the channel edges (marginal and bank features) or on the floodplain, and include secondary aquatic habitats within the floodplain. Some geomorphic features (biogeomorphic units) are formed in association with living and dead (e.g. large wood) vegetation as well as sediment.
Geomorphology	The scientific study of landforms and the processes that shape them
Human disturbance (direct and indirect) of river channels	Interruption and modification of natural river processes and forms by human activities. Direct human disturbance occurs at the site where its effect on the river is observed (e.g. stabilisation of river channel form by bank and bed reinforcement). Indirect human disturbance occurs at a location remote from the site where its effect is observed (e.g. incision of a river bed as a result of the removal of sediment from the river channel at sites upstream).
Hydraulic unit (of a river)	Spatially distinct patch of relatively homogeneous surface flow and substrate character. A single geomorphic unit can include from one to several hydraulic units.
Hydrological responsiveness	The rate at which river flows respond to rainfall inputs to the catchment.
Hydrology	The scientific study of the movement, distribution, and quality of water.
Hydromorphology	A term used to describe the combined scientific study of hydrology and fluvial geomorphology.
Hydropeaking	Sharp variations of river flow as a result of the release of water from dams through turbines into a river during the generation of hydropower.
Hypsometric curve	Cumulative frequency distribution of elevation within a catchment.
Incision (of a river bed)	The lowering of a river bed by erosion of bed sediment, leaving the floodplain at a higher level relative to the bed (and thus reducing the lateral connectivity of the river). Incision is usually a result of a reduction of the supply of sediment to an affected reach from upstream reaches or the upstream movement of a nick point from downstream reaches.
Intermittent flow (in a river)	Flow that does not occur continuously so that there are periods when the river channel dries out and contains no flowing water.
Landscape Unit	Portion of a catchment with similar landscape morphological characteristics (topography / landform assemblage).
Landslide	Mass of soil or rock material that moves down a slope (valley side) under the influence of gravity.
Large wood	A piece of wood that is more the 1 m long and 10 cm in diameter.
Life cycle	Organisms have life cycles that include birth, development into adults, reproduction and death. Different life cycle stages may have different environmental requirements.

Term	Description
Magnitude-frequency	Natural events (e.g. floods, droughts) can be characterised by their size (magnitude) and how often they occur (frequency). Magnitude and frequency are related, since large events tend to occur infrequently and small events occur frequently. Therefore, forecasting the occurrence of natural events is usually based on an analysis of their combined magnitude-frequency characteristics.
Morphodynamics (of rivers)	The form of rivers and the degree to which that form changes (is dynamic) through time as a result of sediment erosion and deposition.
Natural flow regime	The naturally occurring changes in water flow in a river through the course of the year that would occur if the river were responding freely to climate.
Naturalised flow regime	The reconstructed flow regime that results from adjusting river flows to compensate for human impacts, such as abstractions, additions and regulations of flow, in an attempt to establish the naturally occurring changes in water flow through the course of the year that would occur if the river were responding freely to the climate.
Nested hierarchy (of spatial units)	A hierarchy of spatial units of different size (from small to large), where smaller units fit within (are nested within) larger ones so that the smaller units do not overlap the boundaries of the larger units.
Perennial flow	Flow that occurs continuously so that the river channel never dries out but always contains some flowing water.
Planform (of a river)	What a river looks like from above (e.g. straight, sinuous (composed of subdued bends), meandering (composed of tight bends), braiding (composed of more than one channel separated by bare sediment bars), anabranching (composed of more than one channel separated by vegetated islands)).
Pristine (river)	In a completely natural state that is unaffected by human activities.
Process-based	Understanding of the features of a system based upon an understanding of the processes that have formed those features.
Reach (of river)	Section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions. (A river segment can contain one to several reaches)
Reference condition	Condition that provides a benchmark for assessing the degree to which the condition of something is different from (degraded from) the reference condition.
Refugium (plural - refugia)	Location with characteristics that permit organisms to survive when they could not survive more widely within a system (e.g. area of slack water in a channel when velocities are too high elsewhere during a flood event).
Region	Relatively large area with internally consistent (environmental) characteristics.
Resilience (of a river)	Degree to which a river can remain relatively unchanged or can recover its form and function despite the (human) pressures placed on it.
Riparian corridor	Area of a river corridor defined by an envelope that is just large enough to include all areas / patches of 'functioning' riparian vegetation, where 'functioning' means interacting with fluvial processes (indundation, sediment and organic matter exchanges etc.).
Riparian vegetation	Plant communities found along river margins and banks.

Term	Description
River corridor	Area of land adjacent to and including a river and its floodplain up to the margins of nearby hillslopes or any confining terraces. It may include areas that have been intensely modified by human activities.
River element	Individual or patch of sediment, plants, wood, etc. within a river.
River health	The health of a river is usually assessed as the degree to which it shows good biotic and geomorphic condition
River network	The integrated network of streams and rivers that combine to drain water from a catchment.
River type	In REFORM: the combination of confinement and planform (simple classification) and bed material calibre (extended classification) displayed by a reach of river.
Sediment calibre	Sediment size, usually characterised by the dominant size fraction (e.g. gravel, sand, silt etc.) or particle size by weight distribution, or one or more parameters of the particle size by weight distribution (such as the median particle size).
Sediment delivery (to a river)	Sediment that is being moved from its release site and delivered to river channels (often within a particular time period such as a year).
Sediment production	Sediment that is being released at a site (by processes such as rock weathering or soil erosion) so that it is available for transport away from the site (often within a particular time period such as a year).
Sediment transport (of a river)	Sediment that is being transported within a river channel by the flow (often past a particlar location within a particular time period).
Segment (of river)	Section of river subject to similar valley-scale influences and energy conditions.
Sensitivity	Degree to which a river reach changes (self-adjusts) in response to (human-) altered processes or other (human-induced) pressures placed upon it.
Stream power	(Total) stream power is the rate of flow energy dissipation against the bed and banks of a river per unit downstream length, which when divided by channel width gives the unit stream power.
Succession (ecological)	The process of change in the species structure of an ecological community over time
Trajectory	Sequence of changes followed. In the present context, usually the sequence of river channel changes followed through time at a site.
Tributary	Smaller river that joins a larger one
Turnover	In the context of river geomorphic units or habitats, turnover is the way in which they pass through cycles of development and removal by fluvial processes.

1. Background

1.1 Introduction

Chapter 2 provides a scientific context and introduction to the hierarchical methodology that is developed in this report. This chapter explains how the science:

- has developed from the original research proposal
- links with current Water Framework Directive (WFD) practice in terms of the way it maps onto the WFD river typology and defined water bodies

1.2 The Aims of Tasks 2.1 and 2.2 of REFORM WP2

This report and its annexes describe the outputs from tasks 2.1 and 2.2 of REFORM work package 2. As described in our original proposal, the aims of tasks 2.1 and 2.2 were as follows:

Task 2.1: Develop a process-based European framework for hydromorphology. This task incorporates three stages to produce a spatially hierarchical framework, scaling methodology, and accompanying data sources and models for hydromorphological assessment.

- Devise a multi-scale framework for investigating hydromorphology emphasizing relevant spatial units and timescales.
- Identify key controlling factors at each spatial scale and associated relevant data sources and models.
- Develop relevant downscaling and upscaling methodologies to make maximum use of data sources and models across time and space scales.

Task 2.2: Develop and test indicators of hydromorphological processes and forms. This task identifies an appropriate mix of approaches, indicators and models for hydromorphological assessment of rivers and floodplains at different spatial scales. It then tests these and the framework into which they fit in case study catchments across a range of European environments.

- Develop a regional structure based on categorizations of flow regimes from existing flow and climate records, and assessment of sediment delivery based on integration of land cover and DTM data
- Develop a network scale characterization of aggregate flow and sediment dynamics based on the spatial structure of flow duration and sediment delivery / aggradation / degradation regimes across the river network
- Develop sector scale definitions of river / floodplain hydromorphological style and sensitivity, based on a functional typing of riparian and aquatic vegetation, assembly of key flow indicators extracted from available or estimated flow records (including groundwater), and morphological indicators extracted from historical and contemporary data sets (e.g. maps, air photographs, LiDAR data

etc) supported by the development and application of hydrological and hydraulic (e.g. 1D) models.

- Develop reach scale indicators of typical habitat composition (i.e. hydromorphological mosaic and diversity), dynamics, turnover and maintenance (i.e. hydromorphological resilience and change), and also hydrological dynamics (i.e. hydrological connectivity - including surface and subsurface hydrological connectivity). Indicators will be developed from (i) existing and new field surveys, emphasizing hydromorphological dynamics and maintenance / change as well as an inventory of habitat types, coupled with (ii) appropriate hydraulic modelling (1D and 2D) to characterize sediment transport, hydrological connectivity and habitat maintenance and turnover.
- Test the robustness of the above framework, indicators and models across a representative range of case studies.
- Assesses the degree to which new surveys or additions to existing surveys may be necessary to implement the framework across a representative range of European regions.

1.3 Contents of this Report in Relation to the Originally Proposed Work

The two tasks, 2.1 and 2.2, described in section 1.1, lead to this Deliverable 2.1, which is a ten chapter document, with two volumes of annexes. The first volume of annexes provides more detailed information on certain thematic aspects of our proposed methodology whereas the second volume provides example applications of various elements of the methodology to different catchments representing a range of contrasting environmental conditions:

In developing and testing the methodology described in this report some elements of the originally-proposed work were adjusted. The main change was to address the research elements at different spatial scales or in a different order from the original proposal:

- Downscaling and upscaling aspects of task 2.1 are largely addressed in the final stages (chapter.9).
- Many of the specific elements proposed under task 2.2 were found to be better suited to analysis at a smaller spatial scale than that originally proposed.

The main report is organised into the following 10 chapters:

1. Introduction
2. Context and Approach
3. The Hierarchical Framework
4. Delineation of Spatial Units
5. Characterisation of the Contemporary Condition of Spatial Units
6. Characterisation of Temporal Change

7. Extended River Typology
8. Indicators of Present and Past Condition
9. Interpreting Condition and Trajectories of Change
10. References

These chapters follow a logical sequence and explain an open-ended approach, which can be adapted according to local expertise, information and environmental conditions.

IMPORTANT NOTE: While every attempt is made to explain elements of the methodology clearly, the participation of a trained geomorphologist in the application of the methodology is essential if misinterpretations are to be avoided, and the inclusion of as much field survey and checking as possible is strongly recommended.

1.4 Links between the Methodology described in this Report and the WFD River Typology and Water Bodies, and CEN standards

1.4.1 WFD Typology

According to WFD Annex II, pr. 1.1.1(ii), EU Member States have differentiated the "relevant surface water bodies" within the river basin district according to systems A or B identified in section 1.2 of the same Annex. These two systems, which require different types of information, are supposed to be equivalent in their results.

An analysis carried out by the Commission (with the support of EEA) has shown discrepancies in the number and type of river typologies among Member States. An *ad hoc* task of the working group ECOSTAT of the Common Implementation Strategy (CIS) for the WFD has been to analyse and group all Member State river typologies into macrotypologies to facilitate their comparability in terms of ecological status of European Rivers. The representativeness of this macrotypology system has still to be proved.

The river typology that is being developed by the above-mentioned group, mostly following the system A approach, currently defines 14 river types (Table 1.1) based upon the altitude, area and geology of the river's catchment. This is a simple, high-level classification within which more detailed classifications and assessments devised by member states may fit.

Our approach to describing and assessing the hydromorphology of European Rivers is multi-scale and process based, but it maps onto the high level classification presented in Table 1.1 in the following ways:

1. At the catchment level of our multi-scale framework, catchments are characterised according to their altitude, area and geology, using threshold values that match those listed in Table 1.1 (see section 5.2). These catchment properties are then used as catchment-scale indicators in the hydromorphological indicators (section 8.2) that feed into the hydromorphological assessments described in chapter 9.
2. At the regional scale, the framework differs from the WFD typology in the use of biogeographic regions as opposed to the WFD ecoregions. Biogeographic regions summarise the unique combinations of climate, topography and

terrestrial vegetation communities that are present in Europe, which are the primary controls on hydromorphological processes, whereas the ecoregions in the WFD typology are based on aquatic ecological communities rather than reflecting the controls on hydromorphology. As the typologies should be developed on the hydromorphological characteristics *per se*, our approach seems to be more consistent with the rationale of the WFD than the latter one, which seems to be based on a slightly circular approach.

3. At the reach scale, 22 river types are identified (Chapter 7), based on their level of confinement, planform, bed material calibre and typical valley gradient. These characteristics provide a further link with the WFD river types, since level of confinement and valley gradient typically vary with topographic setting (altitude). The 22 river types are also related to 10 floodplain types that once more reflect valley confinement but also typical ranges of bankfull unit stream power (a function of bankfull discharge, gradient and channel width). This provides a further link with topographic setting and also links to river size. These linkages are discussed in section 7.5. The river types are characterized by an assemblage of geomorphic units, which represent a fundamental component of the characterization of the channel and the river corridor. Geomorphic units and features at lower (finer) spatial scales (hydraulic units, river elements) provide a fundamental link between morphological and biological conditions, as they provide information on the presence and diversity of physical habitats. Therefore, classification of river types also provides fundamental information on these aspects.

1.4.2 WFD water bodies and CEN standards

The multi-scale framework proposed in this document has relevance to the CEN (2004) guidance on the assessment of hydromorphology and also the definition of WFD water bodies. However, it is important to understand that the REFORM multi-scale framework aims to be process-based with an explicit focus on understanding hydromorphology in a dynamic way that takes account of changes through time and across spatial scales. This is a different aim from the CEN (2004) guidance, which provides a protocol for 'recording the physical features of rivers' rather than providing any process-based understanding. It is also different from the WFD water bodies, which are management units that should be homogeneous with respect to the pressures by which they are affected and should not contain elements of a different ecological status. Therefore, further considerations than hydromorphological factors influence their identification.

In relation to WFD water bodies, application of the REFORM framework to delineate segments will generate boundaries that often correspond to WFD water body boundaries. Furthermore, there is no reason why these segments should not be subdivided using additional boundaries that correspond to those of water bodies.

The European Standard 'Water Quality – Guidance standard for assessing the hydromorphological features of rivers' (CEN, 2004) sets a 'survey unit' assessment into the context of the WFD river typology (types A and B, see section 1.4.1). Each catchment is subdivided into subcatchments or subareas (called 'river types'), based mainly on area, altitude and geology, reflecting the WFD typology. The river network within these subareas is then subdivided into 'reaches' based on similarity of geology, valley form, slope, planform, discharge (specifically inputs from significant tributary / change in stream order), land use, and sediment transport (lake, reservoir, dam, major weirs). Finally reaches are subdivided into survey units.

The REFORM hierarchical framework uses a more standard geomorphological terminology for the spatial units and, although there is some correspondence in delineation criteria, the procedures recommended for the REFORM framework include a more comprehensive and explicitly process-based set of criteria. Thus, the REFORM framework defines catchments and landscape units which are not dissimilar to the WFD river types. It also defines segments and reaches, where the segments have many similarities to the CEN (2004) reaches but exclude planform as a criterion. This is because planform and other river channel characteristics can vary widely over much shorter river lengths than a segment. These shorter river lengths of similar river channel characteristics are defined as reaches in the REFORM framework. Thus in the REFORM framework, segments describe river lengths subject to a set of broadly consistent external controls on river geomorphology (valley confinement and gradient, land cover, flow amount and regime, etc.) whereas reaches refer to river lengths with similar local geomorphological controls and river channel characteristics (planform, bed and bank material and structure, assemblage of geomorphic units, etc.). The rules for delineating landscape units, segments and reaches are detailed in section 4 of this report.

Table 1.1 Provisional river typology of the WFD CIS Working Group (March 2014)

Broad type number and name	Altitude (masl)	Catchment area (km2)	Geology
1 Very large rivers (all Europe)		>10,000	
2 Lowland, Siliceous/Organic, Medium-Large	<200	100 – 10,000	Siliceous/Organic
3 Lowland, Siliceous/Organic, Very small-Small	<200	<100	Siliceous/Organic
4 Lowland, Calcareous/Mixed, Medium-Large	<200	100 – 10,000	Calcareous/Mixed
5 Lowland, Calcareous/Mixed, Very small-Small	<200	<100	Calcareous/Mixed
6 Mid altitude, Siliceous, Medium-Large	200 – 800	100 – 10,000	Siliceous
7 Mid altitude, Siliceous, Small	200 – 800	<100	Siliceous
8 Mid altitude, Calcareous/Mixed, Medium-Large	200 – 800	100 – 10,000	Calcareous/Mixed
9 Mid altitude, Calcareous/Mixed, Very small-Small	200 - 800	<100	Calcareous/Mixed
10 Highland, Siliceous	>800		Siliceous
11 Highland, Calcareous/Mixed	>800		Calcareous/Mixed
12 Mediterranean, Lowland, Medium-Large	<200	100 – 10,000	
13 Mediterranean,Mid altitude, Medium-Large	200 – 800	100 – 10,000	
14 Mediterranean, Very small-Small		<100	

2. Context and Approach

2.1 A Brief Background to a Hierarchical Approach

The hydromorphological character of river reaches depends not only upon interventions and processes within the reach but also within the upstream and sometimes the downstream catchment. For example, natural (bedrock) or human-constructed (dam) impoundments induce impacts on the hydromorphology of upstream reaches that may propagate for very considerable distance in low-gradient segments of river networks. In addition, the character of river reaches responds in a delayed way to processes and interventions within the catchment. As a result, understanding hydromorphology at the reach scale requires an understanding of current and past processes and interventions at larger spatial scales. Without such a multi-scale understanding, management strategies are not fully informed and may not provide sustainable solutions.

A multi-scale approach to investigating hydromorphology inevitably focuses on geomorphological characteristics and the hydrological and geomorphological processes that influence those characteristics across time and space, but these are also crucial for river ecology. Hydromorphological processes drive longitudinal and lateral connectivity within river networks and corridors, the assemblage and turnover of habitats, and the sedimentary and vegetation structures associated with those habitats. All of these processes and structures are relevant to the provision of habitats to support the entire life cycle of organisms including refugia, feeding, spawning etc. As a result, a process-based, multi-scale understanding of hydromorphology is essential for identifying degraded segments and reaches of river and for developing sustainable restoration approaches that are in sympathy with hydromorphological functioning from catchment to reach scales.

The literature provides many proposals concerning spatial hierarchical frameworks to support better understanding of the functioning of river catchments, corridors and networks. Several authors have reviewed this topic (e.g. Naiman et al., 1992; Kondolf et al., 2003). Some well-documented examples of such approaches are, in chronological order, Frissell et al. (1986); Montgomery and Buffington (1998); Montgomery (1999); Habersack (2000); Thomson et al. (2001); Snelder and Biggs (2002); González del Tánago and García de Jalón (2004); Brierley and Fryirs (2005); Thorp et al. (2006); Dollar et al. (2007); Beechie et al. (2010); Splinter et al. (2010); Ibisate et al. (2011); Ollero et al. (2011); Rinaldi et al. (2012, 2013); Wang et al. (2012). Each of these reviews was developed with a particular application or set of applications in mind.

Addition of a formal temporal analysis to such frameworks is rare, although Brierley and Fryirs (2005) provide an excellent description of how this may be achieved. Nevertheless, many researchers acknowledge space and timescales over which processes may be influential and forms may persist (e.g. Frissell et al., 1986; Habersack, 2000; Thorp et al., 2006; Dollar et al., 2007; Beechie et al., 2010); while others consider scenarios of process dynamics and change (e.g. Montgomery and Buffington, 1998; Montgomery, 1999).

2.2 Rules of Engagement

As already stressed, rivers and floodplains are dynamic systems. They adjust to changes in processes and human interventions across a spectrum of spatial and temporal scales. This report attempts to support river managers in developing understanding of the hydromorphology of river corridors and how it changes in response to the many processes and human interventions that operate across time and space. However, this is not a simple task, and so:

- This main report is accompanied by two volumes of Catchment Case Study Applications (Deliverable 2.1 Parts 3 and 4), which illustrate the application of the proposed methodologies. In particular, Deliverable 2.1 part 3 includes complete case studies, which illustrate all stages of the approach described in this volume (Deliverable 2.1 Part 1) and applied to catchments in different regions of Europe with different environmental conditions, human pressures and also data availability. Case Study 1 on the River Frome UK, provides a particularly detailed explanation and application of the framework stages, explaining how information was derived and why some aspects were adjusted / modified for the particular catchment application. Therefore, it is important to read this report (Deliverable 2.1 Part 1) in association with one or more case studies presented in Parts 3 and 4.
- Some 'rules of engagement' need to be born in mind before embarking on the application of the proposed methodologies:

1. This report describes the essence of a hydrogeomorphological approach to river appraisal. Engagement of a professional geomorphologist in the assessment team is strongly recommended if misinterpretations are to be avoided.
2. Although the proposed methodology stresses the use of readily available data sets, there is no substitute for field survey by a geomorphologist, at least at the reach scale, to verify information extracted from secondary sources; to record features and other information that cannot easily be identified from secondary sources; and to interpret forms and processes directly in the field. Therefore, if pre-existing field surveys are absent or limited, new field surveys should be implemented as widely as possible by an expert in order to ensure the robustness of inferences drawn from secondary information.
3. The proposed methodology is deliberately open-ended and adaptable so that (i) best use can be made of existing information, and (ii) elements of the approach can be tailored to local circumstances. Therefore, this report should be treated as 'guidance' rather than a 'fully specified set of tools'. In particular, chapters 5 and 6, which consider the spatial and temporal characterisation of spatial units, and the accompanying thematic annexes (Deliverable 2.1 Part 2), aim to give a range of options that can be considered rather than a shortlist of tools.
4. A crucial aspect of this methodological approach is the concept of 'reference'. In a European context, pristine, truly natural, river environments are extremely rare. Even the most remote rivers are affected to some degree by human actions. Furthermore, there is no time in the past for which detailed information is available that can be considered to represent pristine conditions for the present.

Indeed, the mid-20th century, which is often used for assessing past conditions (mainly because it marks the time when aerial photograph and high resolution map cover became widely available) was a time when most rivers were more heavily impacted by human activities than at present. These imapcts were often indirect, reflecting a time when forest clearance was at a peak and agricultural activity was intense and was rarely based on conservation principles.

5. Because of the long and intense impact of humans on European rivers and floodplains, assessment cannot be related to any pristine 'reference' condition, but it can focus on the effective functioning of hydromorphological and ecological processes (Bertoldi et al., 2009). Therefore, our approach attempts to discriminate function and human alteration / artificiality, emphasising the reach scale within a spatially hierarchical context, and attempts to assess the degree to which there is a potential for function to improve / recover. This approach maps well onto the concept of water bodies that are or are not 'heavily modified'.
6. Lastly, while the chapters of this report follow a logical sequence, chapters 5 and 6 should be considered to provide a broad perspective on characterisation, while the core elements of the methodology are described in chapters 3, 4, 7, 8 and 9. Furthermore, chapter 6 attempts a full literature review of methods for characterising temporal change, while chapter 5 includes only essential references to the literature, since literature reviews of the broader perspectives of characterising spatial features have been compiled within WP1 and, where necessary, chapter 5 is supported by detailed Annexes.

Users of the hierarchical framework may find the task rather daunting at first sight, but it is important to emphasise, that its application is flexible. In section 3, some suggestions are made regarding how the mix of spatial units and quantity of information gathered can be adapted according to the purpose of each user's application and the size of the catchment being investigated (see page 24).

3. The Hierarchical Framework

For the present application, the hierarchy of spatial units within which relevant properties, forms and processes can be investigated to understand and assess hydromorphology is presented in Figure 3.1. The spatial units are arranged according to their relative size (indicative spatial scale). The reach is the key spatial scale at which the mosaic of features found within river channels and floodplains (i) responds to the cascade of influences from larger spatial scales and (ii) is influenced by interactions and feedbacks between geomorphic and hydraulic units and smaller elements such as plants, large wood and sediment particles within the reach. Geomorphological interpretation or modelling approaches can be used to link the scales through upscaling or downscaling in order to understand how properties at different scales influence properties at other scales.

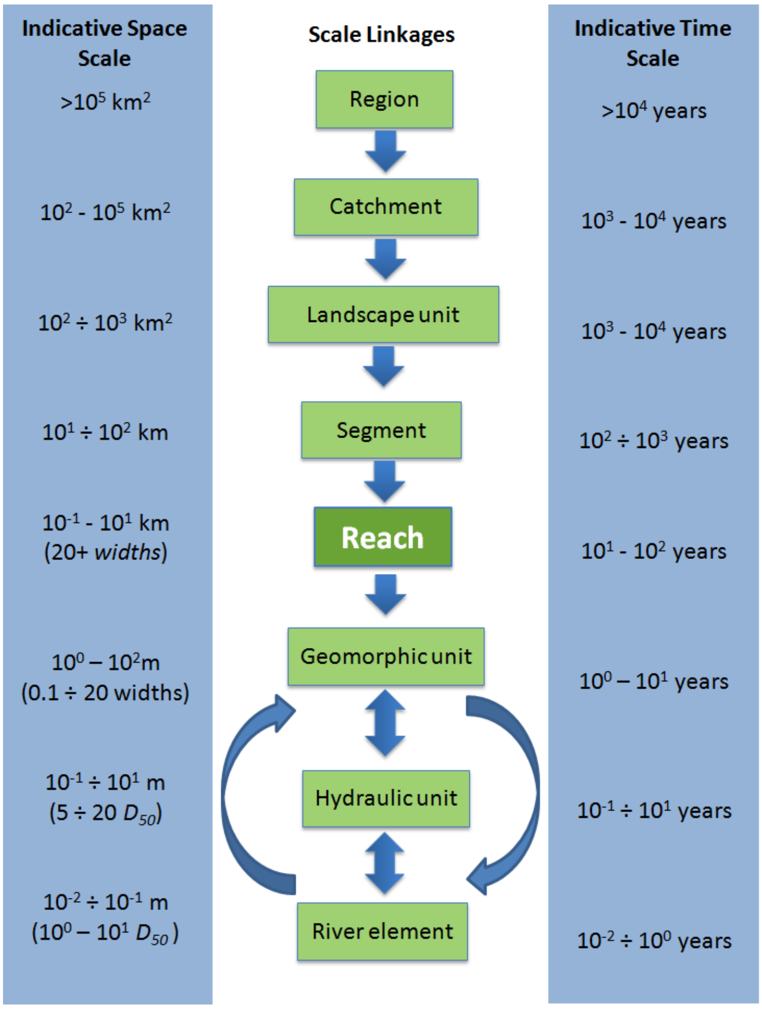


Figure 3.1: Hierarchy of spatial scales for the European Framework for Hydromorphology, including indicative spatial dimensions and timescales over which these units are likely to persist. (D_{50} refers to the median size of river bed sediment)

Application of the hierarchy may vary according to catchment size and management application:

- For catchment assessment and management purposes, the aim should be to subdivide the entire catchment into a complete set of units at all spatial scales from catchment to reach (e.g. Catchment Case Studies 1 to 4, Deliverable 2.1 part 3).
- However, in large catchments, it may not be possible, at least in the first instance, to achieve a complete set of units for the entire catchment. Under these circumstances, it is necessary to subdivide the catchment to the scale of its major landscape units, and then isolate representative subcatchments within each landscape unit and linking segments and reaches along the main channel and major tributaries for detailed analysis (e.g. Catchment Case Study 7, Deliverable 2.1 Part 4).
- If the purpose is to focus on a particular reach or segment and a complete catchment assessment has not been completed, then a minimum assessment needs to focus on spatial units that contain and are immediately upstream of the reach under consideration (e.g. Catchment Case Study 6, Deliverable 2.1 Part 4).

4. Delineation of Spatial Units

This section defines each of the spatial units considered in the hierarchical framework (Figure 3.1) and describes how they are delineated. For applications of the delineation process, see Deliverable 2.1 Parts 3 and 4. The River Frome case study (Part 3, Case Study 1), in particular, provides full details of how every stage was undertaken, including some guidance on which ArcGIS functions to use. Table 4.1 lists the hierarchy of spatial scales within the REFORM framework, provides a definition of each scale, the criteria that are used to delineate the spatial units, and some possible data sources to support delineation. Table 4.2 provides more information on the pan-European data sources referred to in Table 4.1. The following text provides detailed information on the delineation of units at each spatial scale.

4.1 Region

Definition: Relatively large area that contains characteristic assemblages of natural communities and species that are the product of broad influences of climate, relief, tectonic processes, etc.

Delineation: At this scale, no delineation is strictly necessary, since most catchments will fall within a single biogeographic region (various regionalisations are available, but the European Environment Agency's regionalisation is recommended as a general classification, and www.globalbioclimatics.org for a more detailed hierarchical classification). However, some large or steep catchments may encompass more than one biogeographical region or subregion, and this information is likely to help to confirm delineation at the landscape unit scale, where factors within the catchment, such as topography, have a significant impact on biogeographical character.

4.2 Catchment

Definition: Area of land drained by a river and its tributaries.

Delineation: is based entirely on topographic and river network information. The catchment boundary to any required (usually gauged) point on the river network is defined by applying GIS tools to an appropriate digital elevation model. In theory, this process should be relatively easy using existing digital elevation models (e.g. SRTM, ASTER GDEM) and widely available GIS algorithms. In practice the process is often quite difficult. In particular, delineation of headwater streams can be problematic if valley width is less than DEM resolution, while vertical accuracy of DEMs often causes problems in flat, plain regions. Further complications in terms of subsequent interpretation of hydrology can arise due to water transfer infrastructure and changes in underlying geology, which may lead to the hydrologically effective watershed not coinciding with the topographic watershed.

Table 4.1 Spatial Units within the Framework: Definitions, Delineation Criteria and Potential Data Sources and Methods

Spatial Unit (equivalent terms)	**Definition / Description**	**Delineation criteria (#)**	**Methods and Data Sources (#)**
Region (Ecoregion, Biogeographical region)	Relatively large area that contains characteristic assemblages of natural communities and species that are the product of broad influences of climate, relief, tectonic processes, etc.	Differences in main climatic variables and distribution of main vegetation types as shown in maps delineated at European scale (see sources column)	www.globalbioclimatics.org, using Biogeographic Region and Sub-Region
Catchment (Drainage basin, Watershed)	Area of land drained by a river and its tributaries.	Topographic divide (watershed)	Digital Elevation Models (e.g. EU-DEM, SRTM, ASTER GDEM) using GIS algorithms to delimit the divide EU-wide CCM2 River and Catchment Database (v2.1) or EEA Ecrins (connected watersheds, rivers, lakes, monitoring stations, dams) data set
Landscape Unit (Physiographic Unit)	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)	GIS overlay of some of the following in the stated order of priority (1) Digital Elevation Model (e.g. EU-DEM, SRTM, ASTER GDEM) (2) Geological maps (One Geology Europe) (3) CORINE Land Cover (4) Supporting information from: Google Earth / Orthophotos
River segment (River sector)	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	(1) Major segments are identified by applying GIS tools to a DEM with river network overlay, to define downstream breaks in valley gradient (and width) and in upstream contributing area. (2) Major segments may be subdivided according to valley confinement interpreted from DEMs Google Earth images Orthophotos

Spatial Unit (equivalent terms)	**Definition / Description**	**Delineation criteria (#)**	**Methods and Data Sources (#)**
River reach	Section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions. (A river segment can contain one to several reaches)	Channel morphology (particularly planform) Floodplain features (minor changes in bed 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)	Segments are subdivided into reaches by visual interpretation of consistent river and floodplain (bio) geomorphic pattern using Google Earth Orthophotos Multi-spectral remotely-sensed data Lidar data (Field reconnaissance can provide useful confirmation / additional data)
Geomorphic unit (Morphological unit, Mesohabitat, Sub-reach)	Area containing a landform created by erosion and/or deposition inside (instream geomorphic unit) or outside (floodplain geomorphic unit) the river channel. Geomorphic units can be sedimentary units located within the channel (bed and mid-channel features), along the channel edges (marginal and bank features) or on the floodplain, and include secondary aquatic habitats within the floodplain. Some geomorphic features (biogeomorphic units) are formed in association with living and dead (e.g. large wood) vegetation as well as sediment.	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)	Requires field survey but preliminary analysis can use: Google Earth Orthophotos Multi-spectral remotely-sensed data Lidar data
Hydraulic unit	Spatially distinct patches 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 narrow range in sediment calibre	Requires field survey
River element	Elements of river environments including individuals and patches of sediment, plants, wood, etc.	Significant isolated elements creating specific habitat or ecological environments	Requires field survey

(#) All spatial scales equal to or greater than the reach scale may be delineated using secondary sources and a desk-based analysis – types of data are suggested here.

Table 4.2 Pan-European Data Sources that can be used for Delineating Spatial units at the Reach Scale and larger.

Data set / source	Description	Web link	Type	Cost/Availability
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	Free
ASTER GDEM	30 m resolution , 7-14 m vertical accuracy	http://asterweb.jpl.nasa.gov/gdem.asp	Topographic	Free
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	Free
NASA SRTM3 DEM	90m resolution, 10 m vertical accuracy	http://www2.jpl.nasa.gov/srtm/ http://glovis.usgs.gov/	Topographic	Free
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	JRC 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	Free
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	Free
ASTER Satellite Imagery	30m resolution	http://asterweb.jpl.nasa.gov/index.asp	Channel planform, vegetation/land use	£30 per 60 km^2 (2013 price)
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	$30 per frame (2013 price)
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	Free

Data set / source	Description	Web link	Type	Cost/Availability
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	Free
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	Free
EU-HYDRO	Two versions: one based on SPOT5 Image 2006 river network and another on EU-DEM (processed by ASTER GDEM) based river network		river network, river lines, river polygons, water bodies (lakes, lagoons, etc.), channels, dams	JRC use
Corine Land Cover	Land cover data (1990, 2000, 2006), resolution = 100 m	http://www.eea.europa.eu/data-and-maps	Land use	Free
One Geology Europe	Surficial geology coverage for Europe, resolution varies	http://www.onegeology.org/	Geology	Free
European Soil Portal (groundwater)	Groundwater resource maps of Europe (38 map sets at 1:500000 scale)	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/groundwater/gw.html#data	Aquifers	Free
European Soil Portal (soils)	Soil data (shapefiles), 1km resolution	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB/index.htm	Soil	Free
European Soil Portal (K erodibility factor)	10 km resolution raster data set of USLE K-factor (t.ha.h)/(ha.MJ.mm)	http://eusoils.jrc.ec.europa.eu/library/themes/erosion/Erodibility/	Soil erodibility	Free
European Soil Portal (PESERA soil erosion estimates)	Modelled soil erosion (t ha^{-1} yr^{-1}) estimates at 1 km resolution	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_download.html	Sediment delivery	Free

Data set / source	Description	Web link	Type	Cost/Availability
European Soil Portal	Topsoil organic carbon content 1 km raster layer, ETRS LAEA projection	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/octop/octop_data.html	Soil property	Free
European Soil Portal	EFSA Topsoil pH (H_20) 1 km raster, ETRS LAEA projection	http://eusoils.jrc.ec.europa.eu/library/Data/EFSA/	Soil property	Free
European Soil Portal	EFSA Topsoil bulk density 1 km raster, ETRS LAEA projection	http://eusoils.jrc.ec.europa.eu/library/Data/EFSA/	Soil property	Free
European Soil Portal	EFSA Topsoil texture class 1 km raster, ETRS LAEA projection	http://eusoils.jrc.ec.europa.eu/library/Data/EFSA/	Soil property	Free
European Soil Portal	EFSA Topsoil Water content at field capacity 1 km raster, ETRS LAEA projection	http://eusoils.jrc.ec.europa.eu/library/Data/EFSA/	Soil property	Free
European Soil Portal	European Landslide Susceptibility Map (Landslides)	http://eusoils.jrc.ec.europa.eu/library/themes/LandSlides/index.html#ELSUS	Sediment delivery	Free
JRC Forest Cover Maps	30 m resolution (1990, 2000, 2006), derived from LandSat and Corine data	http://forest.jrc.ec.europa.eu/download/data/	Vegetation	Free

Notes:

- Annex J in Deliverable 2.1 Part 2 discusses the information that can be extracted from remotely sensed sources and how to extract it.
- The table lists the data sets available at pan-EU scale that are free or mainly managed by EU institutions. There are however a large variety of other private products and data which cover most of EU.
- One of these other products is the following DEM at almost EU-scale: NEXTMap Database (intermap.com), a multi-sensor derived digital elevation model (at least in part from LIDAR data). Digital surface model (DSM) and digital terrain model (DTM) available, ground resolution 5 m. Coverage: Western Europe. Vertical accuracy <1 m LE90% for 40% of coverage, 1-3 m LE90% for 40 %, and >3 m LE90% for 20 % of coverage.
- Lists of all data available through the European Soil Data Centre (ESDAC) is available here: http://eusoils.jrc.ec.europa.eu/library/esdac/OnLine_Data.cfm (from which a number of relevant new products are anticipated).

Simple GIS tools are available (e.g. for ArcGIS) to delineate the catchment boundary for any location on a river network and a variety of DEMs are also freely available (e.g. SRTM, ASTER, GDEM). Accurate digital mapping products could also be utilised (e.g. OS Mastermap dataset for the UK). At pan-European scale, the CCM2 River and Catchment Database v2.1 (Table 4.2) is a purpose-designed product. The CCM2 database was originally defined using the SRTM 90 m DEM but it has been refined continually to remove errors in river line positions. While exact channel planform boundaries are not defined in CCM2, the database can be used to accurately define catchment boundaries and quantify the upstream contributing area to any point on a river network.

Within a catchment, the river course is best delineated using a digital representation of the actual network rather than any inferred network based on DTM analysis.

4.3 Landscape unit

Definition: Portion of a catchment with similar landscape morphological characteristics (topography/landform assemblage).

Delineation: The aim is to delineate substantial areas of the catchment that are physiographically similar. The number of landscape units should not be large (typically up to four), but a higher number may be necessary if the catchment is particularly large and complex. These units are important for understanding the hydrological responsiveness of a catchment and also its sediment source / delivery characteristics, and so topography and rock type are the key characteristics underpinning unit delineation, although other factors (e.g. climate, vegetation cover and land use) may be considered to help confirm the appropriateness of divisions based on topographic and geological information. In addition to national data sets, there are several readily-available pan-European data sets that can contribute to the delineation of landscape units, including ASTER GDEM, NASA SRTM3 DEM, CCM2 data base, One Geology Europe, European Soil Database, JRC Forest Cover Maps, Corine land cover data (Table 4.2).

Overall, topographic information underpins delineation of areas of internally consistent elevation range, relief and topographic dissection. Geology (lithology and tectonics) is also a fundamental control on topography as well as hydrological processes and the delivery of sediment to the fluvial system. Landscape units can be composed of many rock types, but broad groupings, as they affect landform and hydrological processes, are needed.

As a first step in delineation of landscape units, consideration is given to topography in terms of the broad elevation, relief and degree of dissection of the landscape. This enables the catchment to be subdivided into major landscape units such as: *plains;* undulating, lower elevation, *hilly areas;* and higher elevation, *mountain areas.* Appropriate threshold elevations or elevation ranges at which to separate plains from low (hills) and high (mountain) areas are likely to depend on the biogeographic region or subregion within which the catchment or its subcatchments are located. However, variations in rock type, land use and 'natural' vegetation cover may all be informative for delineation, since they often show a clear structure with increasing elevation. Furthermore, guidance from the Water Framework Directive (high: > 800 m; mid-altitude: 200-800 m; lowland: < 200 m) is a potentially useful starting point.

It may then be important to introduce subdivisions of these initial landscape units, into any clear, characteristic sub-types that are likely to be important for understanding hydromorphology (e.g. *very steep mountain zones; intermontane plains*, etc). Geology (lithology) can also be highly relevant when identifying subdividisions of the initial landscape units. For example, a subdivision of the initial units according to the hydrological (aquifers, aquicludes, aquifuges) or stability characteristics of the major groupings of rock type could be crucial for understanding hydromorphology. Thus, it might be appropriate to subdivide a single initial landscape unit such as a mountainous area, into a unit characterized by metamorphic rocks and a unit characterised by sedimentary rocks, because of differences in their detailed morphology (e.g. slope failures, landslide tracks, tallus slopes) that are indicative of their different resistance to erosion.

4.4 Segment

Definition: Section of river subject to similar valley-scale influences and energy conditions.

Delineation: The boundaries of landscape units (section 4.3) form the first delineation of segments of the river valley network, but subdivision of these large segments is likely to be necessary. The aim is to delimit major segments of the river network (at least 10 km in length but often much longer) that are subject to similar valley-scale influences and energy conditions. Therefore, as with the delineation of landscape units, excessive numbers of segments should be avoided, with typically between one and three segments delineated along a river valley within a single landscape unit. Segments most closely correspond to the scale of WFD water bodies, and so it is recommended that the boundaries of these units are delineated to match one another wherever possible, even if there is some nesting of one within the other.

To achieve any necessary subdivision of the initial segments based on landscape units, three main factors are taken into account: (i) the degree to which the fluvial system is laterally confined (limited in its lateral mobility) by its valley; (ii) major discontinuities in valley gradient, including large dams; and (iii) major changes in catchment area (which take account of major tributary junctions). In addition, in steep mountainous areas, (iv) major lateral inputs of sediment from, for example, large debris flows and torrents may form additional points for segment delineation. These deliver massive amounts of sediment to the valley floor, and the largest of these will also cause discontinuities in valley gradient, which is already identified under factor (i).

All of these segment properties are investigated using topographic data, with (ii) and (iii) readily assessed using GIS tools. Automated methods are becoming available to achieve (i) and (iv) although visual checking is strongly recommended. Automated delineation of segments and reaches is investigated in Thematic Annex A (Deliverable 2.1 part 2) and is also discussed below at the reach scale. ASTER GDEM, NASA SRTM3 DEM, and the CCM2 data base are all useful data sets for this purpose, but additional useful information with regard to valley confinement can be drawn from Google Earth imagery, air photographs or, when available, LiDAR data (see Thematic Annex J in Deliverable 2.1 Part 2).

Thus, large dams form an initial basis for defining segments and then (i) an overlay of the river network on a DEM, allows abrupt changes in valley gradient to be recognised; (ii) it also allows the upstream catchment area to be calculated to regularly spaced points along the river network, thus capturing large, abrupt changes in catchment area. Boundaries based on (i) and (ii) often occur at the same location. Finally (iii) inspection of DEM and other data sources, allows the presence of a floodplain to be recognised within the river valley with the aim of distinguishing river segments that abut directly onto the valley edges or ancient terraces (confined), from segments where a discontinuous floodplains exist (partly-confined), and segments that possess a continuous floodplain along both sides of the river (unconfined).

Based on Brierley and Fryirs (2005) and Rinaldi et al. (2012, 2013), the following approach to defining segment 'valley' confinement is recommended.

Confined: more than 90% of the river banks are directly in contact with hillslopes or ancient terraces. The alluvial plain is limited to some isolated pockets (< 10% bank length).

Partly-confined: river banks are in contact with the alluvial plain for between 10 and 90% of their total length.

Unconfined channels: less than 10% of the river bank length is in contact with hillslopes or ancient terraces - the alluvial plain is virtually continuous, and the river has no lateral constraints to its mobility.

4.5 Reach

Definition: Section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions. (A river segment can contain one to several reaches). As a general rule, the length of a reach should not be smaller than 20 times the mean channel width, although shorter reaches can be defined where local circumstances are particularly complex.

Delineation: The boundaries of river segments form the first delineation of river reaches. However, subdivision may be necessary, since the aim is to define reaches of similar channel and floodplain morphology, which are likely to reflect local changes in bed slope that were too small to demarcate a segment, and changes in sediment calibre, discharge and sediment supply associated with smaller tributary confluences or artificial discontinuities such as dams, major weirs / check dams that disrupt water and sediment transfer. Changes in river confinement as indicated by the ratio of channel width to alluvial plain width within a segment can also affect channel and floodplain characteristics and so a river confinement index (Rinaldi et al., 2012, 2013), defined as the ratio between the alluvial plain width (including the channel) and the channel width (or the reciprocal, defined as 'entrenchment', e.g. Polvi et al., 2010), can help in delineating reaches.

Automated methods are becoming increasingly available that delineate or aggregate homogenous reaches using topographic and other data (e.g. Alber and Piégay, 2011, Bizzi and Lerner, 2012, Notebaert and Piégay, 2013). The application of such automated procedures to a Spanish river is presented in Thematic Annex A (Deliverable 2.1 Part 2). However, it may be necessary to refine the outputs of automated delineations for the present purposes or to base the entire delineation on a visual analysis of imagery and map data (see Annex J, Deliverable 2.1 Part 2).

At this scale, the controlling factors are mainly reflected in the planform characteristics of the river channel and floodplain, including the geomorphic units that are present, which can be viewed on aerial imagery. The following provides a simple working definition and classification, based on Rinaldi et al. (2012) and summarised in Table 4.3 and Figure 4.1.

Confined reaches

In the case of valley-confined reaches, streams are first divided into three broad categories based on the number of threads, i.e. single-thread; transitional (wandering); multi-thread.

Type 1: Single-thread confined reaches. In the case of single-thread, confined reaches, sinuosity is not meaningful as it is determined by the valley rather than the channel planform. Therefore, single-thread confined channels are not further sub-divided at this stage, because it is not possible to make accurate distinctions based on other characteristics, particularly the bed configuration, from remotely sensed sources.

Transitional and multi-thread confined reaches are identified using the same criteria as for unconfined and partly-confined transitional and multi-thread channels (see below). These confined channel types are usually sufficiently large to be discriminated by remote sensing. It is also possible that some small transitional or multi-thread streams can only be confirmed following field survey. In that case they are classified as Type 1 reaches during the delineation phase.

Unconfined and partly-confined reaches

Six broad types (*2. Single-thread: Straight; 3. Single-thread: Sinuous; 4. Single-thread: Meandering; 5. Transitional: Wandering; 6. Multi-thread: Braided; 7. Multi-thread: Anabranching*) are distinguished, based on a planform assessment (from aerial imagery) of three indices:

The *sinuosity index (Si)* is the ratio between the distance measured along the (main) channel and the distance measured following the direction of the overall planimetric course (or ‘meander belt axis’ for single thread rivers).

The *braiding index (Bi)* is the number of active channels separated by bars at baseflow. (Recommended method for estimating *Bi* is the *a*verage count of wetted channels in each of at least 10 cross sections spaced no more than one braid plain width apart - Egozi and Ashmore (2008) suggest that this is the least sensitive to flow stage, channel sinuosity and channel orientation).

The *anabranching index (Ai)* is the number of active channels at baseflow separated by vegetated islands (*Ai*). (Recommended method for estimating Ai is the average count of wetted channels separated by vegetated islands in each of at least 10 cross sections spaced no more than the maximum width of the outer wetted channels apart)

Single-thread

Bi and *Ai* equal or very close to 1 (i.e. only local braiding or anastomosing is possible).

Type 2: Single thread: Straight (*Si*<1.05)

Type 3: Single thread: Sinuous (1.5<*Si*<1.05)

Type 4: Single thread: Meandering (*Si*>1.5)

Transitional

Transitional channels exhibit intermediate characteristics in terms of braiding or anabranching between single-thread and multi-thread channel types. As a consequence, *Ai* and *Bi* indices are between 1 and 1.5.

Type 5. Transitional: Wandering

A distinctive characteristic of many wandering rivers is the presence of a relatively wide channel (high width / depth ratio) occupied by active bars, similar to those of braided rivers. Therefore, 1 < *Bi* < 1.5, but bars are continuously present, occupying most of the channel bed. This morphology is close to multi-thread, with a relatively wider channel than single-thread rivers and a significant presence of braiding or anabranching phenomena. Rivers with a relatively high value of *Ai* (but <1.5) and no braiding phenomena can also be classified as wandering. The latter type could be described as 'wandering anabranching' whereas the former could be described as 'wandering braiding'.

Multi-thread

Multi thread (channel) planforms have *Bi* > 1.5 or *Ai* > 1.5. Two types are distinguished: braided systems have individual threads (low-flow channels) that are highly unstable within the 'bankfull' channel bed, while anabranching/anastomosing systems have relatively stable low-flow channels.

Type 6. Multi-thread: Braided (*Bi*>1.5 and *Ai*<1.5).

Type 7. Multi-thread: Anabranching (*Ai*>1.5 and *Bi*<1.5 or *Bi*>1.5)

<u>*Highly altered reaches*</u>

Type 0. It is important to identify reaches of sufficient length with highly modified characteristics (e.g. urban and other highly channelised / reinforced reaches) as a separate category, since their lateral stability and geomorphic units cannot reflect 'natural' boundary conditions.

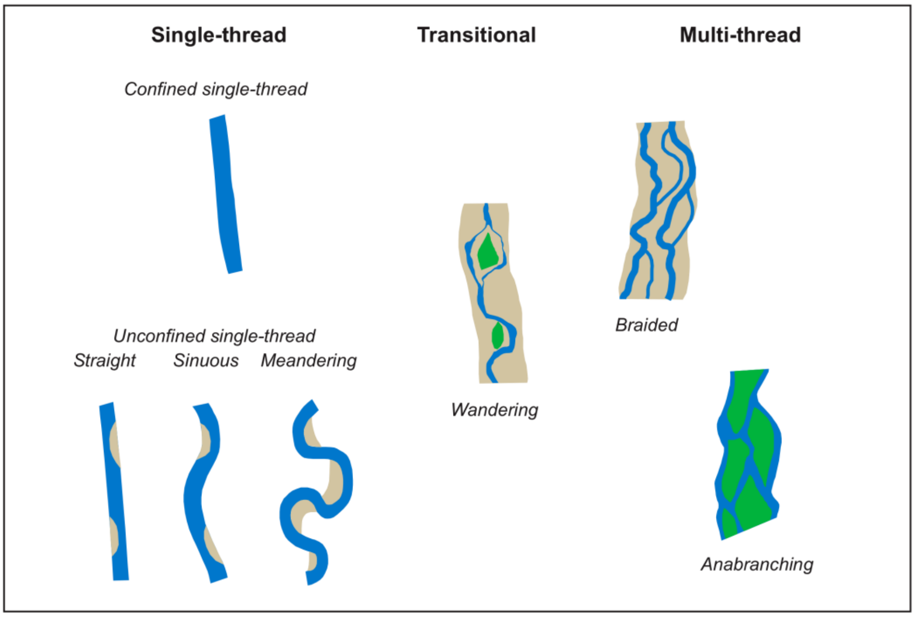


Figure 4.1 Seven types of channel configuration identified from the analysis of areal imagery

Table 4.3 Simple Classification of River Types based on Confinement and Planform

Type	Valley Confinement	Threads	Planform	*Si*	*Bi*	*Ai*
1	Confined	Single	Straight-Sinuous	n/a	approx. 1	approx. 1
2	Partly confined / Unconfined	Single	Straight	< 1.05	approx. 1	approx. 1
3	Partly confined / Unconfined	Single	Sinuous	1.05 < *Si* < 1.5 *	approx. 1	approx. 1
4	Partly confined / Unconfined	Single	Meandering	>1.5	approx. 1	approx. 1
5	Confined / Partly Confined / Unconfined	Transitiona l	Wandering		1 < *Bi* < 1.5	*Ai* < 1.5
6	Confined / Partly Confined / Unconfined	Multi-thread	Braided		*Bi* ≥ 1.5	Ai < 1.5
7	Confined / Partly Confined / Unconfined	Multi-thread	Anabranching		*Bi* < 1.5 or *Bi* > 1.5	Ai > 1.5

4.6 *Geomorphic and Hydraulic Units and River Elements*

Definitions:

Geomorphic unit - Area containing a landform created by erosion and/or deposition of sediment inside (instream geomorphic unit) or outside (floodplain geomorphic unit) the river channel. Geomorphic units can be sedimentary units located within the channel (bed and mid-channel features), along the channel edges (marginal and bank features) or on the floodplain, and include secondary aquatic habitats within the floodplain. Some geomorphic features (biogeomorphic units) are formed in association with living and dead (e.g. large wood) vegetation as well as sediment.

Hydraulic unit: Spatially distinct patches of relatively homogeneous water surface flow and substrate character. A single geomorphic unit can include from one to several hydraulic units.

River element: Relatively small element of a river environment that includes individuals and patches of sediment, plants, wood, etc. A single geomorphic unit can include many river elements. For example a bar may contain a continuum of surface elements or patches of different paticle size. However, sometimes an element such as a piece of large wood (fallen tree) can have enough impact on flow and sediment transport to 'force' geomorphic units such as pools and bars, so reversing the relative spatial scale of elements, hydraulic units and geomorphic units.

Delineation: These three spatial units underpin the habitat mosaic that is present in and around a river. They do not require 'delineation' at this stage of the analysis, but in later analytical stages we emphasise the identification of geomorphic units as key characteristics of river reaches. Hydraulic units and river elements are usually closely related to geomorphic units. Since identification of hydraulic units is affected by river stage and river elements form small components of geomorphic and hydraulic units, in the remainder of this report we focus on geomorphic units as the key spatial unit that is smaller than the reach. Geomorphic units are sufficiently large and prominent that they can often be recognised from remotely sensed sources and are the most straightforward to recognise consistently in the field

5. Characterisation of the Contemporary Condition of Spatial Units

Having delineated the boundaries of the spatial units (chapter 4), the next task is to characterise or describe these units in order to support understanding of the condition and functioning of the fluvial system and to provide information that will feed into the assessment of indicators (chapter 8). Although the focus is on characterising properties of the 'natural' functioning of catchments and river channels, the characterisation also provides information that can contribute to the assessment of hydromorphological pressures and degradation. Therefore, reference will be made to human-induced properties that must be characterised. In this chapter, characterisation is considered in relation to the contemporary condition of the spatial units. Chapter 6 focuses on characterising historical changes within spatial units.

The approach to characterisation is deliberately open-ended to allow for optimum use of locally available data sets, particularly information already gathered to meet WFD requirements. At all of the considered scales, relevant information is available from pre-existing Pan-European (e.g. Table 4.2) data sets. In addition, at the segment, reach and geomorphic unit scales, significant quantities of information can be drawn from pre-existing physical, morphological, or riparian habitat surveys and also from hydrological assessments. Where fieldwork may be required eventually, this is clearly highlighted as a 'NOTE' in the following text.

Chapter 5 considers each spatial scale in the hierarchy from region to geomorphic unit, repeating the definition of each (as an *aide memoire*) and then describing the aims of the characterisation, the groups of characteristics that are of interest at each scale and how they may be quantified. The aims and relevant data sources at each scale are summarised in Table 5.1. Table 5.2 lists the groups of characteristics and the specific quantifiable characteristics at each spatial scale. Throughout it is assumed that GIS will be a key tool in the characterisation process and that users will focus on spatial scales and characteristics that are relevant to their specific objectives.

For applications of the characterisation process, see the example Case Studies in Deliverable 2.1 Parts 3 and 4. Case Study 1 in Part 3 (the River Frome case study), in particular, provides full details of how every stage was undertaken, including some guidance on which ArcGIS functions to use.

Table 5.1 Overview of the aims and potential data sources for characterising spatial units at different spatial scales

Spatial Unit	Aim	Data layers and hydromorphologically relevant properties	Potential Data Sources (see Table 4.2 for further information)
Region	Broad description of the nature of the hydroclimate and natural land cover that are primary controls on all spatial scales of hydromorphological processes	Climate/ Biogeographic Region	www.globalbioclimatics.org, Bioclimate and Biogeographic regions of Europe
Catchment	Characterisation of the size, morphology, geological/soil and land cover controls on water (including groundwater) and sediment delivery to the drainage network.	Essential GIS layers: DEM, geology (solid), land cover Optional GIS layers: soil permeability; geology (superficial). From these derive the catchment area, relief, drainage density, extent of broad land cover types and extent of broad rock types. The latter can be subdivided according to their water holding properties (aquifers, aquicludes, aquifuges) and susceptibility to weathering / erosion.	Digital Elevation Models (e.g. EU-DEM, SRTM, ASTER GDEM) CCM2 River and Catchment Database (v2.1) Ecrins database One Geology Europe European soils data base CORINE land cover JRC Forest Cover Map

Spatial Unit	Aim	Data layers and hydromorphologically relevant properties	Potential Data Sources (see Table 4.2 for further information)
Landscape Unit	Characterisation of the form and process domain(s) associated with water and sediment delivery potential of the landscape unit: Rainfall, topography (broad characterisation of elevation range, slope, form); geology / soils (aquifers and weathering/erosion susceptibility); land cover, which controls water and sediment delivery to the drainage network; natural riparian vegetation influences interaction between hillslopes/floodplain and river network. In addition, if all upstream river segments or reaches are not to be characterized for a particular analysis, it is important to develop an overview of physical pressures / human influences on sediment regime by hydropower plants, retention structures (e.g. torrent controls) at this spatial scale to gain some knowledge of whether the sediment regime is disturbed, and is influencing downstream areas.	Essential GIS layers: DEM, geology (solid), land cover. Optional GIS layers: soil permeability; geology (superficial). Rainfall records From these and aerial imagery derive measures of landscape form, river network extent, erosion susceptibility. Assemble appropriate publications, maps and databases to establish potential 'natural' floodplain forests or riparian (and aquatic) vegetation. Data sets are required which indicate the position of hydropower plants, retention structures and their ability to totally or partially retaining sediments and large wood.	Digital Elevation Models (e.g. EU-DEM, SRTM, ASTER GDEM) CCM2 River and Catchment Database (v2.1) Ecrins database One Geology Europe European soils portal (soil maps, USLE K erodibility factor, PESERA soil erosion estimates, G2 model) CORINE land cover CORINE biotope Nature 2000 JRC Forest Cover Map JRC Riparian Woodland Map Google Earth / other satellite imagery / Orthophotos Some information can be extracted from aerial imagery but many countries have digital map layers or data bases describing the locations and properties of such structures

Spatial Unit	Aim	Data layers and hydromorphologically relevant properties	Potential Data Sources (see Table 4.2 for further information)
River segment	More detailed characterisation of the process domains associated with fluvial processes at segment scale and the physical pressures affecting them: Quantification of flow regime, valley characteristics, river bed sediment calibre, extent and structure of the riparian corridor, and pressures on longitudinal connectivity.	River flow records assembled or modelled and 'natural' flow record assembled / estimated. DEMs analysed to estimate average valley slope and, for larger rivers, indication of river confinement within its valley. Analysis of aerial imagery, (where available) Lidar, and (for river bed sediment) existing morphological/habitat surveys to assess characteristics of the valley, riparian corridor and longitudinal physical pressures.	Flow gauging station records Digital elevation models (e.g. SRTM, ASTER GDEM) Google Earth images Multi-spectral remotely-sensed data Orthophotos Lidar data, National surveys including: Physical habitat surveys Riparian habitat surveys Morphological surveys
River reach	Characterisation of river energy, channel and floodplain dimensions, morphology /geomorphic units, sediments, vegetation and physical pressures, including: Quantification of channel dimensions, stream power, bed and bank sediment calibre, vegetation extent and structure / patchiness, pressures, particularly on lateral connectivity.	Remotely-sensed data sets (including Google Earth) can provide much of the basic information on channel dimensions, hydromorphological and vegetation features (geomorphic units) and sometimes a crude indication of bed material size. Flow information is drawn from the segment scale. DEMs provide reach slope estimates. Where available, Lidar surveys provide very accurate information on channel slope, channel-floodplain morphology and width, and riparian vegetation distribution, height and structure.	Google Earth Orthophotos Multi-spectral remotely-sensed data Digital Elevation Models (e.g. SRTM, ASTER GDEM) Lidar data Pan-European and National vegetation databases

Spatial Unit	Aim	Data layers and hydromorphologically relevant properties	Potential Data Sources (see Table 4.2 for further information)
Geomorphic unit	Identification of the type and abundance of geomorphic units present and interpret their significance in relation to reach-scale morphodynamics	Remotely-sensed data sets (including Google Earth) can provide initial assessments. Lidar is excellent for identifying units beneath vegetation Habitat, morphology and riparian surveys provide additional but widely varying information according to the conventions used in different EU member states.	Google Earth Orthophotos Multi-spectral remotely-sensed data Lidar data National surveys including: Physical habitat surveys Riparian habitat surveys Morphological surveys (Field reconnaissance can provide useful confirmation / additional data)

Table 5.2 List of characteristics that can be extracted at different spatial scales and are described in the text.

Spatial Scale	Category	Characteristic Type	Quantifiable Characteristics
5.1 Region			5.1.1 River Basin or District 5.1.2 Biogeographic Region or Ecoregion
5.2 Catchment		5.2.1 Size, morphology, hydrological balance	(1) Catchment area; (2) WFD size category; (3) max., average, min. elevation; (4) relative relief; (5) WFD elevation zones; (6) Average rainfall and runoff.
		5.2.2 Geology-soils	proportion with (1) exposed aquifers; (2) rock type classes; (3) soil permeability classes
		5.2.3 Land cover	(1) proportion under land cover classes
5.3 Landscape unit	5.3.1 Water delivery potential	(i) Rainfall	(1) summary characteristics of rainfall amount and regime
		(ii) Relief / topography	(1) drainage density; (2) hypsometric curve; (3) surface slope - elevation
		(iii) Surface:Groundwater	proportion with (1) exposed aquifers; (2) soil/rock permeability classes
		(iv) Land cover	(1) proportion under land cover classes
	5.3.2 Sediment production	(i) Potential fine sediment production	(1) soil erosion map layer; (2) average soil erosion rate
		(ii) Potential coarse sediment production	(1) potential sources map layer (2) Sources-slope gradient map layer
	5.3.3 Physical pressures on sediment regime (only required if a full characterisation of all segments is not intended)	(i) total or partial retention of sediment and large wood by hydropower plants	(1) Hydropower plant layer (location, type, size etc) (2) Other retention structures map layer (location, type, size etc)
		(ii) total or partial retention of sediment and large wood by other structures (e.g. torrent control structures)	
5.4 Segment	5.4.1 Flow regime	(i) Flow regime classification	(1) Assign to one of nine types (Table 5.3) (2) Annual pattern of monthly flows (Table 5.4)
		(ii) Flow characteristics	(1) Morphologically representative flows: median, 2yr or 10 yr frequency flood flows (Qp_{median}; Qp_2; Qp_{10}.) (2) Extreme flows (Table 5.4) (3) Abrupt anthropogenic flow: number, size, duration (Table 5.4)

Spatial Scale	Category	Characteristic Type	Quantifiable Characteristics
5.4 Segment (ctd)	5.4.2 Valley characteristics		(1) gradient; (2) degree of valley confinement; (3) degree of river confinement
	5.4.3 Sediment	(i) Sediment size	(1) dominant bed material calibre
		(ii) Lateral sediment delivery	(1) eroded soil delivered to channel; (2) land surface instabilities connected to channel (3) sediment delivery from bank erosion
		(iii) Sediment load and budget	(1) estimated sediment transport, (2) segment gaining, losing or in-balance with respect to sediment transfer.
	5.4.4 Riparian vegetation	(i) Presence of a riparian corridor	(1) average width; (2) area; (3) proportion of valley bottom; (4) continuity
		(ii) Riparian corridor vegetation coverage	(1) proportion trees, shrubs, short, bare
		(iii) Wood delivery potential	(1) proportion bank top under mature trees
	5.4.5 Physical Pressures	(i) Longitudinal continuity	(1) channel blocking structures; (2) channel crossing / partial blocking structures;
5.5 Reach	5.5.1 Channel dimensions (width, planform, gradient)		(1) Average reach and channel gradients; (2) Bankfull and baseflow channel width; (3) Bankful and baseflow channel sinuosity index (4) Braiding index (5) Anabranching index
	5.5.2 River energy		(1) total stream power; (2) specific stream power; (3) average bed shear stress
	5.5.3 Bank and bed sediment	(i) Sediment size	(1) Bedrock exposure; (2) Composition (>64 mm); (3) Composition (<64 mm);
	5.5.4 Riparian and aquatic vegetation	(i) Riparian vegetation	(1) Age structure; (2) Lateral structure; (3) Patchiness; (4) Species
		(ii) Large wood	(1) Large wood presence and abundance
		(ii) Aquatic vegetation	(1) Extent; (2) Patchiness; (3) Species presence and abundance

Spatial Scale	Category	Characteristic Type	Quantifiable Characteristics
5.5 Reach (ctd)	5.5.5 Physical Pressures and Impacts	(i) River bed condition	(1) Bed armouring (gravel-bed rivers); (2) Bed clogging / burial (gravel-bed rivers); (3) extent of bed reinforcement (4) number of channel blocking structures (5) sediment, wood, vegetation removal
		(ii) River bank condition and lateral continuity	(1) hard bank reinforcement; (2) bank edge levées/embankments; (3) set-back levées/embankments; (4) bank top infrastructure; (5) immobilised river margin; (6) actively eroding river margin (7) width of erodible corridor; (8) number of channel-crossing /blocking structures;
		(iii) Riparian corridor connectivity and condition	(1) floodplain accessible by flood water; (2) riparian corridor accessible by flood water (3) riparian corridor affected by intense woodland management activities; (4) abundance of alien, invasive plant species (5) extent of impervious cover, severe soil compaction, excavations / extractions / infilling.
5.6 Geomorphic units	5.6.1 Information from aerial imagery		List of features found within the channel and floodplain that can potentially be identified from aerial imagery (Table 5.7)
	5.6.2 Information from field survey		Information drawn from existing or purpose specific field surveys to: (1) confirm and extend features identified from aerial imagery (2) identify characteristics that suggest particular trajectories of channel changes

5.1 Region

Definition: Relatively large area that contains characteristic assemblages of natural communities and species that are the product of broad influences of climate, relief, tectonic processes, etc.

Aim: At the regional scale, macro-features of biogeography and hydroclimate are considered. These provide boundary conditions for the characteristics of the study catchment at all spatial scales and a broad description of the nature of the hydroclimate and natural land cover that are primary controls on all spatial scales of hydromorphological processes

Characteristics and their quantification: Two characteristics or properties are suggested: the main river basin or district; and the biogeographic region.

5.1.1 The Main River Basin or District

to which the studied catchment belongs, since this provides a useful geographical reference, and should correspond to the Water Districts that each European country has defined in the context of the Water Framework Directive.

5.1.2 Biogeographic Region

where the studied catchment is located, since this provides an essential information on climate and main flow regime patterns, as well as potential vegetation typologies. As with delineation, the biogeographic region can be obtained from the maps shown in www.globalbioclimatics.org, extracting details on the 'Biogeographic Region' within which the study catchment is located.

5.2 Catchment

Definition: Area of land drained by a river and its tributaries

Aim: At the catchment scale, the aim is to characterise the size, morphology, geological/soil and land cover controls on water (including groundwater) and sediment delivery to the drainage network.

Characteristics and their quantification: are gathered under three themes: size, morphology, hydrogical balance; geology / soils; land cover.

5.2.1 Size, Morphology, Hydrological Balance

The size and morphology of a catchment are the primary drivers of its hydrological responsiveness and are derived using the catchment boundary (to a gauged point) created during the delineation phase:

- catchment area (km^2). (Where interbasin water transfers are present also calculate the functioning catchment area (km^2), which is the catchment area minus any area from which water is being exported or plus the catchment area from which water is being imported).

- WFD catchment size category (small: 10-100 km^2; medium: 100-1000 km^2; large: 1000 to 10 000 km^2; very large: > 10 000 km^2).

Altitude and relief constrain hillslope processes, valley types and river energy as well as properties of the climate such as (orographic) rainfall and temperature. These can be characterised by analyzing a DEM:

- Catchment average, maximum and minimum elevation (m) – the properties relevant to the likely form of precipitation and any orographic influences
- Relative Relief (m) and Relative Relief / Longest distance from watershed to catchment outlet (m/m) – indicators of catchment gradient and thus potential to generate rapid runoff
- WFD elevation zones (i.e. the proportions of the catchment area falling within three zones: high: > 800 m; mid-altitude: 200-800 m; lowland: < 200 m).

Although detailed hydrological analysis is most usefully conducted at finer spatial scales, it is useful to assemble a broad overview of the hydrological (water) balance at a catchment scale. This can usually be achieved from pre-existing national mapping and data sets:

- Average annual rainfall (in mm, over a standard (e.g. 20 to 30 year) period)
- Average annual runoff (in mm, over a standard period and estimated at the nearest gauged point to the catchment outlet)
- Runoff ratio (coefficient) = Average annual runoff / average annual rainfall).

5.2.2 Geology/Soils

The geology of the catchment is a further driver of its hydrological responsiveness as well as influencing sediment production and water chemistry. For hydromorphological analysis, rock types are most usefully subdivided according to their water-bearing properties (aquifers, aquicludes, aquifuges), their susceptibility to weathering, mass failure and erosion, and their propensity to produce coarse or fine sediments.

Such subdivisions are best made using national geological map sources. However, information on the extent of aquifers can be obtained from the European Soil Portal. Geological maps can be downloaded from onegeology.org and then classified into broad types. The minimum level to which rock types are characterized should meet WFD requirements (i.e. subdivision into four groups - calcareous, siliceous, organic, mixed or others). A solid geology map layer is essential for achieving such a subdivision. In addition, when available, a map layer of soil permeability classes (e.g. the winter rainfall acceptance classes defined for the UK) is particularly useful for characterizing the water absorbing properties of a catchment. Information on soil properties is available for Europe (http://eusoils.jrc.ec.europa.eu/projects/spade/) and so in the absence of soil permeability classes, a first approximation could be assessed using information on the percentage of coarse fragments, and particle size distribution (% clay, silt and sand content) of soils, obtainable from this source. A superficial geology map layer can also aid interpretation of the extent of floodplains, and glacial deposits that may act as shallow aquifers and sediment sources.

These data sources can support extraction of the following characteristics:

- Proportion of catchment where aquifers are exposed at the land surface
- Proportions of catchment underlain by calcareous, siliceous, organic, mixed / other rock types
- Proportions of the catchment under different permeability / rainfall acceptance classes.

5.2.3 Land cover

Land cover is a further driver of hydrological responsiveness, an important contributor to sediment production; and an important indicator of anthropogenic impacts on a catchment. Several sources are available that can be used to characterise land cover, of which the CORINE land cover maps provide European coverage (resolution 25 hectares) as a ready-prepared map layer. At a minimum, the proportion of the catchment under the four CORINE level 1 cover types should be estimated.

- artificial surfaces
- agricultural areas
- forest and semi-natural areas
- wetlands

5.3 Landscape Unit

Definition: Portion of a catchment with similar landscape morphological characteristics (topography/landform assemblage).

Aims: Landscape units are the building blocks from which water and sediment are delivered to the river network. The aim is to characterise the form and process domain(s) associated with water and sediment delivery potential of the landscape unit.

Characteristics and their quantification: fall into three categories: water production; sediment production; and (where analysis does not incorporate all segments and reaches) physical pressures on the sediment regime.

5.3.1 Water Production

(i) Rainfall

Information from a network of high quality rain gauges representative of the altitudinal range of the landscape unit should be assembled. The data from these may then be used to underpin any modelling that may be required when extracting other characteristics at a range of spatial scales (e.g. soil erosion estimation, flow regime properties). Useful properties to record include:

- The number of rain gauges with over 10 years of at least daily observations within the landscape unit.
- Summary information drawn from at least one 'representative' gauge on the average, maximum and minimum annual and monthly precipitation and an intensity-duration-frequency analysis.

(ii) Relief / Topography

Relief / topographic characteristics are characterised for the entire landscape unit by a DEM from which a river network can be derived using GIS functions. In addition a 'blue line' river network layer describing the perennial river network allows differences between the perennial and derived network to be displayed, indicating potential ephemeral / intermittent flow pathways.

Three properties that characterise the likely efficiency of the landscape unit to deliver water to the river system that can be derived from the DEM and river network map layers:

- Drainage density (km/km^2). This can be estimated from the derived river network (topographic dissection) or the perennial river network, giving an indication of drainage efficiency during extreme high flow and baseflow conditions, respectively.
- The hypsometric curve (land area above given elevations) is indicative of land surface gradient at different altitudes.
- Land surface slope-elevation distribution is indicative of the elevations at which the steepest slope gradients occur.

(iii) Surface:Groundwater

The geology and soil map layers created at the catchment scale (5.2.2) are used to characterise water-bearing properties of the landscape unit:

- Proportion of the landscape unit area where aquifers are exposed at the land surface
- Proportions of the landscape unit underlain by calcareous, siliceous, organic, mixed / other rock types
- Proportions of the landscape unit under different permeability / rainfall acceptance classes.

(iv) Land Cover

At this scale, land cover can be characterised in greater detail than at the catchment scale using information sources such as CORINE level 2 classes (or similar categories from national surveys):

- paved or compacted area
- urban fabric

- industrial, commercial, transport units
- open spaces with little or no vegetation (includes bare rock)
- arable land
- permanent crops
- pastures
- shrub and/or herbaceous vegetation
- forests
- wetlands

In addition, where relevant, the following hydrologically-important land cover types:

- large surface water bodies (area under large lakes / reservoirs) should be quantified from air photos or satellite imagery, since these large water stores strongly affect water storage and runoff characteristics of the landscape unit.
- glaciers and perpetual snow (i.e. those that persist from year to year – CORINE Level 3, class 3.3.5).

5.3.2 Sediment Production

The quantity and particle size of sediment that may be delivered to the river network strongly controls the styles and dynamics of river systems that are present. Sediment delivery potential is very difficult to quantify accurately, however many sources of information can be interrogated to characterise likely sediment delivery properties. The information sources used and the degree to which simple or complex characteristics are extracted depends on the landscape unit type (e.g. largely fine sediment is delivered in low-gradient units, but high coarse sediment inputs are of fundamental importance in steep-gradient units, particularly where rivers are closely confined by hillslopes) and the degree to which such estimates are needed to support or replace direct measurements of sediment transport.

(i) Potential Fine Sediment Production

Soil erosion is responsible for a large part of the finer (i.e. sand and finer) sediment delivered to river systems, so estimation of at least the typical level of soil erosion across the landscape unit can support relative estimates of fine sediment delivery, which are needed at segment and reach scales.

Map layers that can help to characterise fine sediment delivery potential include USLE K-factor maps, and modeled soil erosion maps such as PESERA (Kirkby et al., 2004). Both can be downloaded from the European Soil Portal. The key characteristics that need to be assembled are:

- a soil erosion map layer, from which is calculated -
- the average soil erosion rate ($t.ha^{-1}.yr^{-1}$) for the landscape unit.

The above can be produced in two ways:

1. The simplest approach is to use the PESERA (Kirkby et al., 2004) map layer. The advantage of this is that it is readily available in ESRI grid format, it is based on a hydrological modelling approach and is harmonised across Europe. The disadvantage is that the map is at 1 km resolution, it was not designed for application at catchment or finer scale but rather as a regional to pan-European tool, and it reflects land use at one point in time.
2. A more complex approach is to estimate the soil erosion distribution within a GIS using the (Revised) Universal Soil Loss Equation (RUSLE / USLE, Wischmeier and Smith, 1978) by combining an appropriate grid size (to represent the L factor - the downslope length of the spatial unit for which erosion is estimated); DEM data (to estimate the S factor - slope); local precipitation data within the landscape unit (to estimate the R factor - rainfall erosivity); land use data (to estimate seasonal C - cover-management factor values); and extract appropriate polygons from USLE – K factor maps (Panagos et al., 2012; download from the European soil portal) to provide values of the K factor. The attraction of this approach is firstly, that estimates can be produced for different years if measures of rainfall and / or land cover changes are available, and secondly, estimates can be produced at a finer spatial scale than PESERA if input data are available at higher resolution (although the Pan-European K-factor map is at 10 km resolution). The modelling that underpins the USLE approach is less sophisticated than that underpinning PESERA and the effort required to pursue this approach is considerable. Therefore, (i) at present we recommend that this approach should only be considered if major changes in land use have occurred, but (ii) in future, note developments of the dynamic G2 erosion model, which is based on USLE family models and is downloadable from http://eusoils.jrc.ec.europa.eu/library/themes/erosion/G2/data.html. This model takes account of contemporary changes of rainfall erosivity and vegetation retention and is designed to use input data from European and Global databases. For a recent GIS-based application of the USLE, see Erdogan et al. (2007).

(ii) Potential Coarse Sediment Production

Soil erosion estimates only provide an indication of finer sediment availability and mobility across the landscape unit. Coarser (i.e. gravel and coarser) sediment often forms a significant component of the sediment delivered to river networks in upland, mountainous catchments.

An indication of the extent of potential sources of coarse sediment across a landscape unit can be established by identifying distinct areas of land surface instability (e.g. rock debris, earth or mud - falls, slumps, slides or flows, major gullies). These can be recognised on aerial imagery as torrents, gullies and other areas of exposed coarse sediment with, at most, a very restricted, patchy vegetation cover. These can be used to generate a map layer delimiting the margins of these features. In addition, there is the European landslide susceptibility map (Table 4.2) which may provide useful information.

5.3.3 Physical pressures on sediment regime

Where characterisation is focussed on selected rather than all segments and reaches, a rough overview of transverse structures which cause major disturbances of the natural sediment regime, in terms of continuity of sediment and woody debris, is required at the landscape unit scale. The knowledge of the location and function of these structures is important to identify whether and how the sediment regime is disturbed and can help to assess if and where downstream restoration measures may be most efficient.

In the production zone and in the upper transfer zone, control (transverse) structures are often located to decrease the risks of natural hazards, thereby retaining large amounts of coarse sediment and wood. Hydropower plants function in a similar way and are also widely distributed having major impacts on sediment and wood transport and thus river morphology.

- Therefore map layers which indicate the location, type and operation method, in terms of sediment and wood continuity of hydropower plants and other large retention structures (e.g. torrent control structures), should be generated.

Larger constructions can be determined from aerial images, however in some regions map layers may already exist. For example in Austria digital maps are available displaying location and types of hydropower plants (Project: DSS_KLIM:EN, BOKU Vienna), torrent control structures (Forest Technical Service for Torrent and Avalanche Control, Austria) and other transverse river structures (National River Basin Management Plan, Federal Ministry of Agriculture, Forestry, Environment and Water Management).

5.4 Segment

Definition: Section of river subject to similar valley-scale influences and energy conditions

Aim: Characterisation of the process domains associated with fluvial processes at the segment scale and the physical pressures affecting them.

Characteristics and their quantification: Five types of property are characterized: flow regime, valley characteristics, sediment size and delivery, riparian corridor features, physical pressures

5.4.1 Flow regime

The flow regime should be characterised using gauging station records from within the segment. Where this is not possible, scaling of nearby gauged records to correct for differences in catchment area may be a feasible alternative. Where flow data are particularly sparse, precipitation data (obtained at the Landscape Unit scale, see 5.3.1) from gauges located in the landscape unit in which the segment is situated, and also those within the upstream catchment, could be used to generate modelled flow estimates.

A minimum of one flow time series should be assembled or synthesized for each segment, since the flow regime is likely to change downstream of each significant tributary confluence. Ideally, a record of at least 20 years length is preferred, but a minimum of 10 years is required, with a minimum temporal resolution of one day. Such records can be complemented by monthly data or historical flood data to provide a richer analysis. Where the flow regime is affected by hydropeaking, hourly flows (for at least one, typical year) or summary information on the typical frequency, magnitude and duration of water releases are needed.

Hydrological alteration inevitably affects river morphology and dynamics as well as ecology. To allow the level of alteration to be assessed, the 'current' and the 'natural' flow record need to be assembled at a minimum daily resolution for each analysed site. The 'current' hydrological regime is that which is currently monitored at a flow gauging site; synthesised using monitored flows elsewhere; or modelled for the current catchment condition. The 'natural' hydrological regime is usually taken to be the monitored regime in the past when flow modifications / regulations were negligible; or the current 'naturalised' regime, where the monitored flow record has been corrected to remove the impact of anthropogenic pressures such as abstractions, artificial storage regulation, and discharges.

Two broad approaches can then be considered to summarise the character of the 'current' and 'natural' flow regime. Both approaches are described in detail in Annex C of Deliverable 2.1 Part 2. The first approach attempts to classify the entire flow regime, whereas the second method extracts a number of specific properties or statistics from the flow series to quantitatively assess differences between current and natural flows (i.e. indicators of hydrological alteration).

(i) Flow regime classification.

Flow regime classification is a useful starting point for summarising the character of the contemporary flow regime, but also for comparing how it has changed by classifiying past flow records. Major changes will be immediately identified by a change in the class of flow regime.

Starting from the classification scheme proposed by Poff & Ward (1989) and Poff (1996) for the streams in the United States, flow regime classification schemes have been devised, with some adaptations, for application to European streams (see, e.g., Oueslati *et al.*, 2010). The flow regime class indicates the overall pattern of flow, including its intermittancy, interaction with groundwater, and the likely water sources contributing to the river flow regime. The classification provides a useful tool for identifying the overall character of the flow regime and the degree to which this may have shifted.

We propose nine types of flow regime, including three intermittent and six perennial regimes. The regime is decided using six properties of the mean daily flow record:

BFI — is a baseflow index (BFI) calculated as the annual mean of the monthly ratio between the "minimum of the monthly discharge" and the "mean monthly discharge".

ZERODAY — is the number of days without channel flow in a year.

FLDFREQ — is the average number of floods per year having a discharge higher than the mean of annual maximum daily discharge (this is a fixed flood threshold)

FLDPRED — is the maximum proportion of all floods over the fixed flood threshold that falls into one of twelve "60-day seasonal windows", divided by the total number of floods. It ranges from 0.167 (absence of seasonality) to 1 (complete predictability of floods).

FLDTIME is the day number of the first day within the seasonal 60-day windows when FLDPRED is highest. For the day count, note that the first 60-day period is January-February and the last is November-December

DAYCV is the average (across all years) of the standard deviation of daily discharge divided by the annual mean discharge (x 100).

Table 5.3 lists the threshold values of the six properties used to define the nine regimes and describes the nine regime types.

The flow regime can be further characterised by compiling information on the typical annual pattern on monthly flows (Table 5.4)

Table 5.3 Threshold values of hydrological properties to define flow regime types.

Hydrological classes	Flow regime	Thresholds
HI Harsh intermittent	Temporary streams without flow for almost the whole year. Flow is activated during intense rainfall. No river-aquifer interaction. Streams exclusively fed by surface water (R > 90%).	ZERODAY > 240
IF Intermittent flashy	Temporary streams having runoff in the river bed for less than 8 months/year; streams predominantly fed by surface runoff. Runoff is present occasionally, because of rainfall, snowmelt or seasonal fluctuations of the aquifer level.	120 ≤ ZERODAY ≤ 240 or (ZERODAY ≤ 120 and FLDFREQ ≥ 0.60)
IR Intermittent runoff	Temporary stream having runoff in the river bed for more than 8 months/year. Streams are fed by surface runoff and groundwater, due to variations in water table levels within the aquifer.	1 ≤ ZERODAY ≤ 120 and FLDFREQ < 0.60
PR Perennial Runoff	Perennial rivers fed predominantly by surface runoff (quick flow) and, secondly, groundwater (baseflow). Flow regime is characterized by low seasonal variability.	BFI < 30 % and FLDFREQ < 0.60 (High contribution by surface runoff to total discharge)
PF Perennial flashy	Perennial rivers fed predominantly by surface runoff (quick flow), with high flashiness of floods. Flow regime is highly influenced by intense flood events and seasonal droughts.	BFI < 30 % and FLDFREQ ≥ 0.60 (High contribution by surface runoff to total discharge)
SG Perennial Stable (*groundwater*)	Rivers having a stable flow regime, due to the regulation effect of groundwater. In the case of unregulated rivers, feeding is predominantly due to groundwater (baseflow).	30 ≤ BFI < 50 % and DAYCV ≤ 100 (High contribution by baseflow to total discharge)
SS Perennial Super-stable (*groundwater*)	Rivers having very low variability in flow regime. In the case of unregulated rivers (natural regime), flow is predominantly fed from groundwater (baseflow).	BFI ≥ 50% and DAYCV ≤ 100 (Very high contribution by baseflow to total discharge)
SR Perennial Snow+rain	Perennial streams fed by a mix of surface runoff and snow melt.	0.6 ≤ FLDPRED < 0.7 and *121 ≤ FLDTIME* ≤ 182 (High seasonal predictability)
SN Perennial Snowmelt	Perennial streams prevailingly fed by snow and glacier melt.	FLDPRED ≥ 0.7 and *121 ≤ FLDTIME* ≤ 182 (Very high seasonal predictability)

(ii) Comparison of Flow Characteristics

There are numerous characteristics that can be extracted from the flow record to reflect magnitude (*how much?*); frequency (*how often?*); timing (*when?);* duration (*how long?*); and rate of change (*how fast?*). Different characteristics may be significant in different climatic regions and hydromorphological settings (Olden and Poff, 2003; Poff et al., 2009).

Several methods for characterizing flow regime properties and their degree of alteration by human actions are already in use within Europe (e.g. IAH/RVA, developed in the USA by Richter et al., 1996, 1997; IAHRIS, developed in Spain by Martínez Santa-María & Fernández Yuste (2010); IARI, developed in Italy by ISPRA). These methods are summarized in Thematic Annex C of Deliverable 2.1 Part 2.

Table 5.4 suggests a range of flow characteristics that are relevant to hydromorphological assessment (including vegetation). The characteristics are grouped to indicate their hydromorphological relevance:

- Annual pattern of monthly flows (the typical regime – see 5.4.1 (i))
- Morphologically representative discharge (often called channel-forming, for further discussion see Leopold et al. 1964; Simon and Castro, 2003).
- Magnitude, duration, timing of extreme flow conditions
- Abrupt anthropogenic flow fluctuations

The characteristics are calculated for the 'current' and 'natural' or 'naturalised' flow regimes, so that comparisons can reveal the nature and degree of alteration of the regime by human activities, since all of these properties affect river channel morphology and dynamics.

Table 5.4 Suggested flow regime characteristics for a hydromorphological assessment: (i) annual pattern of monthly flows ;(ii) morphologically representative discharges; (iii) extreme flows; abrupt anthropogenic flow fluctuations

Group and Rational	Characteristics
(i) Annual pattern of monthly flows The typical annual distribution of monthly flows influences vegetation recruitment / growth and the aquatic / riparian species that can be supported	From mean monthly flow data for the period of records: • Calculate median, lower quartile (LQ), upper quartile (UQ) flows for each month.
(ii) Morphologically representative discharge Qp_{mean}, Qp_{median} or Qp_2 are frequently used as indicators of channel-forming flows, whereas Qp_{10} has been linked to channel size in areas where flows are naturally extremely variable	• Qp_{median} (Qp_{mean} omitted because unreliable when estimated from short flow records) • Qp_2 • (Qp_{10} if a long enough record is available). - These are calculated from instantaneous peak flows in each year where possible, but otherwise from the annual maxima 1-day flow series (see below)
(iii) Short term (1 day) and prolonged (30 day) extreme flow conditions and their timing These are important for sediment and vegetation disturbance (high flows) and vegetation growth (low flows)	From daily flow data for the period of records extract series of: • Annual maxima 1-day flows • Annual maxima 30-day flows • Annual minima 1-day flows • Annual minima 30-day flows For each of the 4 series calculate: • median, lower (LQ) and upper quartile (UQ) values and the month of most frequent occurrence -
(iv) Abrupt anthropogenically-controlled flow fluctuations. Where frequent, abrupt flow fluctuations, such as hydropeaking, occur that are large enough to constitute a significant proportion (e.g. > 50%) of the flow that the bankfull channel can accommodate, they have an enormous impact on sediment calibre, landforms and vegetation within the bank-full channel.	From detailed (at least hourly) flow records or information on hydropower releases, estimate typical values of the following statistics: • Number of flow release events in a year. • Median, LQ, UQ of (i) peak release (additional discharge above background) and (ii) event duration • Typical rates of rise and fall of release events

5.4.2 Valley characteristics

Two main valley characteristics have hydromorphological significance: gradient and confinement. Valley gradient or slope, which can be extracted from a DEM, is a very important control on river energy and thus the river's ability to transport sediment. The degree of confinement of the river by valley side slopes or high terraces limits the planform and potential lateral mobility of the river. This characteristic has already contributed to segment delineation (section 4.4), but additional information on the relative width of the active river channel and the valley can be identified from aerial imagery. Three valley characteristics should be quantified:

- The average valley gradient or slope within the segment
- The valley confinement: confined, partly-confined, unconfined (from section 4.4)
- The river confinement: the typical alluvial plain width divided by the typical river bankfull width (the latter can be based on an average of reach estimates - see section 4.5).

Note that for an anabranching river the bankfull width is the total width of the anabranch channels, excluding the intervening vegetated areas of the floodplain, whereas for a braided channel, the bankfull width is the width of the active braid plain (i.e. the width of the flowing channels and intervening bare sediment bars) but excluding the width of any established, heavily-vegetated, islands within the braid plain.

5.4.3 Sediment

(i) Sediment size

At the segment scale, a qualitative assessment of the dominant calibre of the river bed material is sufficient (e.g. bedrock, boulders, cobbles, gravel, sand and silt, clay). This level of information is usually recorded in habitat surveys, although such estimates are usually very subjective. Bedrock or boulder dominated reaches can sometimes be distinguished from aerial imagery.

- Dominant bed material calibre (bedrock, boulder, cobble, gravel, sand, silt, clay) is the required characteristic. Where there is a mix of two dominant sediment sizes, a combined descriptor can be used such as boulder-cobble.

(ii) Sediment supplied to the channel

Estimating sediment delivery to rivers or sediment yield from catchments is a very inexact science.

Analysis of large data sets of monitored sediment yield data (from gauging stations and reservoir sedimentation measurements) can provide useful regional sediment yield estimates that can be further refined for catchments of different size. Such an analysis has been performed at a European scale by Vanmaerke et al. (2011) revealing clear spatial patterns in sediment yield (SY) in which 'the temperate and relatively flat regions of Western, Northern and Central Europe generally have relatively low SY-values (with ca. 50% of the SY < 40 $t.km^{-2}.yr^{-1}$ and ca. 80% of the data < 200 $t.km^{-2}.yr^{-1}$), while Mediterranean and Mountainous regions generally have higher SY-values (with around

85% of the SY-data > 40 $t.km^{-2}.yr^{-1}$ and more than 50% of the data > 200 $t.km^{-2}.yr^{-1}$) (Vanmaerke et al., 2011, p142). If sufficient measurements are available for the study river network, their analysis provides an excellent basis on which to develop understanding of sediment delivery.

For site-specific applications, numerous models are available (Annexes F and I of Deliverable 2.1 Part 2) but all depend on the input of a significant body of information about the catchment and / or a variety of empirical relationships estimated from field or experimental plot studies (see de Vente and Poesen, 2005, for a recent review in a European context). Relatively simple empirical models can work very effectively when developed for specific geographical regions (e.g. the FSM model of de Vente et al., 2005, which predicts basin sediment yield in Spain). However, the development of such regional models requires a very significant research effort and so is beyond the scope of the present report. For those working in areas of Europe where such models exist, they provide a good basis for evaluating sediment delivery and yield, particularly if the models take account of all the key factors that are relevant in the biogeographical region that is being considered.

Whatever approach is used, it is important to gain at least relative estimates of sediment delivery to the river between segments (or reaches), since these will aid understanding of the hydromorphological characteristics of those segments and their contained reaches. The potential fine and coarse sediment availability map layers assembled at the landscape unit scale (section 5.3) can be used to gain a broad and relative spatial view of sediment delivery and can thus generate indicators of potential lateral sediment delivery to the river at the segment (or reach) scale. Separate characterisations are derived for fine and coarse sediment. In the former case, characterisation is based on creating a buffer zone around the channel network (e.g. a 500 m buffer) within a GIS and then assuming that the available fine sediment within the buffer zone is likely to reach the channel network within a year. For coarse sediment, the area of land surface instabilities connected to the channel is used to characterise potential sediment delivery.

From the above the following potential sediment delivery characteristics can be estimated:

- Eroded soil delivered to channel – the total soil erosion per year estimated within the buffer zone divided by the length of bankfull channel margin (fine sediment delivery in $t.yr^{-1}.km$ river edge)
- Land surface instabilities connected to channel – the total unstable area divided by the length of the bankfull channel margin.

These quantitative characteristics are subject to very large errors, so should be treated with caution as giving only a broad indication.

An important *intermediate* source of both fine and coarse sediment to river channels is bank erosion. This can be a major element in a segment (or reach) sediment budget when bank erosion and bank deposition / construction are not in balance. Estimation of retreat / advance rates of banks can be coupled with knowledge of the sedimentary structure of the banks to quantify this potentially important component of sediment delivery. Channel enlargement is usually recognised from field surveys at the reach scale (section 5.6.2), but longer term estimates at the segment scale can be derived by estimating the area affected by lateral bank movement from historical sources (section 6.4.1), multiplying this area by the average bank height (to provide a total volume, which can be further refined using an estimate of bank sediment bulk density) and then estimating the average volume or weight of sediment added to the channel per unit of time:

- Bank erosion input per unit time

(iii) Sediment Transport and Budget

The ability of a river segment or reach to transport the sediment delivered to it is a further crucial factor affecting channel and floodplain hydromorphological characteristics. This is even more difficult to assess than the sediment delivery indicators described above. However, the above analyses coupled with supporting information from field measurements and surveys, formula estimates (Annex H, Deliverable 2.1 Part 2) and modelling (section 9.6 of this report; Annex I Deliverable 2.1 Part 2) can provide very useful information on segment (and reach) sediment transport and budgets. This topic is discussed at the segment scale because it is most likely that good quality flow data are available at this scale.

A combination of field mapping and monitoring (e.g. repeated cross section measurements, development of low water levels at gauging stations over time or along the river, sediment transport measurements), formula estimates (e.g. sediment transport formulae) and models (mainly 0D or 1D models) deliver quantitative information and estimates on sediment transport and the sediment budget. In the latter case, at a minimum, river segments in approximate equilibrium, or showing a surplus or deficit in their sediment budget are identified. Additionally data on any significant dredging or addition of sediment to segments is essential for analysing the sediment budget.

Possible modelling approaches are reviewed in section 9.6. The River Frome (UK) case study provides an example application of the SIAM (Sediment Impact Analysis Methods) model (Annex I.1 Deliverable 2.1 part 2). This model, coupled with HEC-RAS and developed by the US Corps of Engineers, is freely available and provides an approach to tracking sediment by particle size through a river channel system. The model can accept a variety of sediment source / delivery information (including those described above) and it assesses the effect of local changes in flow, slope and sediment inputs to estimate sediment movement and develop a map of potential sediment budget imbalances in the channel network. Thus it characterises:

- Sediment transport / load
- Sediment budget (quantitative or qualitative)

5.4.4 Riparian Corridor Features

Characterisation of the riparian corridor attempts to discriminate between the potential corridor and 'functioning' riparian vegetation within the corridor, since in many parts of Europe, much of the potential corridor is under agriculture, leaving only 'islands' of true riparian vegetation (e.g. in ox-bows or other wet areas that are not easily cultivated). Therefore, the 'corridor' is defined by an envelope that is just large enough to include all areas /patches of 'functioning' riparian vegetation, where 'functioning' means interacting with fluvial processes (indundation, sediment and organic matter exchanges etc.).

Qualitative information concerning the main riparian corridor features within a segment are extracted from air photographs and satellite imagery. There are many automated techniques being developed for this purpose, especially using LiDAR data (e.g. Michez et al., 2013; Annex J Deliverable 2.1 Part 2), but here we generally propose simple approaches.

(i) Presence of a Riparian Corridor

Four characteristics clearly distinguish degraded / patchy types of corridor from those with more extensive and connected riparian vegetation.

Two characteristics illustrate the dimensions of the entire corridor (which could potentially be covered by riparian vegetation under present conditions)

- Average riparian corridor width (m) – includes contained agricultural areas
- Riparian corridor area (km^2) – includes contained agricultural areas

Two characteristics illustrate the degree to which the potential riparian corridor is actually under 'functioning' riparian vegetation.

- Proportion of the riparian corridor under functioning riparian vegetation
- Riparian corridor continuity: proportion of the length of the bankfull channel margin abutting functioning riparian vegetation.

(ii) Vegetation Cover of the Riparian Corridor

Visual analysis of aerial imagery within the riparian corridor or quantitative analysis of LIDAR data allows the broad structure of the areas of functioning riparian vegetation to be characterised:

- Proportions of the corridor under different vegetation patches of predominantly mature trees, shrubs and shorter vegetation, or bare soil (the latter are potential regeneration sites): approximate coverage / proportions can be assessed visually from aerial images or, using LIDAR data, these categories can be delimited using appropriate canopy height thresholds. In agricultural floodplains, only the areas of 'functioning' riparian vegetation should be considered, and in these areas, individual patches of riparian vegetation may only contain one vegetation patch type (i.e. predominantly mature trees, shrubs and shorter vegetation, or bare soil). When the percentages are estimated, they should be for the total corridor so that their rarity is properly represented.

(iii) Potential Wood Delivery

- Proportion of the active / bankfull river channel edge (bank top and island margins) covered by mature (living or dead) trees.

5.4.5 Physical Pressures

At the segment scale, physical pressures on the fluvial system that affect the longitudinal continuity (upstream to downstream) of hydromorphological processes and forms can be recognized (Lateral continuity is assessed at the reach scale). Hydrological pressures attributable to interventions such as water transfers and water abstractions as well as flow regulation by reservoirs are already recognized in aggregate through differences in flow regime characteristics (5.4.1) between 'current' and 'natural' or 'naturalised' flows, but here, the main contributors to these hydrological changes and also to sediment changes are characterised.

Interventions may add or remove sediment and water from the fluvial system. Information on these can be recorded in the form of a list:

- A list of major abstractions and additions of water and their approximate magnitude within the segment provides important supporting information for interpreting hydromorphological changes at the reach scale.
- Major 'point' sediment interventions (dredging, gravel mining) can similarly be summarized by a list of intervention types and their approximate magnitude, again providing important information for interpreting hydromorphological changes at the reach scale. However, data concerning the removal of sediment or large organic material (dead wood, vegetation) from the channel are often difficult to obtain, and may be estimated more effectively at the reach scale (see 5.5.6):

The longitudinal (upstream to downstream) continuity of water and sediment as well as large wood is also affected by interventions that regulate the flow of these elements. These interventions also frequently influence the base level of the river profile. They include the presence of blocking (dam / check dam / weir / pier-deflector) structures; and spanning / crossing structures (bridges), and they can be enumerated using aerial imagery if other information sources are not available:

- Count of high, medium and low impact blocking structures:
  - high – substantial structure and upstream storage area, sufficient to intercept > 90% river flow, or the majority of transported sediment and wood;
  - medium – substantial structure completely blocking the channel but with relatively low storage giving lower impact on flow, sediment or wood continuity;
  - low – minor channel blocking (e.g. low check dam) structure with minor impact on flow, sediment, or wood continuity.

In the above assessment of high, intermediate or low, the higher class is identified according to the structure's impact on flow or on sediment and wood retention and this may vary with river type as much as with the nature of the structure, since, for example, a physically small structure on a low gradient, low energy stream, could intercept virtually all transported sediment and wood.

- Count of high, medium and low impact spanning / crossing and partial blocking structures:
  - high – reduction of the active river channel width by > 20%;
  - medium - reduction of the active river channel width by 5 - 20% channel width;
  - low – little (< 5%) or no blockage of the active river channel width.

5.5 Reach

Definition: Section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions

Aim: Characterisation of river energy, channel and floodplain dimensions, morphology /geomorphic units, sediments, vegetation and physical pressures.

Characteristics and their quantification: Five types of property are characterized: channel dimensions; river energy; bed and bank sediment; riparian and aquatic vegetation; physical pressures and impacts.

5.5.1 Channel Dimensions (width, planform, gradient)

The size and gradient of the river channel are fundamental properties at the interface between process and form. Many channel dimensions can be extracted from aerial imagery based on measures of water, bare sediment and vegetation extent (including Google Earth, Table 5.5). Additionally, DEMs or other digital map data can provide sufficient resolution to estimate a channel gradient to 3 decimal points (in $m.m^{-1}$) but otherwise field survey is essential. The channel gradient should be estimated using the length of the bankfull channel centre-line.

Two measures of gradient are useful: the average reach gradient, which indicates a maximum gradient to which the river can adjust; and the channel gradient, which is the actual gradient of the contemporary river channel. The average reach gradient is calculated by dividing the difference between the upstream and downstream elevations of the floodplain surface adjacent to the main channel by the 'axis of the overall planimetric course' or 'meander belt axis' (e.g. Brice, 1964; Malavoi and Bravard, 2010; Alber and Piégay, 2011) length of the reach. The channel gradient is estimated by dividing the difference between the same two elevations by the length of the main channel mid-line for single thread and anabranching channels or the midline of the braid plain for multi-thread braided and wandering channels. In both cases, if a DEM is available, a more accurate assessment of average slope / gradient can be derived by splitting the channel into subsections (e.g. every 100 m) to calculate several slopes and then calculating the average.

Channel width can be separated into the 'bankfull' or 'active' channel width, which extends to the lower limit of terrestrial and riparian vegetation and includes all bank-attached bars, and the typical 'baseflow' width that generally contains water during the summer months, when many bars are exposed. While a consistent definition of baseflow that could be applied across Europe would require at least some simple hydrological modelling, a simple working definition is Q90 (flow exceed 90% of the time). This could be extracted from long-term daily flow records such as those used in the flow regime analysis. For an anabranching river the bankfull width is the total width of the anabranch channels, excluding the intervening vegetated areas of the floodplain, whereas for a braided channel, the bankfull width is the width of the active braid plain (i.e. the width of the flowing channels and intervening bare sediment bars) but excluding the width of any established, heavily-vegetated, islands within the braid plain.

Bankfull channel width is required to specify the degree of river channel confinement within the valley bottom at both segment (5.4.2) and reach scales, and also to estimate specific stream power within the contemporary river channel (5.5.2). Variability in channel width is a property that is often used to indicate the naturalness of the channel margins, since it is indicative of a lack of channelisation of the river channel by humans, and also the likely variability in the cross profile.

Channel depth (as well as other channel dimensions that cannot be extracted from aerial imagery), is often recorded during habitat or morphological surveys. Where such surveys are available, an additional useful dimension for characterizing a river reach is the channel width to depth ratio, which should be estimated at bankfull width using either the average or maximum bankfull channel depth. Variability in channel depth in long and cross profile is another property that is indicative of naturalness and the presence of a diversity of physical habitats. In the absence of qualitative or quantitative field observations, the variability in channel depth can be deduced to some extent from the frequency and types of geomorphic units present (section 5.6).

NOTE: The potential for analysis of aerial imagery in this context is limited by stream size, vegetation coverage and the resolution of the imagery that is available. Where streams are too small to be quantified remotely, field observations are necessary.

Table 5.5. Channel dimensions measurable from areal images

Channel feature	Definition	Single thread rivers	Multi thread and transitional-wandering rivers
Bankfull / active channel width	Width of the active channel(s) to the lower limit of continuous terrestrial and riparian vegetation	√	√
Baseflow channel width	Width of the water-filled channel(s) under typical baseflow conditions. Note – this must be extracted from images taken at low flow and so is subject to higher potential error than the bankfull width.	√	√
Bankfull / active channel sinuosity index	Length of a line defined at the mid-point between the margins of the active channel divided by the 'axis of the overall planimetric course' or 'meander belt axis' (e.g. Brice, 1964; Malavoi and Bravard, 2010; Alber and Piégay, 2011) (extracted during delineation – section 4.5)	√	√
Baseflow sinuosity index	Length of a line defined at the mid-point between the margins of the water-filled channel at typical baseflow conditions divided by the 'axis of the overall planimetric course' or 'meander belt axis'	√	
	Length of a line defined at the mid-point between the margins of the main (widest) water-filled channel at typical baseflow conditions divided by the 'axis of the overall planimetric course' or 'meander belt axis'		√
	For ephemeral single or multi-thread channels, measure the length of the thalweg (deepest section of the channel) divided by the 'axis of the overall planimetric course' or 'meander belt axis'.	√	√
Braiding index	The number of active channels separated by bars. (Average count of wetted channels in each of at least 10 cross sections spaced no more than one braidplain width apart (index recommended by Egozi and Ashmore (2008) as being the least sensitive to flow stage, channel sinuosity and channel orientation). (extracted during delineation – section 4.5).		√
Anabranching index	The number of active channels separated by islands. (Average count of wetted channels separated by vegetated islands in each of at least 10 cross sections spaced no more than one width of the area enclosed by active channels apart). (extracted during delineation – section 4.5)		√

5.5.2 River Energy

The energy of the river controls its ability to erode and transport material (sediment, vegetation and plant propagules, wood) and thus it is a fundamental influence on river channel size, form and dynamics (e.g. Bizzi and Lerner, 2013).

Energy characteristics are estimated from properties of the flow regime. Because gauged flow information is rarely available at a reach scale, characterisation of the flow regime is achieved at the segment scale (see section 5.4.1), although some scaling may be necessary where gauged flows come from a distant site with a distinctly different catchment area. Three characteristics summarise different aspects of river energy and are calculated in relation to the bank full channel within the reach:

- Total stream power (Ω – the rate of energy dissipation per unit downstream length): estimated by combining a morphologically representative discharge (e.g. Qb (bankfull discharge), Qp_{median}, $Qp_{2,}$ Qp_{10}, Table 5.4) and a measure of channel slope (e.g. average reach gradient or channel gradient, 5.5.1), using the formula:

  $\Omega = \rho.g.Q.S$

  where: Ω is in $W.m^{-1}$, ρ is the density of water (1000 $kg.m^{-3}$), g is acceleration due to gravity (9.8 $m.s^{-2}$), Q is discharge (in $m^3.s^{-1}$) and S is slope (in $m.m^{-1}$). For general application including sites where only short flow records are available, Qp_{median} is recommended as the discharge estimate.

  Although Qb (bankfull discharge) is widely mentioned in the literature (i.e. the discharge that just fills the channel up to the top of its banks) as a geomorphologically-informative index, it is a more challenging index to use than those based on a flow return period. This is because river channel size has a natural variability, but more importantly because the size of many European river channels reflects human modifications rather than any natural balance between flow and sediment transport processes and channel size.

- Specific stream power (ω – stream power per unit channel width in $W.m^{-2}$): is calculated by dividing Ω by the bankfull / active channel width (5.5.1)

- Average bed shear stress (τ_b): requires information on channel depth and is estimated from the following formula

  $\tau_b = \rho.g.h.S$

  where τ_b is in Pa (Pascals - kg m^{-1} s^{-2}), and h is average bankfull channel depth (in m).

5.5.3 Bed and bank sediment

(i) Sediment Size

The calibre of sediment at the channel boundaries (bed an banks) is another fundamental control on river channel morphodynamics. The calibre of the surface bed and bank material places a limit on their erodibility and mobility, on the types of bedforms and bank profiles that may arise, and on the width:depth ratio of the channel. Furthermore, the silt and clay content of bank material is an indicator of the cohesiveness of bank sediments. The characteristic calibre of bed surface and bank materials need, at a minimum, to be distinguished to the qualitative level of bedrock, boulders, cobbles, gravel, sand and silt, clay. This level of information is usually recorded in habitat surveys and bedrock- or boulder-dominated reaches are sometimes distinguishable on aerial imagery.

- The dominant material calibre (bedrock, boulder, cobble, gravel, sand, silt, clay) forms the minimum indicator that is needed. Where there is a mix of two dominant sediment sizes, a combined descriptor can be used such as boulder-cobble.

However, bed and bank materials are so crucial to reach hydromorphology that we strongly recommend the collection of representative sediment samples from the field. Annexe C of Deliverable D2.1 Part 2 describes and recommends optimum methodologies for such surveys to yield high quality data with a minimum of field and laboratory effort. Although surface and subsurface sediment size can be investigated separately or in combination, we recommend that the following useful summary characteristics are estimated at least for the surface sediment layer:

- Bedrock exposure: % bed or bank surface comprised of exposed bedrock
- Sediment composition (>64 mm fraction): % bed or bank surface covered by boulders
- Sediment composition (<64 mm fraction): % gravel (cobble), %gravel (pebble+granule), %sand, %silt plus clay (Table 5.6)

In addition, the following can be extracted if a complete particle size distribution is available (see Annexe C Deliverable 2.1 part 2):

- Median particle size / D_{50}
- Sorting coefficient (width of the particle size distribution)
- Skewness (asymmetry of the distribution)
- Kurtosis (peakedness of the distribution)
- Relative rugosity (if channel depth is known; = 90^{th} percentile particle diameter / channel depth, Montgomery and Buffington, 1997)

Table 5.6 Particle size categories and descriptions (after Wentworth, 1922)

Particle size (phi)	Particle size (mm)	Particle size (microns)	Size class description
<-8	>256		Boulder
-6 to -8	64 to 256		Cobble
-2 to -6	4 to 64		Gravel (pebble)
-1 to -2	2 to 4	2000 to 4000	Gravel (granule)
0 to -1	1 to 2	1000 to 2000	Sand (very coarse)
4 to -1	0.0625 to 2	63 to 2000	Sand
9 to 4	0.00195 to 0.0625	2 to 63	Silt
>9	<0.00195	<2	Clay

5.5.4 Riparian and Aquatic Vegetation:

(i) Riparian Vegetation

Having defined the broad extent and structure of the riparian corridor at the segment scale, more detailed analysis is possible at the reach scale. Riparian forest age structure is an indicator of the health of the riparian zone and the degree to which it is being modified and turned over by fluvial disturbances. This can be estimated visually from aerial images. However, raw LIDAR data (i.e. data before processing to remove vegetation 'noise' from the underlying terrain) is particularly useful for extracting information on tree or shrub height and density that can be translated into approximate age classes, either using local ground surveys or larger area relationships between tree height and age. The following characteristics can be estimated:

- Proportion (coverage) of the riparian corridor supporting riparian vegetation under different vegetation height / age classes. As a minimum estimate the proportions of the corridor under predominantly mature trees, shrubs and shorter vegetation, or bare soil. Where LIDAR or riparian survey data are available it may be possible to extend the estimates of proportions of the riparian corridor to more classes, e.g. bare, pioneer (1-2 y), early growth (< 5y), juvenile (5-15 y), mature forest (15-50 y), and old forest (> 50y).
- Lateral gradient in riparian vegetation age structure across the riparian corridor (suggesting natural lateral connectivity) according to whether (i) there is a clear lateral change in the proportion of the corridor under mature trees, shrubs and shorter vegetation, or bare soil with distance from the river channel; (ii) a subdued difference; or (iii) no lateral gradient in the proportions.
- Patchiness in riparian vegetation structure (suggesting natural disturbance and interaction between vegetation and fluvial processes, including potential to retain large wood) – a visual assessment of the degree to which discrete patches of mature trees, shrubs and shorter vegetation, and bare soil are present to determine whether vegetation cover is (i) strongly patchy; (ii) shows some patchiness; or (iii) predominantly consists of large areas of similar vegetation structure. (note that in riparian corridors interrupted by agriculture, the patchiness needs to be assessed *within* areas of riparian vegetation to illustrate the degree of active interaction between fluvial processes and vegetation within these remaining areas of true riparian vegetation cover)

Another set of important characteristics is:

- The dominant species present (particularly trees and shrubs, but also shorter vegetation) or the typology of any riparian forest that is present (identified from field surveys, available literature, aerial photographs). This information may be valuable to understand successional stages or physical pressures.

NOTE: Field survey may be necessary to record plant species present.

(ii) Large Wood

Large wood is closely related to the riparian vegetation, but its presence also represents the transport of wood into and out of a reach. Therefore, it is useful to have some assessment of the wood present within the reach:

- Presence / abundance / distribution of large wood – a visual assessment of the abundance (absent, present, extensive) of (i) isolated large wood pieces in the active channel; (ii) accumulations of large wood pieces in the active channel; (iii) channel-blocking jams of wood in the active channel; (iv) accumulations of large wood in the riparian corridor.

NOTE: Field survey may be necessary to record the presence of wood effectively, because accumulations are often obscured by vegetation in aerial photographs.

(iii) Aquatic Vegetation

Where emergent aquatic / wetland vegetation is present, its extent and patchiness at baseflow during the main growing season (June to August), can be assessed from aerial imagery. However, a comprehensive survey of all aquatic vegetation is best achieved by field survey in the middle of the growing season:

- Extent: (i) absent, (ii) occasional patches; (iii) abundant stands along baseflow channel margins; (iv) abundant across > 50% baseflow channel area
- Patchiness: (i) numerous (small) patches; (ii) a moderate number of (medium / large) patches; or (iii) a few very large, quasi-continuous, stands.
- The main aquatic plant species (or morphotypes, Gurnell et al., 2010) present (requires field survey) and their relative abundance or coverage (most consistent results recorded at the height of the growing season)

NOTE: Field survey is usually necessary to record characteristics of aquatic vegetation.

5.5.5 Physical Pressures and Impacts

Characteristics are subdivided into three groups:

(i) River bed condition

'Condition' is used here to reflect the degree to which the sedimentary structure of the river bed may or may not be indicative of sediment supply-transport pressures. If such pressures are indicated by the bed structure, this often has adverse ecological implications, in relation, for example, to degradation of spawning beds or water clarity. This is particularly relevant to gravel-bed rivers, where the bed may become subject to clogging or armouring, but this can only be assessed if surface and subsurface sediments are investigated which necessitates field sampling unless information is already available (see Annex C, Deliverable 2.1 Part 2 for recommended methods). Such investigations can identify:

- Bed armouring: absent (no obvious difference between surface and subsurface bed sediment calibre), present (surface bed sediment coarser than subsurface across > 50% of the bed), severe (D_{50} surface >> 3 times D_{50} subsurface across >50% of the bed).
- Bed clogging / burial: absent (no obvious increase in sand and finer particle content between surface and subsurface bed sediment); present (higher sand and finer particle content in subsurface than surface sediment); severe (subsurface intergranular spaces completely clogged with sand and finer particles across > 50% of the bed); very severe (sand and finer sediment layer completely burying > 90% of the gravel river bed).

In all river types, the degree of anthropogenic modification of the river bed can be characterised:

- Proportion of the river bed that is artificially reinforced
- Number of high, intermediate and low impact channel blocking structures within the reach (a subset of the segment scale data)
  - high – substantial blocking structure and upstream storage area, sufficient to intercept > 90% river flow, transported sediment and wood;
  - intermediate – substantial structure completely blocking the channel but with relatively low storage giving lower impact on flow, water and wood continuity;
  - low – minor channel blocking (e.g. low check dam) structure with minor impact on water, sediment, or wood continuity.
- Estimates of sediment, wood, aquatic vegetation removal from the active channel. Records may be available for all of these activities but information can also be extracted from contemporary and historical aerial imagery to allow broad estimates to be assembled. These activities occur patchily both in time and in space. The aim should be to assess, over a decadal timescale, whether each of sediment mining, wood removal, or aquatic vegetation management have been:
  - high,
  - moderate
  - negligible.

(ii) River bank condition and processes

Some of these characteristics are not easily extracted from aerial imagery, but are usually recorded in morphological or habitat surveys.

- Proportion of bank length with 'hard'-reinforcement (concrete, stone, bricks, metal, gabions etc)
- Proportion of bank length with 'soft'-reinforcement (bioengineered banks)

- Proportion of banks with artificial levées / embankments at the bank top
- Proportion of banks with set-back levées / embankments within 0.5 channel width of bank top
- Proportion of banks with infrastructure (buildings, roads etc) within 0.5 channel width of bank top
- Total proportion of potentially erodible channel margin (i.e. proportion not subject to the five types of immobilisation listed above – thus bedrock channel margin would count as 'potentially erodible').
- Proportion of actively eroding channel margin
- Width of erodible corridor. The erodible corridor is the floodplain or, where a true floodplain is absent, the extent of erodible sediment adjacent to the river, that is not protected from erosion by flood or transport infrastructure embankments, or bank reinforcement (bedrock channels would generally have no erodible corridor). The erodible corridor width (including the channel) can be recorded as absent, narrow (< 1 bankfull width); moderate (10 bankfull widths); wide (> 10 bankfull widths).
- A count of high, medium and low impact spanning / crossing and partial blocking structures (a subset of the segment scale data):
    - high – reduction of the active river channel width by > 20%;
    - intermediate - reduction of the active river channel width by 5 - 20% channel width;
    - low – little (< 5%) or no blockage of the active river channel width.

NOTE: Field survey may be necessary to assess some of these characteristics.

(iii) Riparian corridor connectivity and condition

- Proportion of the floodplain or valley bottom accessible by flood water (the proportion that is not fully or partly protected by flood or transport infrastructure embankments) estimated by overlaying the boundaries created by these raised areas on the boundaries of the floodplain or valley bottom. In this context, extraction of the area should be guided by hydrological information (such as the extent of the 100 year flood plain, which is designated by many national agencies), topographic information (e.g. breaks of slope at the floodplain edges interpreted from a map or DEM), and the location of embankments and other structures limiting the area accessible by floodwaters.
- Proportion of the riparian corridor accessible by flood water: (the proportion that is not fully or partly protected by flood or transport infrastructure embankments) estimated by overlaying the boundaries created by these raised areas on the extent of the riparian corridor (produced at the segment scale).
- Proportion of the riparian edge (active channel margin) and corridor (for agricultural corridors, only consider the area under riparian vegetation) affected

by intense woodland management activities such as clear-felling, thinning, coppicing / severe pruning, large wood clearance:

  - High (>50% riparian edge / > 50% riparian corridor)
  - Moderate (>10% riparian edge / > 10% riparian corridor)
  - Negligible.

- Abundance of alien, invasive plant species:
  - None
  - Occasional
  - Frequent patches
  - Extensive (>25%) cover
  - List main species
- Proportion of the riparian corridor affected by impervious cover (e.g. sealing / pavement), severe soil compaction (e.g. vehicle dirt tracks), excavations / extractions, infilling (e.g. refuse tips)

NOTE: Field survey may be necessary to assess some of these characteristics.

5.6 *Channel and Floodplain Geomorphic Units*

Definition: Area containing a landform created by erosion and/or deposition inside (instream geomorphic unit) or outside (floodplain geomorphic unit) the river channel. Geomorphic units can be sedimentary units located within the channel (bed and mid-channel features), along the channel edges (marginal and bank features) or on the floodplain, and include secondary aquatic habitats within the floodplain. Some geomorphic features (biogeomorphic units) are formed in association with living and dead (e.g. large wood) vegetation as well as sediment

Aim: Identify the type and abundance of geomorphic units present and their significance in relation to reach-scale morphodynamics.

Characteristics and their quantification: Using a combination of existing surveys, aerial imagery and field surveys, list the presence and, where relevant, the abundance of geomorphic features; list and quantify those units or assemblages indicative of a trajectory of change.

5.6.1 Information from aerial imagery

Only a purpose-specific field survey can provide a comprehensive record of the geomorphic units present within the active channel and alluvial plain. However, characteristic geomorphic units can be extracted from aerial imagery and existing habitat / morphological surveys.

Table 5.7 provides descriptions of geomorphic units that can often be identified from aerial imagery. In particular, emergent units within the channel and channel margin, and floodplain features may be identifiable from aerial images. However, small or submerged units and units that are overhung (e.g. by riparian trees) may not be identifiable. Units that cannot be identified from aerial image are included in Table 5.7 using an italic font. Other data sources such as habitat surveys, morphological and fluvial audit surveys provide additional information concerning geomorphic features that are either not identifiable from aerial imagery because they are predominantly vertical structures or that may not be seen from aerial images because of over-hanging trees or other structures.

5.6.2 Information from field surveys

Where not already available, fundamental measurements during field surveys should include:

- Bankfull channel depth
- Bed material and bank material calibre (median / D_{50} size and other particle size characteristics, see section 5.5.3 and Annex C, Deliverable 2.1 Part 2)
- Bank profiles are vertical features that have to be identified in the field. Assess the proportion of the active channel margin occupied by the different natural bank profiles shown in Table 5.7.

Where available, the following information on geomorphic units should be extracted from existing field surveys or, whenever possible, acquired during field campaigns:

(i) Confirm that those units identified from remote sources are present

(ii) Check for the presence of other geomorphic units included in Table 5.7 but not recognized from remotely sensed sources, in particular emphasizing those that are more easily identified from the ground (e.g. bank features such as the types of bank profiles; bank reinforcement extent, type and materials; bed features, particularly those that are submerged at low flow; large wood and vegetation-related units)

(iii) Assess the abundance of each type of geomorphic unit using a simple scale such as: single, occasional, frequent, numerous

(iv) Assess the extent of bar, bench and island features within the bankfull channel as these are indicative of sediment retention and turnover and channel self-adjustment.

(v) Assess the extent of total bank length occupied by channel margin features indicative of bank erosion (i.e. banks where at least the lower part of the profile is vertical, vertical-undercut, or vertical with toe).

(vi) Assess the extent (of total bank length) occupied by channel margin features indicative of sediment deposition and lateral bank accretion (i.e. marginal bars and benches – differentiate between active and stabilizing features – the latter show distinct encroachment by vegetation)

(vii) Assess the extent (of total bankfull channel area) occupied by mid-channel features indicative of significant sediment retention (i.e. bars and islands, differentiate between active and stabilizing features – the latter show distinct encroachment by vegetation)

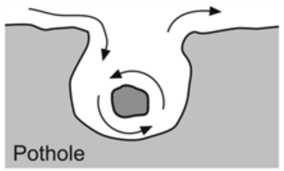
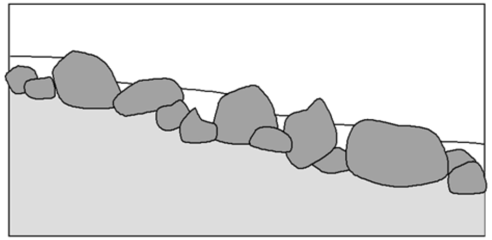
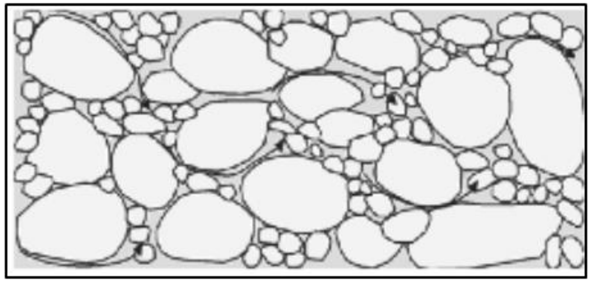
When a field survey is undertaken, features that are indicative of a trajectory of channel adjustment should be recorded, such as.

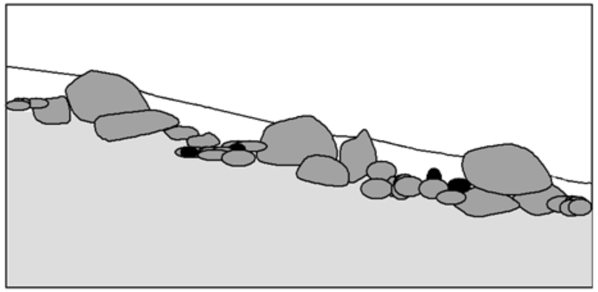
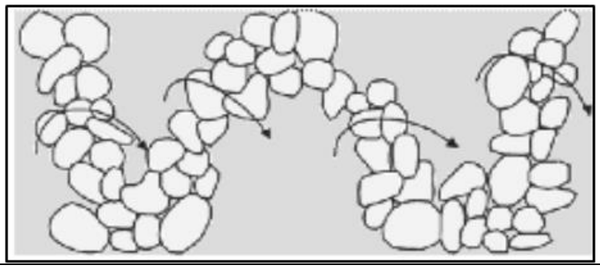
- Evidence of channel widening (e.g. bank erosion and / or undercutting occurring on both banks)
- Evidence of channel narrowing (e.g. stabilizing, vegetated bars or benches on both banks or frequent presence of wide benches)
- Evidence of bed incision
    - Narrow and deep channel cross profile
    - Bank failures on both banks
    - Bed sediments (e.g. gravel, overlain by finer true bank material) exposed in banks above current bed level
    - Trees collapsing / leaning into channel on both banks
    - Compacted, armoured bed
    - Exposed foundations of structures such as bridge piers
- Evidence of bed aggradation
    - Buried soils (often revealed in bank profiles)
    - Burial of coarser bed material by deep finer sediment
    - Widespread loose, uncompacted bars
    - Burial of structures and contracted channels relative to bridge openings
    - Partial burial of established vegetation (visible around old stems)
- Evidence of extremely stable (static / moribund) channels
    - Well vegetated banks and bars
    - Mature trees on both banks
    - Active bank erosion negligible

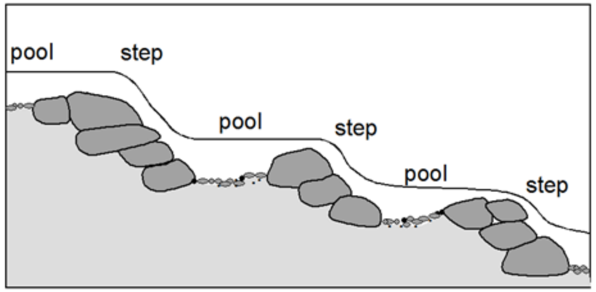
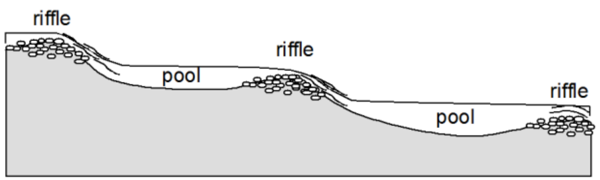
Table 5.7 Geomorphic units: A. features within the bankfull channel; B. marginal and bank features; C. floodplain features.

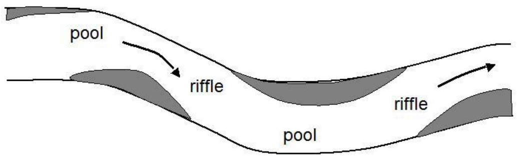
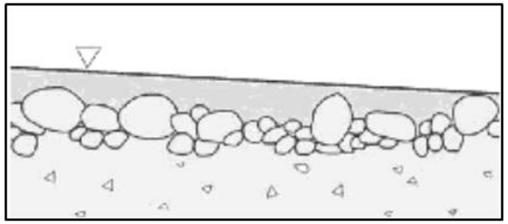
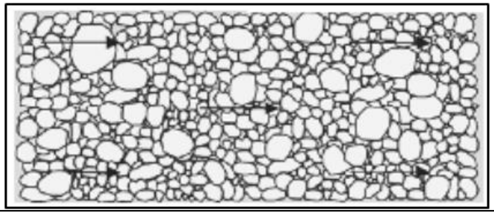
Note: Many of the units listed in this table, particularly emergent units within the channel, channel margin and floodplain features may be identifiable from aerial images. However, small or submerged units and units that are overhung (e.g. by riparian trees) may not be identifiable. Units that definitely cannot be identified from aerial image are described in italics

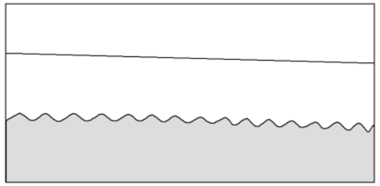
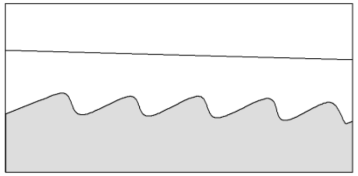
A1. Geomorphic Units within the Bankfull Channel: The River Bed:

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Pothole		Features found in bedrock channels and often associated with weaknesses or structural changes in the rock of the cannel bed. Deep, circular holes, scoured in bedrock where flow energy is concentrated, as a result of abrasion by transported particles trapped in the hole.	pothole (profile) 	Brierley and Fryirs (2005); Fryirs and Brierley (2013).
Cascade		Composed of disorganised boulders covering the channel bed, exposed through the water surface and surrounded by mainly supercritical flow with (> 50% channel area). Some small, shallow pool areas may occur but they contain highly turbulent flow and do not span the channel width. Cascades are typical of very steep (slope often > 7%) and confined channels, that are adjacent to a supply of coarse sediment (e.g. steep hillslopes covered with coarse sediment, including debris flows, moraines etc).	cascade (profile)  cascade (plan) 	Grant et al.,1990; Halwas and Church, 2002

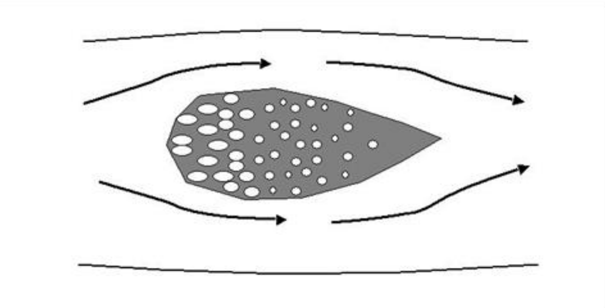
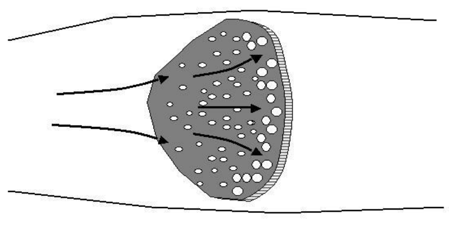
Geomorphic Unit	Sub-type	Description	Diagram	Reference
Rapids		Rapids occur in steep confined channels, but gradients are lower than for cascades (typically > 4 %) and they show a lower extent of supercritical flow (15 - 50% channel area) than cascades. The boulder bed is often organised into irregular lines (ribs) oriented approximately perpendicular to the channel and partially or completely crossing the channel width. The ribs are only exposed at low flows, being fully submerged during bankfull flows. Some small, shallow pool areas may ocur but they are poorly developed	rapid (profile)  rapid (plan) 	Grant et al.,1990; Halwas and Church, 2002.

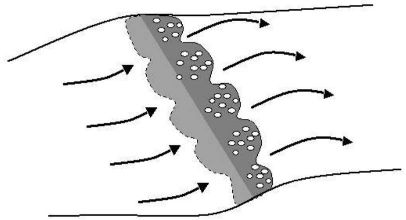
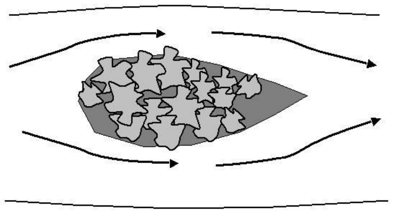
Geomorphic Unit	Sub-type	Description	Diagram	Reference
Step (-pool)		A steep accumulation of boulders and cobbles transverse to and crossing the channel, generally with a pool downstream that is scoured by the plunging (waterfall) flow over the step. Steps and pools are common bed forms in boulder-cobble bed mountain stream channels where gradients exceed approximately 2%.	step-pool (profile) 	Chin, 2003; Halwas and Church, 2002; Church, 1992.
Riffle		Zone of relatively shallow, rapid flow in comparison with pools (see below) with which riffles frequently alternate. These mainly submerged features are distinguished by local disturbance of the water surface, which is generally subcritical but near critical. They also generally occur where the channel is dominated by a sequence of alternating bars with intervening crossovers on the riffles. Riffles are common bedforms in gravel bed streams whose local gradient is less that approximately 2%.	riffle-pool (profile) 	Richards, 1976; Bridge, 2003; Church, 1992; Grant et al., 1990; Wood-Smith & Buffington, 1996.

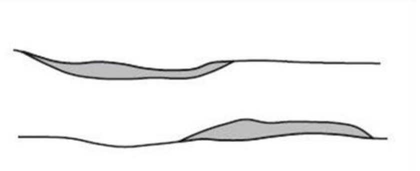
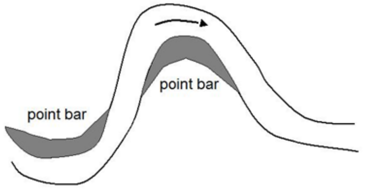
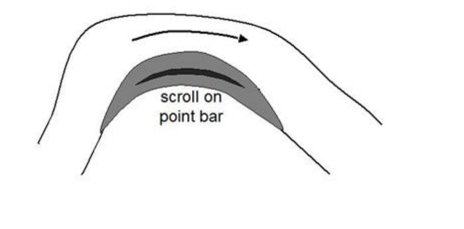
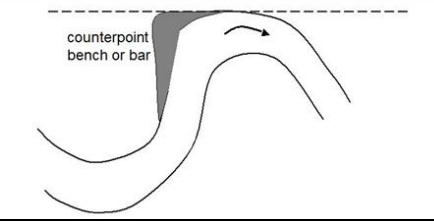
Geomorphic Unit	Sub-type	Description	Diagram	Reference
Pool		Closed (obstructed/unobstructed) topographic depression in the river bed, which may completely span the channel, providing deep areas of water and tranquil flows along an undulating longitudinal bed profile. Free-formed (unobstructed) pools reflect interactions between flowing water and sediment and occur at quasi-regular intervals, often alternating with steps or riffles, along gravel bed rivers.	riffle-pool (plan) 	Bridge, 2003; Church, 1992; Grant et al., 1990; Richards, 1976; Wood-Smith & Buffington, 1996.
Run / glide		Runs and glides are areas of relatively shallow flow, with runs showing more rapid flow on relatively steeper gradients than glides. They may alternate in some channels, replacing riffles and pools, since they are intermediate features between pools (which are deeper and support slower flow velocities and smoother flows) and riffles (which are shallower features and support faster and more turbulent flow). Glides are not usually distinguished from runs in strictly morphological classifications, but they represent significant habitat units.	Run/glide (profile)  Run/glide (plan) 	Bisson et al., 1982; Church, 1992; Grant, 1990; Sullivan, 1986

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Ripple		Small fine sediment (sand-silt) features (maximum of a few cm in height), linear in plan, aligned perpendicular to flow, with triangular cross section comprising gentle upstream and steep downtream slope.	Ripples (profile). 	Bridge, 2003; Knighton, 1998; Simons and Richardson, 1966.
Dune		Large fine sediment (sand-silt) features (can be several m in height in large rivers) that are similar in shape and often in alignment to ripples; upstream slope may be rippled	Dunes (profile). 	Bridge, 2003; Knighton, 1998; Simons and Richardson, 1966.

A2 Geomorphic Units within the Bankfull Channel: Depositional Emergent Sediment Features:

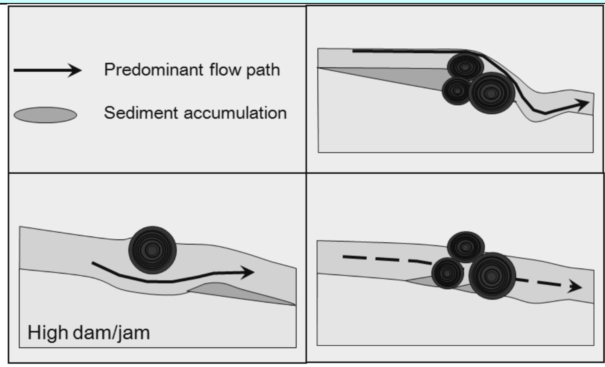
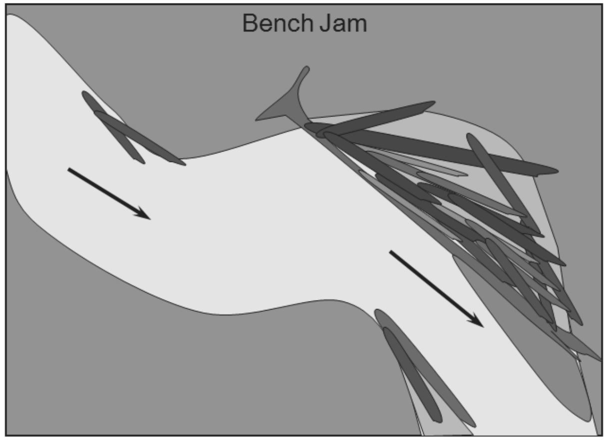
Geomorphic Unit	Sub-type	Description	Diagram	Reference
Mid Channel Bar		Depositional bed feature located in the central part of the river channel, whose surface is exposed for most of the time but is submerged at bankfull flow.		
	Longitudinal bar	Mid-channel, elongate, lozenge-shaped or lobate bar found in gravel and mixed bed channels; bar sediments typically fine downstream away from coarser bar head; common in active meandering and braided rivers.	Longitudinal bar (plan) 	Ashmore, 1991; Brierley and Fryirs, 2005; Church and Jones, 1982.
	Transverse bar	Mid-channel bar found in gravel and mixed bed channels oriented perpendicular to flow with a smooth to sinuous or lobate front that is marked by an avalanche face. Sometimes show an arc-shaped planform.	Transverse bar (plan) 	Brierley and Fryirs, 2005; Church and Jones, 1982.

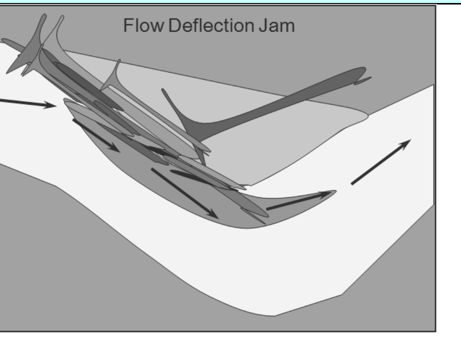
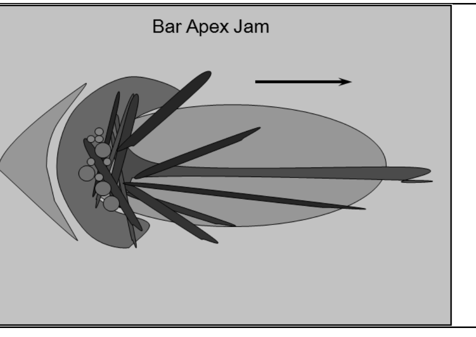
Geomorphic Unit	Sub-type	Description	Diagram	Reference
	Diagonal bar	Mid channel bar that is attached to the banks and runs obliquely across gravel and mixed bed channels. Diagonal bars are often associated with riffles, with a series of diamond shaped units exposed above the water surface..	Diagonal bar (plan) 	Brierley and Fryirs, 2005; Church and Jones, 1982.
	Medial bar	Larger, more complex mid-channel bar in mixed and gravel bed rivers, made up of a mosaic of erosional and depositional forms comprising an array of smaller-scale geomorphic units. Variable morphology depends on sediment texture, flow energy and flood history responsible for formation and subsequent re-working; includes chute channels, ramps, dissection features, and sometimes lobes and ridges.	Complex medial bar (plan) 	Brierley and Fryirs, 2005; Church and Jones, 1982.
Island		Landform within channel that is emergent at bankfull stage and is surrounded by areas of the channel bed. Supports mature vegetation, usually shrubs or trees, with the landform surface aggraded to floodplain / bankfull level.	Established island (plan) 	Gurnell et al., 2001; Osterkamp , 1998.

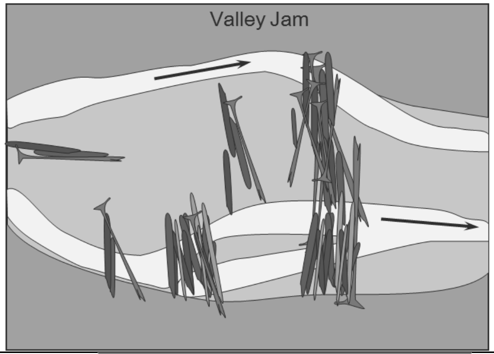
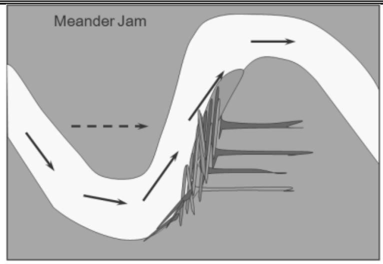
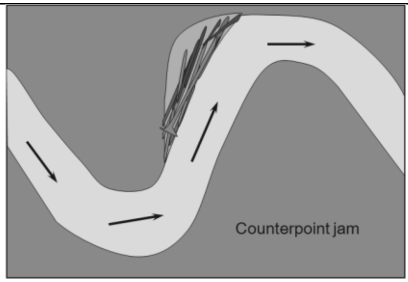
Geomorphic Unit	Sub-type	Description	Diagram	Reference
Marginal Bar		Depositional bed feature attached to the margins of the river channel, whose surface is exposed for most of the time but is submerged at bankfull flow.		
	Lateral bar	Bank attached bar, often distributed periodically along one and then the other side of channel to form alternate bars. Bar surface slopes towards the channel. Sediment particle size becomes finer in a downstream direction along the bar and also away from the channel towards the banks.		Church and Jones, 1982; Knighton, 1998
	Point bar	Bank attached arc-shaped bar developed along convex banks of river bends with bar surface towards channel and typically devoid of vegetation. Sediment particle size becomes finer in a downstream direction along the bar and also away from the channel towards the banks. Point bars are characteristic of actively meandering streams and tend to extend into the channel and downstream, keeping roughly parallel with the eroding bankline.		Church and Jones, 1982; Bridge, 2003
	Scroll bar	Elongated ridge-like bar formed along convex banks of meander bends, commonly on point bars. Caused by deposition in the shear zone between the helical flow cell in the thalweg zone and flow in a separation zone adjacent to the convex bank of a bend. These features are often cored by trees deposited on point bars during floods and may develop into shrub- and tree-covered ridges following a similar mechanism to pioneer islands (see below).		Nanson, 1980, 1981; Bridge, 2003; Brierley and Fryirs, 2005
	Counter-point bar	Bar that develops in the separation zone formed against the upstream limb of the convex bank of tightly curving bends. The tight bends are often created when the river is constrained by the valley wall or a major terrace. Material deposited in the slackwater area of the bend, often contains a high proportion of organic material and silty sediment, making a notable contrast to the much coarser point-bar sediments they adjoin.		Hickin, 1984; Lewin, 1983; Page and Nanson, 1982; Thorne and Lewin, 1979

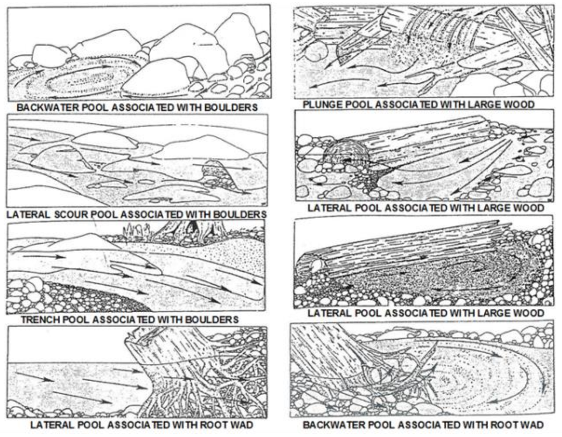
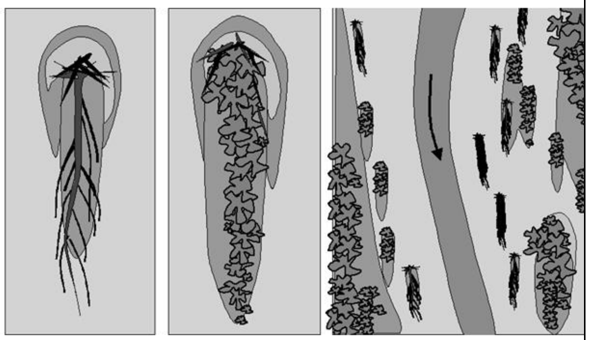
A3. Geomorphic Units within the Bankfull Channel: Large Wood and Vegetation Features

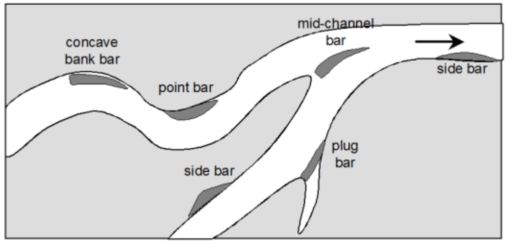
Geomorphic features formed in association with deposition of large wood or vegetation colonisation in various locations within and around the river channel. Many of these features are similar to bed and marginal features created by sediment deposition, but large wood and vegetation act to protect and accelerate feature development and to induce/'force' the development of related erosional and depositional features (e.g. forced pools, bars etc.)

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Wood dam/jam	Simple (*active,complete, high*)	A feature of relatively small channels, where a tree(s) or large wood piece(s) spans a channel such that water flows over the top (termed a log step by Abbe and Montgomery, 2003). *(Sub-types (Gregory et al., 1985, 1993) include 'active' (completely crossing channel and causing a step in water surface level at all flow stages); 'complete' (as for active but does not cause a step in water surface level at low flow stage); 'high' (water flows beneath the wood at low flow stage but wood interacts with flow at higher flow stages)).*		Abbe and Montgomery, 2003, Gregory et al., 1985, 1993
	Bench jam	Found in relatively steep channels where oblique key wood pieces are wedged into irregularities or obstructions in channel margins, funnelling flow and creating a barrier behind which fine sediments and wood accumulate to form benches that gradually aggrade as the wood accumulates. This is a special case of bench formation.		Abbe and Montgomery, 2003

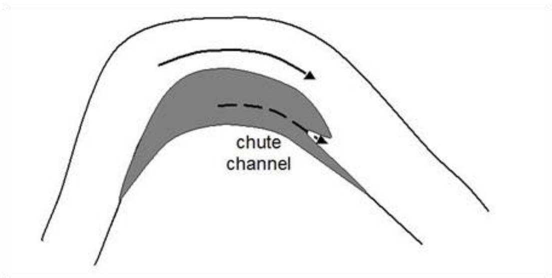
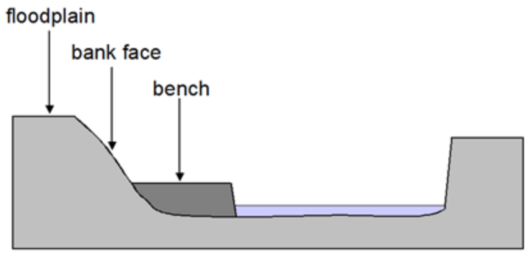
Geomorphic Unit	Sub-type	Description	Diagram	Reference
	Flow deflection jam	Found in relatively lower gradient channels than bench jams, where local fallen trees deflect flow, leading to channel widening, pool development and the accumulation of fine sediment and wood in a bar or bench-like feature behind the wood barrier that eventually becomes incorporated into the floodplain		Abbe and Montgomery, 2003
	Bar apex jam	Typically located at the upstream end and on the top of mid-channel bars and islands on multi-thread braided and transitional wandering channels. Can also be found towards the upstream end of well-developed point bars on meandering rivers. These features are formed around large wood pieces that retain fine sediment and often induce scour holes or pools at their upstream end. They can initiate or accelerate bar and island formation.		Abbe and Montgomery, 2003

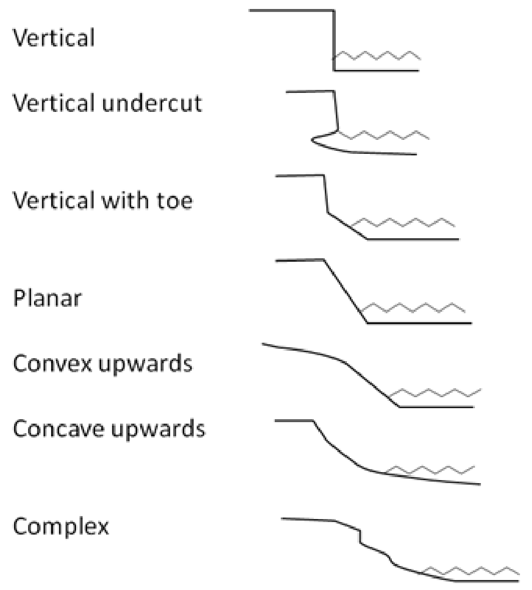
Geomorphic Unit	Sub-type	Description	Diagram	Reference
	Valley jam	A very large wood jam with a width greater than both the bankfull channel width and the largest pieces of wood. These large features consist of a sizeable accumulation of fallen trees and other wood pieces and often extend across a significant portion of the valley bottom, constricting the channel cross-section		Abbe and Montgomery, 2003
	Meander jam	Found on the outer margins of bends of large meandering channels where whole trees and large wood pieces transported from upstream jam against the downstream bank of river bends, protecting the bank from erosion and so affecting channel curvature		Abbe and Montgomery, 2003
	Counterpoint jam	Found on the outer margins of bends of large meandering channels where whole trees and large wood pieces transported from upstream jam accumulate within a dead zone within the upstream bank of river bends. The counterpoint deposits associated with these jams are composed of fine sediment with much organic material including small wood pieces		Gurnell,pers. obs; Page and Nanson, 1982

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Forced pools, bars, riffles		A common feature of relatively small rivers and streams, where growing or fallen trees, large wood and other roughness elements (e.g. boulders, bed rock outcrops) can induce significant ponding of water, bed or bank scour, and erosion and deposition of sediment, and as a result force the development of pools, bars and riffles.	forced pool types (from Bisson et al., 1982) 	Bisson et al., 1982; Montgomery et al., 1995
Pioneer island		Pioneer islands develop around flood-deposited trees on bar surfaces and are a later stage of development of a bar apex jam. The deposited tree may die and form an obstruction around which finer sediment accumulates and acts as a seed bed for tree seedlings. Alternatively, the deposited tree may sprout, anchoring itself to the bar surface by root development and accelerating the process of fine sediment and seed deposition. In either case a characteristic small linear island feature develops, which through sediment retention, vegetation development and coalescence with nearby pioneer islands, leads to the development of larger islands and extensions to the floodplain.	plan view of pioneer islands (left and centre) in association with established islands (right) 	Gurnell et al., 2001, 2005

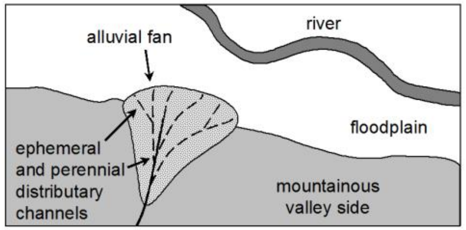
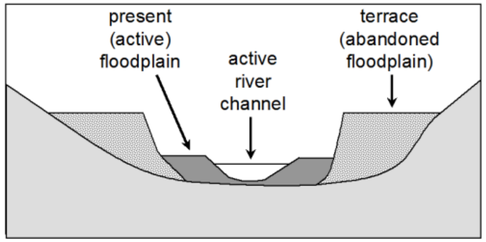
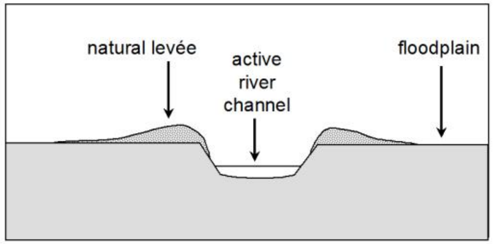
Geomorphic Unit	Sub-type	Description	Diagram	Reference
Vegetation-induced bars, benches, islands		Found in relatively low energy, low gradient rivers, where emergent aquatic plants trap and stabilise fine sediments to produce root-reinforced bars and related features. Sediment trapped and stabilised by plants forms bars that gradually emerge from the river bed and build laterally and vertically to the water surface, at which point wetland species colonise them, and the vegetation sediment trapping and stabilising process continues. Such bars often form along the margins of the low flow channel, where they can aggrade to form submerged bars and shelves; emergent bars and benches; and eventually extensions of the river bank and floodplain. Alternatively, sediment may be retained by plants in the centre of channels, leading to the development of mid-channel vegetated bar or island features. In very low energy systems, plants and retained sediment may completely block or plug the river channel. All of these features are components of river morphodynamics induced by aquatic and wetland plants.	plan view of some vegetated bar types (after Gradzinski et al., 2003) 	Gradzinski et al., 2003

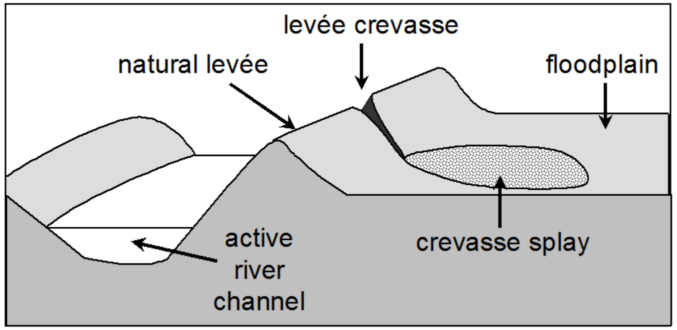
B. Marginal and Bank Features: Geomorphic features formed at the interface between the bankfull channel and the floodplain

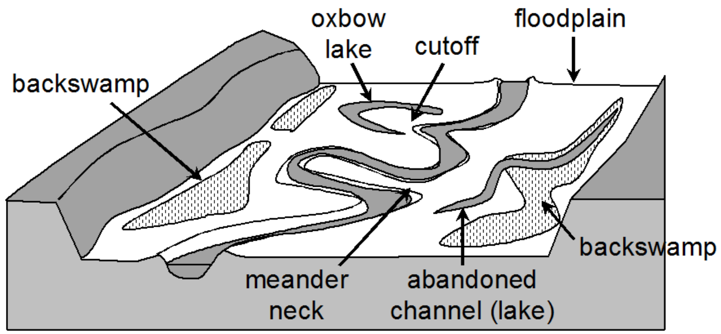
Geom-orphic Unit	Sub-type	Description	Diagram	Reference
	Chute channel	Chute channels are formed where flow across a bar or floodplain surface leads to scour and incision of a channel. In the diagram, a chute channel is illustrated on a point bar but they also form across large medial bars, across the floodplain at the neck of meander bends, and elsewhere on floodplains where flood waters become concentrated as they drain back into the main channel.	- 	Bridge, 2003; Church and Jones, 1982; Grenfell et al., 2012
Berm / bench		A distinct, step-like, sediment storage unit located against the bank face with a relatively flat upper surface and steep edge sloping into the active channel. These features develop as bars, aggrade, become vegetated, and develop a steep edge due to lateral erosion and trimming by river flows. They may occur along one or both banks, are usually fully vegetated and discontinuous and are sometimes found in association with (and located at a higher elevation than) point, counterpoint or lateral bar deposits. They can be described as point, counterpoint or lateral benches according to their position with respect to the channel planform		Gurnell et al., 2012; Veitz et al., 2011; Brierley and Fryirs, 2005; Smith et al., 2009 Shi Changxing et al., 1999.

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Bank	Bank profile types vary widely but can be divided into subtypes according to their steepness and the degree to which they display one or more profile elements (see diagram)	Large, vertical feature at the junction between river channel and floodplain. The morphology of a river bank varies as a result of its sediment erosion and deposition history and may include or grade into specific marginal depositional (e.g. bar and bench features and toe deposits) or erosional (e.g. undercut) features. Vertical profiles are associated with significant bank erosion. Vertical and vertical with toe illustrate situations where the material eroded from the banks is being transported away by the river, with undercut banks showing a susceptibility to sudden faillure once the undercutting becomes sufficiently deep. Vertical with toe suggests that some eroded material is accumulating at the bank toe rather than being completely transported away by the river.		
	Toe deposit	Loose material or solid blocks (sometimes vegetated) at base of bank as a result of failure of the upper bank.		
	Undercut	River bank where vertical profile is characterised by a notch at their base and overhanging material above. Commonly associated with upward fining river banks and/or with root reinforcement of the upper bank profile		

C. Floodplain units: These units are found outside of the bankfull channel.

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Alluvial fan		Fan-shaped landform associated with piedmont locations, formed by ephemeral or perennial streams emerging from steeply dissected terrain onto a lowland; sediments rapidly decrease in grain-size with distance from the fan apex; several fans may coalesce to form an alluvial plain (bajada)		Knighton, 1998.
Terrace		A relatively flat (planar) valley marginal feature perched above the contemporary channel and/or floodplain. It is an abandoned inactive floodplain separated from the contemporary floodplain by a steep slope called a terrace riser. Remnants of former floodplains become abandoned to form terraces when the river incises into its floodplain, leaving the remnants at a height that is rarely inundated. Several terraces may occur together (following a series of floodplain incisions) to form a flight of terraces. Terraces often confine the contemporary channel and its floodplain.		Knighton, 1998.
Levée	Natural levée on floodplain rivers	Raised elongated asymmetrical ridge bordering the river channel composed of river-deposited sediment. Sediment-size reflects river energy.		Knighton, 1998.
	Boulder levée	Found in association with steep headwater channels (frequently found on steep alluvial fans), these levée features are composed of poorly sorted boulders and cobbles and are associated with debris flows.		

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Levée crevasse		Natural break eroded in a levée that allows water and sediment to spill onto the floodplain. Leads to the formation of splays.		Brierley and Fryirs, 2005
Crevasse splay		Local accumulation of sand and/or gravel, formed when water escapes from channels onto adjacent floodplains through breaks (crevasses) in natural levees.		Brierley and Fryirs, 2005
Ridges and swales		Ridge features represent old scroll bars that have been incorporated into the floodplain as the channel migrates. Swales are the intervening low areas between the ridges, which may retain water and support wetland vegetation. These arcuate forms have differing orientations and radii of curvature reflecting the pathway of lateral accretion across the floodplain and whether they have developed from point or counterpoint scroll bars or benches		Brierley and Fryirs, 2005; Nanson and Croke, 1992.

Geomorphic Unit	Sub-type	Description	Diagram	Reference
Abandoned channel (lake, wetland)		Channel crossing a floodplain or other riparian landforms that has originated as a result of a shift in the main channel position (avulsion) or as a result of a channel cut-off. Abandoned channels can be reactivated during high flows. They may be fully or partially filled with water or sediment and may support wetland vegetation. They extend over more than one meander wavelength thereby differentiating them from oxbow lakes.		
Oxbow (lake, wetland)		A meander bend that has been cut off at the neck leaving a single abandoned meander loop on the floodplain. These lakes are generally horseshoe or semi-circular in planview.They may contain standing water or be infilled with fine grained materials and wetland plants.		Nanson and Croke, 1992 Constantine and Dunne, 2009
Backswamp		These major wetland features occur on floodplains towards the valley margins, away from the main channel, and in the lowest areas of the valley floor. They are a major store for fine-grained suspended-load sediments.They have a flat morphology that includes depressions with ponds, wetlands and swamps. They often form where tributary streams drain directly onto the floodplain.		Nanson and Croke, 1992

6. Characterising Temporal Change in Spatial Units

Rivers change over time. This is an inherent property of natural rivers and floodplains, and is driven by forces operating within the channel (i.e. intrinsic) and as a result of changes in the wider catchment (i.e. extrinsic). Of course truly natural rivers and floodplains are extremely rare within Europe, since even those that are apparently naturally-functioning will inevitably have been influenced by climate change that may have induced, for example, changes in the natural vegetation cover (and thus the processes of runoff and sediment production / delivery to the river network) which would cascade through the river network as a changed flow and sediment regime. Therefore, this chapter illustrates how a temporal analysis at different spatial scales can track changes and their implications for hydromorphology. By recognising that rivers are dynamic over time and characterising these temporal changes, significant insights are gained into contemporary channel condition and behaviour.

An analysis of temporal change supports integrated catchment management and river restoration by providing the following information:

- Previous condition of the catchment, floodplain and channel. For example, information on the channel planform in the past and whether it has changed over time.
- Rates of change in channel and floodplain characteristics. For example, information on how dynamic the system is; whether the channel migrates laterally across the floodplain; and if so, how quickly it migrates, and whether this rate has changed over time.
- Identification of human pressures and how they have changed over time. For example, whether land cover or use has changed; and if so, when these changes occured, and whether they have intensified, diminished or changed in spatial extent.
- Channel response to past natural disturbances and human pressure. This type of information helps to appraise the current condition of the river and floodplain, the responsiveness of the river to external forcing, and where it sits in relation to thresholds for change in river patterns.
- Evolutionary trajectories. By analysing the previous channel conditions, how the river has changed over time, and its links to external pressures, it is possible to have a better understanding of its past evolutionary trajectory and to start to predict likely future river channel and floodplain changes under a range of management scenarios.

The purpose of this chapter is to summarise the techniques used to investigate change in hydromorphology over time. The chapter is structured around the spatial scales of the hierarchical framework (Chapter 3), and the characteristics that are investigated at each scale are based on the previous spatial characterisation (Chapter 5; Table 6.1). Similar to earlier chapters, chapter 6 starts at the largest spatial scale and works down to the finer scales. Because of the overlap in characteristics at the catchment and landscape scale, these are presented together. Characteristics that are derived from similar sources or related to similar processes are also grouped together within a spatial unit. Consequently, pressures are presented within the characteristics that they impact, e.g. set-back levées and valley setting. The finest scale considered is the reach scale. This is because of the difficulty in extracting geomorphic unit scale information from historical sources. For recent (decadal) changes, geomorphic units can be interpreted from aerial imagery and field observation using the techniques already described in section 5.6 but for longer term changes they need to be inferred from reach scale dynamics, and so they are referred to in discussion at the reach scale (section 6.4), particularly in relation to river planform dynamics.

In this chapter, recommendations are provided on the approaches to use for each characteristic, the range of data that can be collected using those approaches, suitable analytical techniques, and a general discussion of the impacts of data reliability on the interpretation of temporal change. For example applications of temporal characterisation, see the volume of Annexes to this report describing Catchment Case study Applications. The River Frome case study, in particular, provides full details of how every stage was undertaken, including some guidance on which ArcGIS functions to use.

Table 6.1 Temporal change is investigated for hydromorphological characteristics at different spatial scales.

Spatial Scale	Characteristics	Key Process
Catchment & Landscape unit	Land cover / use	Water yield and production Coarse sediment production Fine sediment production
	Land topography (Tectonic / Seismic activity, Mass movements)	Coarse sediment production Fine sediment production
	Rainfall and groundwater	Water yield and production
Segment	River flows and levels	Water flow
	Sediment delivery	Sediment flow
	Sediment transport	Sediment flow
	Valley setting	River morphological adjustments
	Channel gradient	Channel change
	Riparian corridor and wood	River morphological adjustments Vegetation succession Wood delivery
Reach	Channel planform, migration and features	Channel self-maintenance Channel change
	Channel geometry	Channel change
	Bed sediment calibre	Channel change

6.1 Approaches, Data Sources and Timescales of Analysis

A diverse array of techniques can be applied to investigate temporal changes in hydromorphological forms and processes from the catchment down to the reach scale. These techniques can be broadly categorised according to the disciplines within which they have been developed, the data sources they utilise, and the temporal scale at which they can be applied. For the present review, techniques are divided into 4 major approaches: field survey, remote sensing, historical, and palaeo approaches.

This section provides an introduction to the data sources included in each approach; the temporal scale over which the approach is relevant (Figure 6.1); its strength and weakness for interpretation of temporal changes (Table 6.2); and general issues of accuracy, error and uncertainty. The choice of approach for an analysis of temporal change is dependent on the data sources that are available for an area, the history of pressures in the catchment, and the responsiveness of the river to pressures. A river situated in a region with a long history of human modifications may require a longer timescale of analysis if causal linkages are to be identified. Likewise, a river that responds slowly to external forces (e.g. a lowland, low-energy river with cohesive banks) may require a longer timescale of analysis to fully capture the trajectory of change that is occurring.

Accuracy, error and uncertainty are discussed in detail in Section 6.5, however it is imperative to have a general understanding of these issues at the outset so that they can be considered during data collection and analysis. Accuracy, error and uncertainty all relate to the reliability of the data. For example, when using maps for analysis of temporal change, it is important to know if a river drawn on a historical map accurately reflects its true size and position at the time of the survey. This question is actually composed of many more specific questions related to accuracy, error and uncertainty. What was the accuracy of the original survey method? Were there any errors implicit in the survey, for example caused by the type of surveying equipment used? How certain was the definition and identification of the bankline? What is the positional accuracy of the cartographic representation? How does the date on the map compare with the date when the river was actually surveyed? At this point, though, it is sufficient to simply acknowledge that issues of accuracy and uncertainty exist for all data sources, that levels of accuracy and uncertainty vary considerable within and between data sources (e.g. historical vs. modern maps), and that when data sources are compared to identify change over time, errors / uncertainties are additive.

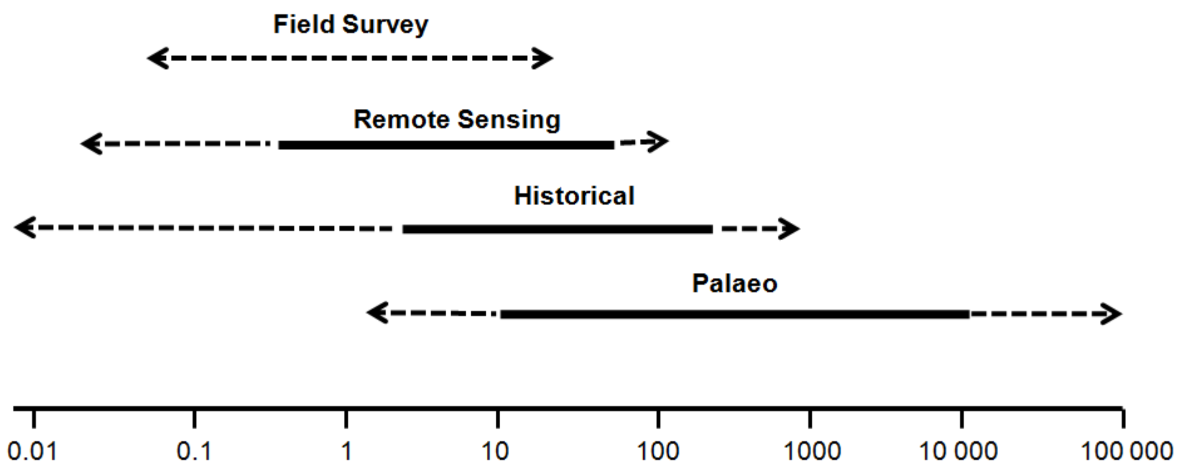


Figure 6.1 Temporal scales over which different approaches may yield useful information (solid lines are the core temporal scales, dashed lines illustrate the potential range of temporal scales)

6.1.1 Field survey (timescale: not/applicable)

At the most basic level, hydromorphological change can be assessed using a geomorphological field survey. In this approach, contemporary channel and floodplain features are interpreted in the context of the channel type by a trained geomorphologist to identify changes that are ongoing or have occurred at some point in the past. For example, recent terraces, perched tributaries, exposed pipelines and undercut bridge piers can indicate channel bed incision, whilst bank undercutting and early-seral vegetation growth in meander bends can indicate lateral migration (see section 5.6.2 for additional characteristics). This approach has been advanced in numerous survey methodologies, one of which is the River Reconnaissance Survey (Thorne, 1998). See Rinaldi (2008) for a related approach with example field survey sheets in Italian.

Table 6.2 Strengths and weaknesses of the four approaches to the analysis of temporal change in hydromorphology.

1.	Strengths	Weaknesses
Field survey	• Quick and relatively inexpensive to conduct • Only means to acquire reach scale information if historical records or high resolution remote sensing data is unavailable	• Can only indicate possible change • Cannot estimate rates of change • Requires an experienced geomorphologist • Only applicable at the reach scale
Remote sensing	• Large variety of data types that are suitable for estimating most characteristics • Good balance between spatial resolution and temporal coverage • Aerial photography archives cover a long time scale • Satellite data has high temporal frequency	• Shorter timescale of analysis • Airborne data is expensive to collect • Most freely-available multispectral data has a low spatial resolution • High resolution multispectral data is expensive to purchase • Data processing and interpretation requires specialist knowledge
Historical	• Historical maps can extend the timescale of analysis to centuries, and be used to study many characteristics • Topographic surveys are often the only data sources for bed level changes (the temporal development of gauged rating curves is sometimes available) • Documentary evidence can corroborate evidence from other data sources	• Scale and original purpose of a map limits its application • Availability and reliability of sources is highly variable, and generally decreases as analysis is extended further back in time
Palaeo	• Insight into the underlying processes • Provides accurate dating	• Requires specialist knowledge • Dating using OSL and radiocarbon is expensive

The field assessment approach offers very limited temporal resolution and is applicable primarily at the reach scale. It provides an indication of channel change that has happened in the past or processes that are currently operating. Exposed bridge pier foundations or buried pipelines suggest channel bed incision, but without any supporting information, all we can determine is that the channel has incised at some point in time post construction. Amounts or rates of change can only be estimated if additional historical documentation exists, e.g. bridge surveys, which would then shift the analysis to the historical approach described below. On the other hand, it should be recognized that for many streams some types of data may be not available, in particular historical bed-levels, and thus geomorphological survey can be crucial to gaining information on past changes.

Geomorphological field surveys can generate accurate assessments of the type and magnitude of change that has occurred in a reach over time. This is particularly true if the geomorphologist conducting the survey is familiar with the setting and river type (chapter 7), and can make comparisons with similar rivers in the area that have better historical records. Without any other supporting information, though, the uncertainty in the assessment can be high, particularly when rivers have gone through several types of changes in succession, thereby masking or removing the evidence of the earlier changes.

6.1.2 Remote sensing (timescale: decades)

Remote sensing approaches use instruments that are not in contact with the ground or water to measure their characteristics (e.g. elevation, spectral signature, etc). They may employ passive sensors that detect the electromagnetic radiation emanating from an object (e.g. photography) or active sensors that emit a signal and measure the properties of the signal after it has reflected off the object (e.g. radar). The sensors may be mounted on satellites, aircraft or at points on the Earth's surface. Data types that are collected using remote sensing approaches include aerial photographs, multispectral, radar and laser-derived information. Other types of sensors, such as bathymetric sonar, can also be considered remote sensing approaches, but these fall outside the focus of this review. For an overview of remote sensing and its use in fluvial geomorphology, see Jensen (2000), Gilvear et al. (2003) and Carbonneau and Piégay (2012).

Remotely-sensed data can be used at all of the spatial scales and to assess temporal changes in most hydromorphological characteristics. Its application is dependent generally on the resolution of the data and the size of the features being identified or the magnitude of change being detected. For example, high-altitude aerial photography and most freely-available satellite data (e.g. Landsat, ASTER) have high spatial coverage and low spatial resolution making them best suited for the identification and monitoring of catchment, landscape unit and segment scale characteristics. These data sources can also be used for exploring some reach characteristics on medium to large rivers (e.g. channel position and width for rivers greater than *ca.* 100 m in width). Conversely, low-altitude aerial surveys (e.g. photography, multi- and hyperspectral), high resolution satellite imagery (sub-metre), and laser-based techniques (airborne LiDAR and terrestrial laser scanning) have lower spatial coverage but higher spatial resolution making them better suited to segment and reach scale characterisation. Another distinction should be drawn between sources that obtain plan (2D) information (e.g. aerial photographs, multi – and hyperspectral data) that may also be interpreted to estimate heights, and those that directly produce altimetry data (e.g. LiDAR, TLS, radar).

The timescale over which remote sensing can be used to investigate changes in hydromorphological characteristics is highly variable, as is the frequency of measurements that are collected. For example, airborne surveys are relatively expensive to commission, thereby limiting the frequency with which they are conducted, but these surveys often have sufficient temporal resolution to observe broad decadal to annual changes in river geomorphology. Furthermore, aerial photograph archives often date back to the mid 20th century and so predate other types of remotely sensed information. In contrast, satellite datasets offer amazing opportunities to observe changes over very short timescales: annually, seasonally or even weekly, and thus immediately before and after specific events (e.g. floods, earthquakes, etc.). For example, since the launch of NASA's Landsat 4 satellite in 1982, Landsat Thematic Mapper data has been collecting data across the Earth's surface every 16 days, providing multispectral information with a spatial resolution of 30 to 120 m. Landsat imagery is freely available from the USGS[1] within 24 hours of acquisition.

Remotely-sensed data products obtained from national governments or commercial sources will typically have well-defined accuracies that are detailed in accompanying manuals and technical documents. When not specified, accuracy / uncertainty can be estimated using standard techniques, such as photogrammetric and GIS-based approaches in the case of aerial photographs.

6.1.3 Historical (timescale: centuries)

Historical approaches examine the human record and enable changes in hydromorphological processes and forms to be estimated or quantified. These techniques rely on documentary evidence (diaries, deeds, etc.); land and tax surveys (i.e. cadastral surveys and maps); historical maps; river topographic surveys (e.g. repeated longitudinal profiles and cross sections of river channels) and terrestrial photography. For an introduction to the use of historical data in fluvial geomorphology, see Gurnell et al. (2003) and Trimble (2012)

The historical approach is applicable to all spatial scales. Due to the diversity of data sources included in this category, it is applicable to a wide range of timescales. In reality, though, the use of historical evidence is severely limited by the availability of data sources for a particular location or time period, the type of data that is available (e.g. observations or scientific measurements), and its reliability or accuracy.

Historical sources should be carefully screened before inclusion in a study of temporal change (Hooke and Kain, 1982). First an internal check of the data source should be conducted to ascertain the purpose of the source, when information was observed and subsequently published, whether it was an original survey or revision, who the observer or reporter was, what methods or instruments were used, and, for surveys and scientific data, what were the reported levels of accuracy. Second, additional sources should be used to corroborate the primary source, verifying its spatial accuracy (e.g. specific features were in the correct geographical location), attribute accuracy (e.g. features were identified correctly) and its temporal accuracy (e.g. information is correct for the reported date). As with remotely-sensed data, it is very important that accuracy be assessed so that genuine spatial and temporal changes can be differentiated from those that are

[1] Landsat imagery, United States Geological Survey (USGS). Earth Explorer, http://earthexplorer.usgs.gov

artefacts of the data collection, interpretation, representation, storage or digitisation. For more information, see Section 6.3.

Some historical sources, like discharge records, offer precise scientifically-derived datasets with daily or even instantaneous measurements, but most historical sources provide widely-spaced or individual snapshots of hydromorphological characteristics. For example, large-scale maps provide researchers with a variety of valuable information (e.g. channel dimensions, planform, land cover, floodplain and channel geomorphological units), but mapped features are subject to surveyor interpretation and modification for cartographic purposes, and revisions may be spaced decades apart, especially in remote or rural areas. Topographic surveys can be very valuable sources of information, but they are commonly available for only the largest streams or for streams crossing populated areas. Documentary evidence is even more limited in its utility for interpreting historical changes since it often describes only a single point in time or space, and its accuracy / precision is rarely defined. Therefore, this type of evidence must be evaluated carefully before it can be used in a robust way in hydromorphological interpretations.

6.1.4 Palaeo (timescale: millennia)

Palaeo approaches examine the geological and archaeological record to establish past hydromorphological forms and processes. These techniques are based on sedimentology, stratigraphy and geoarchaeology, and use different techniques (e.g. C-14, optically stimulated luminescence (OSL), geo- and dendro-chronology) for dating and estimating rates of change. For an overview of the use of palaeo data in fluvial geomorphology, see Jacobson et al. (2003).

Palaeo approaches can be used at all spatial scales and to gain insight into most hydromorphological characteristics. They are the only approach capable of investigating changes in hydromorphological characteristics that have occurred over very long timescales (i.e. millennia). However, this does not imply that they are not relevant to management timescales. Traditionally their temporal resolution was quite poor, but improvements in dating techniques, particularly OSL and dendrochronology, mean that properly constrained stratigraphic layers can now be dated to a decadal or even annual resolution. Consequently, sedimentology and stratigraphy can be used to investigate significant changes in hydromorphological characteristics that occurred thousands of years ago, but they can also be used to document recent changes. Stratigraphic and sedimentological evidence is commonly paired with geomorphological surveys (Section 6.1.1) to shed light on the underlying mechanisms and rates of change.

The accuracy of palaeo approaches is dependent on the techniques used, the skill and experience of the scientist to identify forms and interpret processes, and the level to which sediment strata can be constrained and dated. Specialist texts should be referred to for estimates of accuracy if palaeo approaches are used.

6.1.5 Integrating data from different sources and scales

One of the main challenges of a temporal analysis is to integrate data from a wide range of sources with varying levels of reliability in order to detect genuine changes in the catchment, floodplain and river channel. This is where a geographical information system

(GIS) becomes particularly useful. In a GIS, we are able to import graphical data based on any geographical projection of the Earth's surface, register the data to the current projection, and assess positional accuracy (See section 6.5 for more information). A GIS can be used to store information for a specific location (e.g. a point on a map can represent a gauging station), and its attributes can be, for example, key characteristics of the flood regime. Once the datasets are correctly loaded into a GIS, they can be queried and analysed using a veritable toolbox of techniques. Therefore, we thoroughly recommend the use of a GIS for this work; ArcGIS[2] is perhaps the most commonly used commercial software for this type of analysis, but excellent freeware is available including QGIS[3] and GRASS[4].

A chronology to visualise the changes that have occurred in the catchment, river corridor, and channel over time (Sear and Newson, 1995; Sear et al., 2010; Downs et al., 2013; Figure 6.2) provides a useful way of synthesising changes and their potential causes. The chronology pulls together information on the characteristics that influence hydromorphological processes and those that respond to changes in those processes. This allows changes in characteristics to be tracked over time (e.g. land cover, riparian vegetation, human interventions, channel discharge, major flood or drought events, planform pattern, channel width, etc.) and also to explore the causal linkages between them.

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[2] ArcGIS, ESRI, http://www.esri.com/software/arcgis

[3] QGIS, www.qgis.org

[4] GRASS GIS, http://grass.osgeo.org

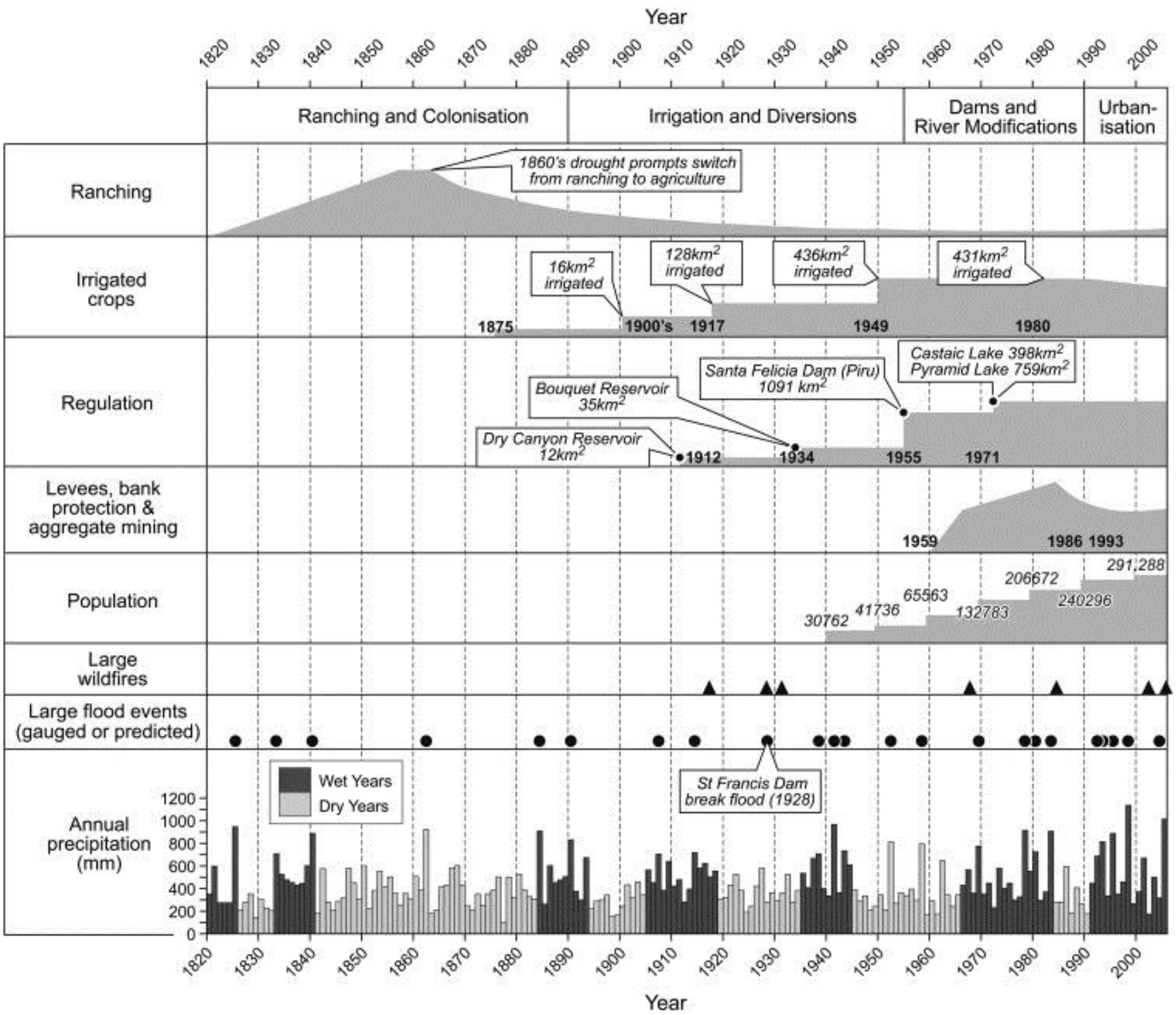

Figure 6.1 A chronology is a valuable tool to integrate data sources, track changes in hydromorphological characteristics over time and explore causal linkages (Downs et al., 2013)

6.2 Catchment / Landscape unit

The catchment and landscape unit spatial scales are combined because characteristics and key processes that are subject to temporal change are similar at both scales. This section presents the methods to analyse temporal changes in land cover/land use and land topography in detail, and briefly introduces variations in rainfall and groundwater. Other characteristics, such as geology, are not discussed as they do not change substantially over the timescales that are being considered.

6.2.1 Land cover / Land use

Land cover / land use (LCLU) is a significant controlling factor on catchment hydrology and sediment production. Large-scale changes in LCLU can alter surface run-off and soil erosion and in severe cases even impact regional climate and precipitation patterns. LCLU can impact both coarse and fine sediment production through processes such as gully and sheet erosion. Typically, an analysis of temporal changes in LCLU relies primarily on remote sensing and historical approaches, utilising data sources such as aerial photography, satellite imagery and land surveys.

Satellite imagery is now the most commonly used remotely sensed data source for quantifying changes in LCLU over time at the catchment and landscape unit scales. A large range of datasets is currently available for this purpose, varying in the type of sensor used, spectral resolution and range, and the spatial resolution of the resulting data (for a recent summary see Giri et al., 2013). Rogan and Chen (2004) give good guidance on the minimum spatial and spectral requirements for land cover attribute identification and classification (Table 6.3), as well as an overview of the types of satellite data available, indicative costs and techniques for processing and analysis. Depending on the availability of satellite data, it is possible to extend the analysis as far back as 40 years (e.g. Landsat). LCLU is classified from the images based on the spectral characteristics of the pixels using manual, semi-automated (i.e. supervised) or automated methods. Temporal change can be investigated by looking at changes in the total area cover of the land cover types, or by noting change in the categorisation of individual pixels over time. However caution must be exercised, particularly in relation to the latter option, to minimise errors associated with the position or classification of pixels (See Section 6.5 for more information).

The CORINE land cover map (CLC) is perhaps the best off-the-shelf product for examining recent LCLU changes in a European context. The CLC was developed by the European Commission and the Joint Research Centre (JRC) using satellite imagery originally from the 1990s, and then updated in 2000 and 2006, and the resulting cover mapping is now freely available on the European Environment Agency’s website. It has a minimum mapping unit of 25 ha and 3 thematic levels, with 44 classes of land cover and land use discriminated at the highest resolution. Several studies have used CLC maps to detect changes in land cover and quantify the direction and magnitude of change across Europe (e.g. Feranec et al., 2007, 2010). It is important to note that many countries have their own national land surveys that can be used for LCUC change detection, and which are often based on satellite data. For example the Countryside Surveys in England and Wales have produced detailed land cover maps for the years 1990, 2000 and 2007.

Aerial photography can be used to extend the temporal analysis of LCLU further back in time, in many countries to at least the mid-20th century. LCLU is classified for the images manually based on a variety of characteristics (e.g. tone, colour, texture, shape size, context) or using image analysis software and pixel-based or object oriented approaches (for an introduction to the subject, see Lillesand et al., 2004; Morgan et al., 2010). Note: other types of data from airborne sensors (e.g. LiDAR and hyperspectral) can be used to investigate land cover but given the high spatial resolution of the data and the correspondingly low spatial coverage, they are more suited to characterisation at the segment scale.

Some countries have long histories of detailed land and tax surveying (i.e. cadastral surveys) that can provide an excellent source of information for the analysis of LCLU. Recent work from Germany (Bender et al., 2005) and Sweden (Skanes and Bunce, 1997; Cousins, 2001) provide good examples of this approach. The records should be checked prior to use to ensure they are spatially complete for the study region, and that LCLU classes are harmonised over time. When maps were produced as a part of the surveys, they were typically at a large-scale and can often be analysed quantitatively in a GIS, following standard processing and georeferencing steps. For example, cadastral maps date back to the 17th century in Sweden and have been used to document transitions in LCLU over time (Cousins, 2001). Where records are in written format, additional map data, such as parcel locations on a more recent cadastral map, are needed to conduct a spatial analysis of change in a GIS.

Table 6.3 The minimum spatial and spectral requirements for satellite data and minimum photographic scale for aerial photograph for identification of land cover and attributes (adapted from Rogan and Chen 2004 and Morgan et al. 2010).

Land cover/use attributes (USGS levels)	**Minimum spatial resolution required for identification from satellite data**	**Spectral requirements+**	**Data sources**	**Minimum scale required if aerial photos are used as the main data source**
Land cover (I)	20 m -1 km	VIS, IR, Radar	MODIS Orbview-1 NOAA AVHRR Landsat MSS EnviSat-1 (MERIS)	1:40,000
Cover types (II)	10 - 100 m	VIS, IR, Radar	Landsat TM 4-7 Landsat ETM 7 IRS (XS) ASTER RADARSAT	1:20,000
Species dominance (III)	1 – 30 m	VIS, IR, Panchromatic	IKONOS Spot 5 Quickbird	1:10,000
Species identification (IV)	0.1 – 2 m	Panchromatic	GeoEye-1 WorldView-1 OrbView-3 LiDAR	1:2400-1:1200

+ Spectral bandwidths: VIS, visible (red, green, blue); IR, near- and middle- infrared; Radar, microwave; Panchromatic, greyscale images sensitive to the visible and ultraviolet spectra.

Box 6.1 Combining approaches to investigate fine sediment production

With the long history of human occupation in Europe, it can be difficult to reconstruct former river condition and to identify causal relationships between pressures and geomorphic responses. Two studies from the Wolsgraben, Bavaria, Germany, illustrate how a combination of approaches can be used to explore temporal changes in land cover and fine sediment production (Dotterweich et al., 2003; Schmitt et al., 2003). Information was collected on the topography, stratigraphy and sedimentology of current sites of gully erosion, supported with dating from radiocarbon and human artefacts, as well as historical documents and maps describing land cover and use. These were used to assemble a model of landscape change over time and a chronology of soil erosion intensity (Figures 6.3 and 6.4).

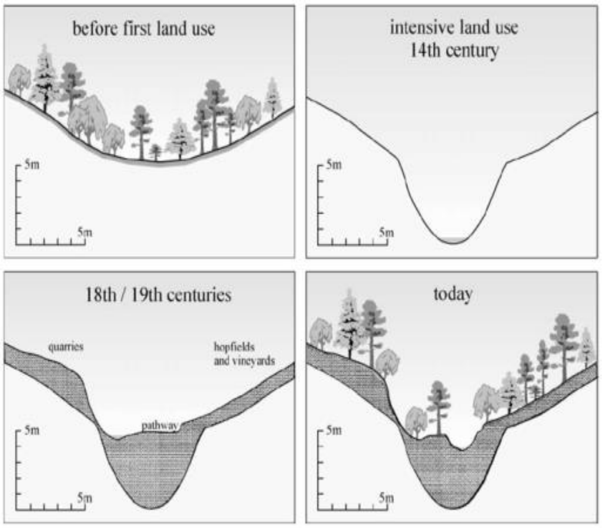

Figure 6.3 Model of landscape change in response to changes in land use in the Wolfsgraben, Bavaria, Germany (Dotterweich et al., 2003).

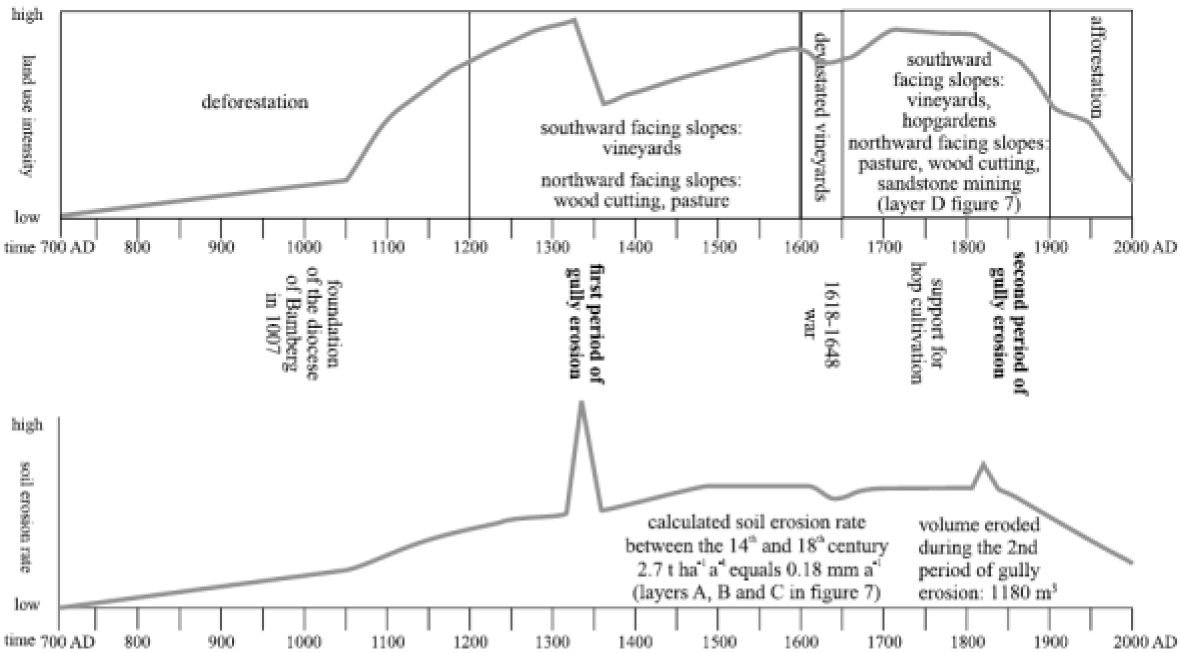

Figure 6.4 Chronology of land use type and intensity with a corresponding estimate of fine sediment production (Schmitt et al., 2003).

Finally, palaeo-ecological techniques can further extend the analysis back to prehistoric time periods. Pollen records obtained from lake sediment cores are particularly useful for this purpose and can track changes in vegetation communities over time as a result of climate and human land use change. Deforestation over the mid- to late Holocene (*ca.* 3000 – 400 years before present), as evidenced by a decrease in the abundance of pollen from arboreal species, has been reported in studies from various locations in the world, such as Europe (e.g. Fyfe et al., 2003) and China (e.g. Ren, 2000). Anthropogenic causes are differentiated from those of climate based on the habitat requirements of the vegetation, the presence of pollen associated with human occupation, and archaeological evidence of human settlement. For example, Dapples (2002) found significant decreases in arboreal species over discrete periods in the mid- to late Holocene in Alpine lake sediments, which were coupled with increases in herb species associated with human settlement.

6.2.2 Land topography (Tectonics, seismic activity and mass movements)

Changes in land topography will impact on both catchment hydrology and sediment production. However, over the timescales of interest for this temporal analysis they are primarily linked to changes in sediment production. Tectonic action, seismic activity and mass movements triggered by a variety of processes (land cover change, climate variation, deglaciation, etc) are major producers of coarse and fine sediment that can be delivered to the channel. In this section, we present approaches to assessing changes in sediment production over time across the catchment or landscape unit. The delivery of sediment to the channel (i.e. hillslope-channel connectivity or coupling) is addressed at the segment scale (Section 6.3) as is sediment transport and storage within the channel (Section 6.3).

In general there are two ways to assess changes in sediment production over time: (i) the identification of landforms associated with mass movement and (ii) surface elevation measurements to assess changes in topography or to quantify the volume of sediment eroded and deposited in a mass movement event. Geomorphological surveys, remote sensing and historical maps can all be used to investigate coarse sediment production.

The identification of terrestrial landslides has traditionally involved geomorphological field mapping and the interpretation of aerial photographs (e.g. Geertsema et al., 2006). However remotely-sensed datasets, such as DEMS estimated from laser (LiDAR) data and information on land surface cover and texture estimated from multispectral data, have the potential to reduce the time and cost associated with air photo interpretation, improve feature identification, and extend spatial and temporal coverage. Recent studies have highlighted the possibility of automatic or semi-automatic extraction using high resolution LiDAR DEMs (e.g. Tarolli et al., 2012; Van Den Eeckhaut et al., 2012). For excellent reviews of landslide identification methods using remote sensing, see Metternicht et al (2005) and Guzzetti et al (2012).

As with feature identification, volumetric analysis of landslides and other mass movements using remotely-sensed data was conducted initially using stereoscopic aerial photography. This type of approach permits calculation of the volume of sediment mobilised in an event: digital elevation models (DEMs) of the landscape prior to and following the event are compared, or differenced, yielding a DEM of Difference (DoD). For example, Coe et al. (1997) used pre- and post-event stereoscopic aerial photographs and photogrammetric techniques to calculate the volume of sediment mobilised in a modern debris flow. As remote sensing technology has advanced, DEMs have been generated from multispectral satellite imagery (e.g. stereo-pair infrared images, ASTER G-DEM) and shuttle based radar (SRTM). However it is the advent of high resolution LiDAR-derived DTMs that has expanded the types of processes that can be investigated and has markedly increased the precision of volumetric measurements. Whilst only large mass movement events could have been realistically quantified in the past, aerial LiDAR and terrestrial laser scanning can resolve small changes in landscapes that yield detailed information on fine as well as coarse sediment production (e.g. DeLong et al., 2012, and references therein) (Figure 6.5).

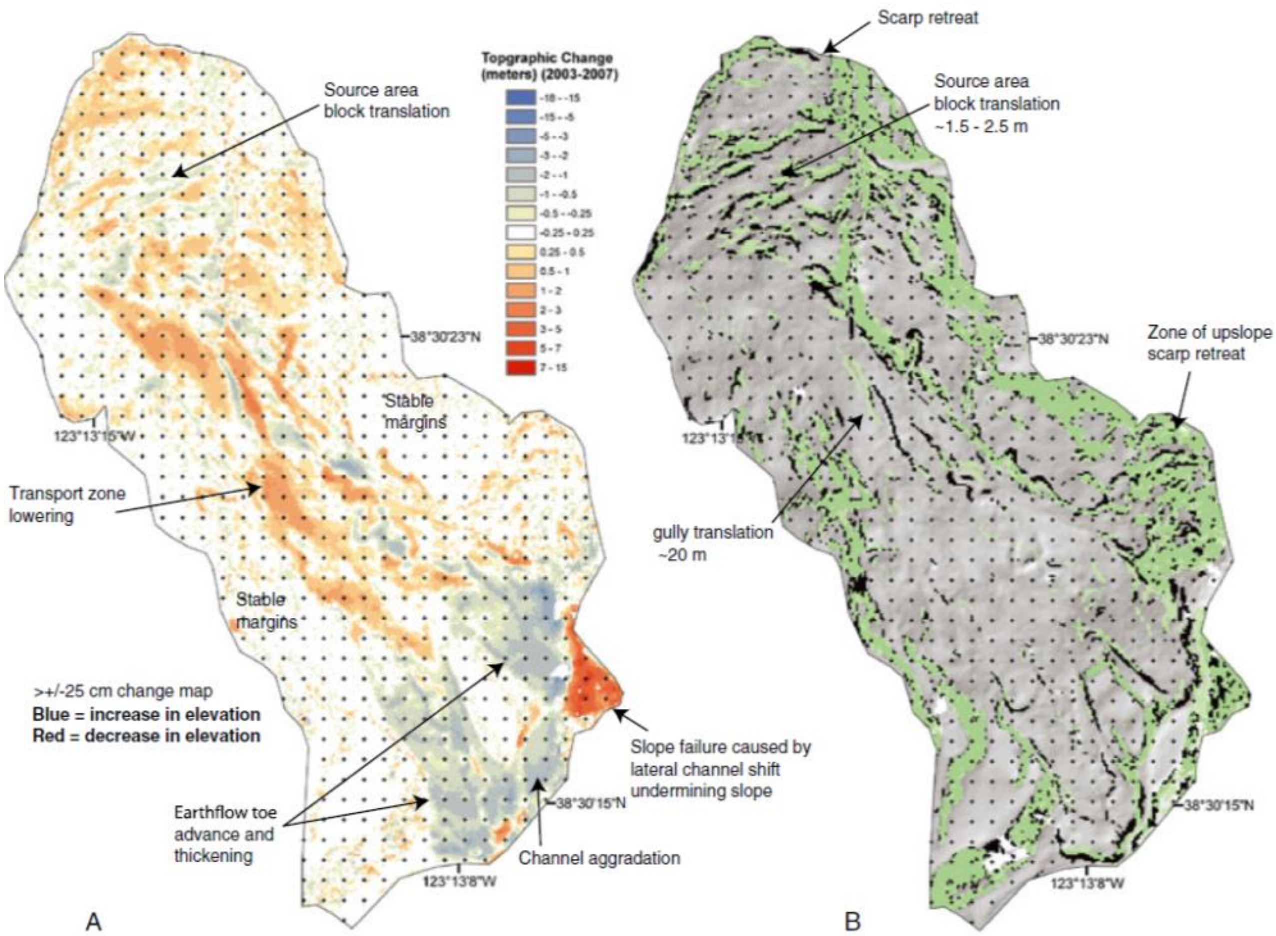

Figure 6.5 DEM of Difference (DoD) of the Mill Gulch earthflow, California, USA generated form LiDAR data. (A) Topographic change from 2003-2007; blue indicates an increase in elevation and red a decrease. (B) Steep areas from 2003 (grean) and 2007 (black) which indicates translation of distinct landforms (DeLong et al., 2012).

Where they exist, historical topographic and landslide inventory maps can help to identify the location and extent of landslides in a region. An individual landslide map can indicate the level of landslide activity, but maps from different periods in time allow the calculation of landslide frequency and, if elevation is included on the maps, a rough estimation of sediment produced. Guzzetti et al. (2012) and Galli et al. (2008) give practical advice on creating landslide inventory maps and comparing and combining maps created at different times, from different datasets and at different spatial scales. Documentary evidence is often used to support geomorphological and stratigraphic interpretations. For example, Glade (2003) used written documents, drawings and photographs to verify stratigraphic evidence for increased landslide activity in New Zealand due to anthropogenically-driven land cover changes.

To lengthen the timeframe of the temporal analysis, paleo-seismic and paleo-landslide activity can be estimated from topographic, stratigraphic and sedimentological evidence (Soldati et al., 2004; Geertsema et al., 2006; McCalpin, 2009). For example, lake sediment deposits have been used to identify the chronology, magnitude and epicentres of prehistoric earthquakes in the Swiss Alps (Schnellmann et al., 2002; Strasser et al., 2006; Beck, 2009; Strasser et al., 2013). Paleo-landslide work based on stratigraphy and radiocarbon dating has demonstrated links between landslide frequency and climate change that are related to glacial erosion and debutressing following glacial retreat (e.g. Holm et al., 2004), anthropogenic land cover changes (e.g. Dapples et al., 2002; Glade, 2003) and fluctuations in temperature and the timing, frequency and magnitude of rainfall (e.g. Borgatti and Soldati, 2010). For a review on the links between landslides and climate change, see Stoffell and Huggel (2012).

6.2.3 Rainfall and groundwater

Water drives rivers. Thus data on precipitation, surface hydrology and groundwater are essential to studies of temporal change in geomorphology. The primary source of information is hydrological monitoring records, which are the focus of this short section, though remote-sensing is increasingly being used to characterize surface hydrology and detect change over time (Tang et al., 2009).

Hydrological monitoring records are crucial to the investigation of temporal changes in precipitation or groundwater levels. A simple analysis of trends in average, maximum and minimum annual and monthly precipitation or historical intensity-duration-frequency analyses can be extracted from precipitation gauge records to examine general changes in the input of water to the catchment (Longobardi et al., 2009; Shaw, 2011). Similarly, spatial and temporal variations in groundwater levels from monitored boreholes can also be investigated (Bui et al., 2012). Because of the complex patterns in time series data as well as the interactions between global climate oscillations and precipitation and groundwater levels, time series data may be better analysed using a standardised procedure, such as the Standardised Precipitation Index (SPI) (WMO, 2012) or Standardised Groundwater level Index (SGI) (Bloomfield et al., 2013) that were designed to identify periods of drought, or they can be investigated using non-stationary approaches like Fourier and wavelet analysis (Holman et al., 2011). Where borehole or piezometer data are unavailable, information on groundwater can be obtained from age dating, chemical proxies or various hydrogeophysical techniques (e.g. electrical / electromagnetic methods or land-based gravity surveying) (Green et al. 2011). If there is evidence of significant changes in climate, land use or groundwater levels and the necessary data are available, a water budget can be assembled from current and historical data to explore changes in the amount of water delivered to the channel (Hiscock, 2005; Claessens et al. 2006).

Additional information on groundwater abstraction or inter-basin water transfers can be obtained from national scientific agencies, municipal water suppliers or private water companies.

6.3 Segment

Hydromorphological characteristics at the segment scale relate to the boundary conditions that dictate channel form and processes, including river flows, the valley setting, channel gradient, sediment delivery and transport, and riparian vegetation are investigated.

6.3.1 River flows and levels

Information on spatial and temporal variations in river discharge and level are vital to any historical analysis of temporal river change. The most accurate and complete records come from river gauging stations; however some information can also be obtained from remotely sensed data and documentary sources. Methods for summarising changes in present, naturalised and past river discharge using gauging station records are described in Section 5.4.1 and Annex C, so this section will focus on remotely sensed data and documentary sources.

Remote sensing has a multitude of uses in hydrology, such as the monitoring of precipitation, land surface temperature and soil moisture (Tang et al., 2009). For the purposes of river flows, remote sensing can provide information on the spatial extent or elevation of the water surface. It is commonly used to estimate flood extents and levels in large or ungauged catchments. Water surfaces can be discriminated from land using aerial photography, infrared images, multi-spectral data sets, radar or LiDAR, but the last two data types (altimetry data) are needed to directly measure water surface elevation / level. Infrared images and multi-spectral data offer excellent discrimination of water and land surface because clear water absorbs the majority of radiant energy in the near- and middle-infrared (Jensen, 2000). Panchromatic and true colour images (RGB) can be used, but they suffer from problems related to shadows and reflectance. Image / data classification can be done manually or via an automated or semi-automated classification technique. The resulting water surface boundaries can be used, for example, to identify the area impacted by flooding, or can be combined with a DEM to estimate flood levels and water depths. Altimetry data from radar and LiDAR offer the additional benefit of vertical measurements of water surface levels at centimetre resolution. LiDAR and radar altimetry have different advantages and disadvantages; airborne LiDAR has a higher spatial resolution and can be deployed when and where it is needed, however satellite-based radar sensors sweep locations across the Earth's surface at regular intervals and can penetrate thick cloud cover.

River discharge cannot be directly quantified from remotely-sensed data, but can be estimated from altimetry data by calibrating river level with gauging station records or through the use of hydraulic relationships (Tang et al., 2009 and references therein). Tarpanelli (2013) demonstrate this approach on the River Po in Italy, where they estimated river discharge using altimetry data from ERS-2 and ENVISAT[5], discharge records for a station upstream of the study reach, and a simple Rating Curve Model.

Despite some notable exceptions, discharge records generally only exist in Europe from the late 19th century, so other documentary sources need to be assessed to extend the analysis further back in time. For example, Uribelarrea et al. (2003) gathered water stage data associated with historical flooding from a range of documentary sources as part of a study of channel change in two rivers in central Spain. Information mentioned in these documentary sources included sites or landmarks reached by a flood, areas of the floodplain that experienced flooding, areas or landmarks that were not flooded, and estimates of flood severity in comparison to earlier floods. Discharges were then estimated from the historic flood levels using a 1-D hydraulic model, and integrated into the gauging station records to produce a timeline of flooding dating back to 1557. To delve further back in time, palaeo-hydrological techniques can be used to estimate bankfull flow based on cross-section or planform geometry of palaeo-channels (Gregory, 1983; Gregory et al., 1987; Starkel et al., 1991; Sidorchuk et al., 2009). For a recent study that has investigated flood events in Europe in prehistorical times see Macklin et al. (2006).

Finally, to assess the impacts of human intervention on the flow of water in the river, a chronology of anthropogenic changes in the segment should be constructed. Of particular interest are the dates of construction and size of water flow impedances or storage structures, be they for water diversion, hydropower, flood management or water consumption purposes. Information to complete the chronology can come from any number of historical sources, including maps, aerial photographs and water company records.

6.3.2 Valley setting (gradient and width)

The valley setting is influenced by forces operating at vastly different timescales, from tectonic uplift acting over millennia to valley blockage by landslides and glacial surges inducing very rapid geomorphic response. These forces can alter the valley gradient, impacting upon river energy and sediment transport, and the valley width, which in turn impacts the planform and lateral mobility of the river as well as the extent of the active floodplain.

Methods from all four of the approaches are typically used in combination to identify, confirm and date topographic features in the landscape that are indicative of changes in valley setting (e.g. Lave and Avouac, 2001; Korup et al., 2006; Bridgland, 2010). These features, such as river terraces and palaeo-landslides, are identified using geomorphological surveys and remote sensing techniques and may be depicted on historical topographic maps. Stratigraphic, sedimentological and dating techniques are used to confirm the origin of the features and constrain the dates for their formation. Indicators of changes in valley setting, such as inset river terraces, can also be associated with rapid channel narrowing and incision caused by anthropogenic interventions (e.g. Surian and Rinaldi, 2003). These changes will be discussed in more detail in the following

[5] The full Envisat and ERS1/2 data series are available at https://earth.esa.int/

sections, but it is important to point out here that in addition to the changes that occur in channel geometry and bed level, the floodplain width may be severely diminished, which can have significant implications for the conveyance of high flows and the distribution of riparian vegetation.

Anthropogenic structures that influence the valley gradient and effective valley width should also be studied. Large dams that span the width of the floodplain have a profound and immediate impact on the water surface slope, and cause significant changes in upstream bed elevation over time due to sediment deposition. Extensive artificial levée networks associated with flood control structures or infrastructure (e.g. rail and road embankments) will constrict the valley width, limiting the spatial extent of flood inundation and restricting the lateral mobility of the channel. Information on engineering structures can be obtained from maps, government records, or can be identified from aerial photographs and remotely-sensed data. Steinfeld et al. (2013) present several semi-automated approaches to identify and classify earthworks in floodplains from (DEMs), satellite multi-spectral data and aerial photography. By linking the spatial representation of engineering structures with a timeline of their constructions and flood levels, it becomes possible to quantify changes in floodplain width over time.

6.3.3 Channel gradient - Changes to longitudinal profile

Channel gradient is set initially by the valley setting, but is further controlled by planform pattern and geometry. Channel gradient will naturally adjust over time, in response to normal geological and geomorphological processes. Significant changes in channel gradient over short timescales, though, are often caused by anthropogenic modifications to the channel or catchment, such as changes to channel planform (i.e. channel realignment and meander cut-off), bed level (e.g. weirs, dams and gravel mining) or sediment delivery from the catchment. Channel depth and gradient were covered at the reach scale in the spatial characterisation stage (Section 5.5.1). Depth will be discussed at the reach scale as part of channel geometry (Section 6.4.2). However gradient is discussed here at the segment scale because it is one of the fundamental properties that determine the amount of fluvial energy available to transport sediment within segment and reach.

An investigation of changes in channel gradient requires information on two variables at multiple points in time: (i) the length of the river in the segment, and (ii) the bed elevation at a minimum of two locations along the segment. In some situations, this information can be gathered from remote sensing sources; however by far the most reliable data come from historical sources, particularly systematic river topographic surveys. In Europe, detailed topographic surveys of rivers began in the mid-19th century in response to the development of rivers for navigation, water resource use and flood control (Gurnell et al., 2003). For example, repeated long profiles were conducted in many French rivers, particularly the Rhone River and many Alpine rivers, and these have been used to quantify aggradation and degradation associated with climate change and anthropogenic impacts (e.g. Piégay and Peiry, 1997).

When historical topographic surveys are unavailable, channel gradient can be estimated by combining channel length and bed level estimates from different sources. Channel length can be derived from plan sources including maps, aerial photographs and other remotely-sensed datasets (for more information on this analysis see Section 6.4.1), whilst bed-level change can be derived from cross-sectional surveys conducted for other purposes, such as bridge construction and maintenance, flood risk management or river restoration (Kondolf and Swanson, 1993; Brooks and Brierley, 1997; Erskine, 1999).

Care must be exercised when comparing historical bed-levels from different sources, as problems can arise due to differences in geographical reference systems, survey techniques, or in the attribute measured (Gurnell et al., 2003). For example, elevations recorded in a long profile may correspond to the thalweg depth, the average level of the bed, or the water surface level. When available, repeated cross-sections offer a more reliable record of bed-level changes and channel gradient than longitudinal profiles, as well as offering additional information on cross-section form.

Gauging station records can also be used to interpret changes in bed level in an approach known as specific gauge analysis. Water surface levels at set discharges are compared over time using empirical ratings curves for each year of the analysis to reconstruct average bed elevation. For a recent and comprehensive example, see Pinter and Reuben (2005) (Figure 6.7).

If no quantitative information on historical bed levels is available, then some indication of bed level changes can be inferred from a field geomorphological survey. For example, inset floodplain terraces, undercut bridge piers and exposed bedrock / former floodplain layers in an alluvial river may all indicate incision (Rinaldi, 2003; Natural Resources Conservation Service, 2007). Conversely, buried engineering structures, large uncompacted point bars, and thick fine sediment deposits overlying a gravel bed may indicate aggradation. The occurrence of these properties varies depending on the catchment characteristics and the location of the segment within the catchment, so must be assessed by an experienced geomorphologist. Field surveys of bed level change should be conducted at multiple locations within a segment to ensure a reliable assessment. Stratigraphic, sedimentological and botanical evidence can support conclusions drawn from a geomorphological survey and help to constrain the timing of bed level changes (e.g.Hupp and Rinaldi, 2007; Dean et al., 2011).

Box 6.2 Assessing changes in bed level using topographic survey data

Topographic survey data have been used extensively to assess temporal changes in bed level resulting from human interventions in the catchment and channel. For example, archives of long profiles and detailed cross-section surveys exist for many Italian rivers. Rinaldi and Simon (1998) used these records to document severe incision in the Arno River over the last 150 years (2 – 4 m in the Upper Valdarno and 5-8 m in the Lower Valdarno). The change in bed levels can be visualised by overlaying longitudinal profiles from several points in time (Figure 6.6)

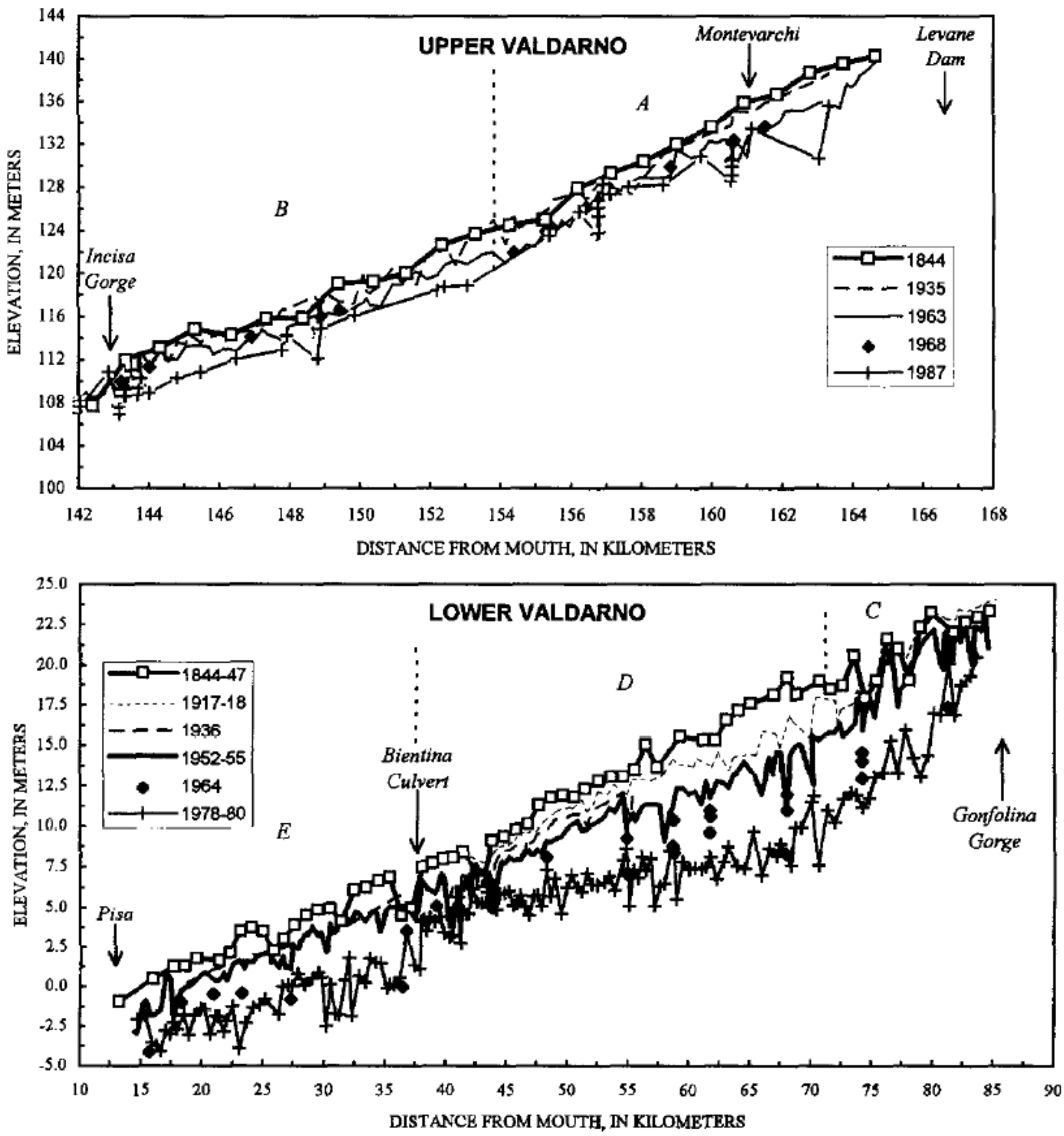

Figure 6.6 Changes in bed level over time for the Arno River, Italy (Rinaldi and Simon, 1998)

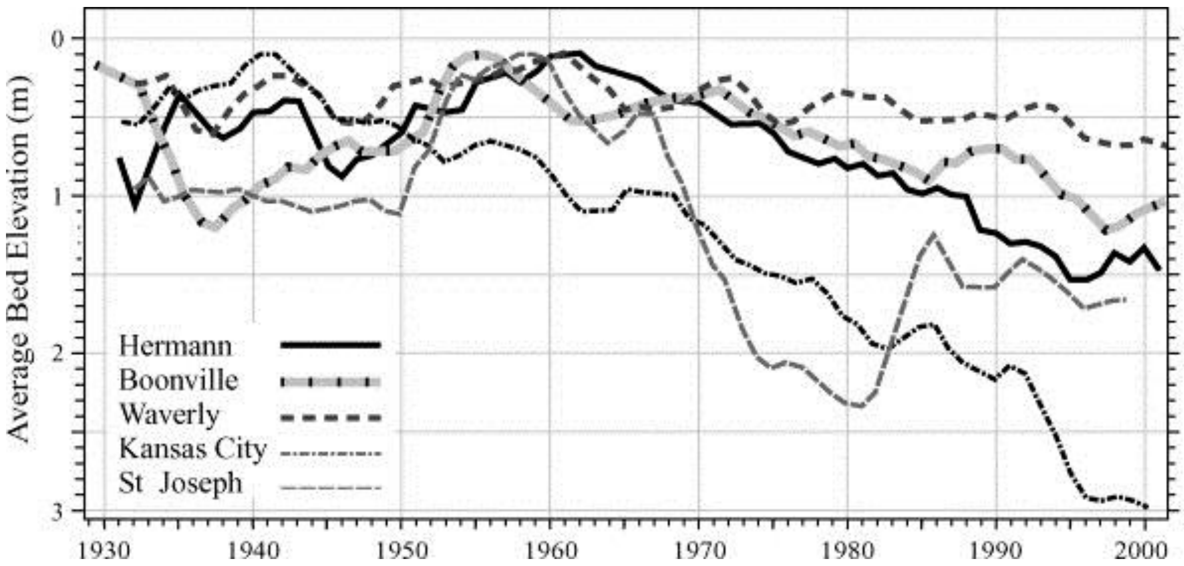

Figure 6.7 Water levels can be used to reconstruct bed levels in a technique known as specific-gauge analysis (Pinter and Heine, 2005)

6.3.4 Sediment delivery

Sediment delivery refers to the transfer of sediment from the areas of production identified at the catchment / landscape scale to the river channel. The importance of coupling (i.e. connectivity) between channels and adjacent hillslopes has been long acknowledged (e.g.Caine and Swanson, 1989; Fryirs et al., 2007). Evaluation of the degree of coupling, and its change through time, is critical to drainage basin sediment dynamics as it controls in what proportion hillslope sediment flux contributes to drainage basin sediment storage and fluvial sediment yield, respectively (e.g.Roberts and Church, 1986; Reid and Dunne, 1996). The concepts of sediment delivery and dis(connectivity) have been recently revisited by Fryirs (2013). However, few studies have attempted to assess the role of connectivity in a systematic way.

A field approach using geomorphological mapping can be used to assess sediment connectivity. A good example of this approach is provided by Hooke (2003), in which channel morphology and sedimentology are mapped in the field. Temporal changes in connectivity can be then be assessed using repeat site visits. It is worth mentioning that the approach was applied at reach scale (Hooke, 2003), but it could be expanded to the segment scale, although this may prove time consuming.

In the remote sensing approach, DEMs are used to track changes in the topography of sediment sources over time to estimate sediment delivery to the channel. For coarse sediment, the sources are typically discrete and in close proximity to the river channel (e.g. landslides), whereas for fine sediment they can be discrete (e.g. earth flows) or diffuse sources (e.g. soil sheet erosion). The DoD method works best with discrete events for which there are DEMs that characterise the topography before and after the event, preferably with multiple post-event DEMS to permit the calculation of delivery rates. DEMs derived from photogrammetry or field surveys are sufficient when there are large changes in the sediment source topography over time. With their high vertical accuracy, LiDAR-derived DEMS have the potential to detect smaller amounts of change in topography. It must be emphasised, though, that uncertainty in LiDAR-derived elevation measurements are still in the centimetre to decimetre range, so care must be exercised in interpreting topographic change over short time spans, or when the amount of change being detect is of similar magnitude to the positional accuracy (Brown et al., 2009; Chartin et al., 2013; Croke et al., 2013).

A combined field survey and remote sensing approach can be particularly useful for assessing sediment connectivity and transfer. For example, Theler et al. (2010) propose a process-based geomorphological mapping method in which sources are identified from aerial photographs, DEMs, and historical topographic maps; mapped and analysed in a GIS; and combined with information on land cover and slope to predicted the transfer potential of sediment from the hillslope to the channel.

Historical data sources are important to a temporal characterisation of sediment delivery; although they usually serve to corroborate evidence gathered for other sources. For example, Walter and Merritt (2008) argued that the geomorphology of mid-Atlantic streams in the US was fundamentally altered following an intense fine sediment delivery pressure associated with land cover changes post-settlement and the construction of mill dams. The gathered information of the size and number of mill dams and their impact on sedimentation within channels from historical maps, diaries, legislation related to milldams, paintings and photographs. Information from all of these sources supported and helped to date evidence from topography, sedimentology and stratigraphy.

Palaeo approaches are the primary methods for estimating the delivery of fine sediment to the river channel. Stratigraphic and sedimentological interpretation of sediment deposits from the channel bed, overbank deposits, fill deposits in cutoffs and avulsions, and reservoir/lake sediments can determine the amount, timing and source of sediment (Macklin and Lewin, 2003; Macklin et al., 2006; Hoffmann et al., 2009; Lewin, 2010; Macklin et al., 2010; Lexartza-Artza and Wainwright, 2011). Cosmogenic approaches are particularly useful for sediment budgeting (e.g. Brown, 2009; Brown et al., 2009), but may only be feasible in areas with severe or complex fine sediment delivery problems due to the cost and expertise involved.

Finally, temporal changes in sediment delivery may be identifiable in field surveys (Sear and Newson, 2003; Sear et al., 2010). For example a decrease in coarse sediment supply may result in bed incision, bed armouring, a reduction in geomorphic features or a change in river pattern (e.g. from braided to wandering). An increase in fine sediment delivery may be result in the clogging or burial of a coarse-grained bed, aggradation, and the presence of fine sediment geomorphic features (e.g. silt bars and benches).

6.3.5 Sediment transport

When available, long-term monitoring data for suspended sediment and bedload provide invaluable information on sediment transport within a segment. Suspended sediment is more commonly monitored than bedload transport, as it is an aspect of water quality that is typically measured by water companies and national environmental agencies. Bedload is more difficult to quantify, and consequently monitoring stations are usually located only in areas where bedload poses a very significant river management problem (e.g. Switzerland, Rickenmann et al., 2012). These sources can be readily analysed and combined with river flow information to assess changes in sediment delivery and transport over time.

Unfortunately, sediment transport is not monitored as commonly as water discharge, and many European rivers have very limited or no sediment monitoring record. In this situation, changes in sediment delivery and transport associated with human disturbance to the system can be explored by creating a historical inventory of engineering structures that impact the lateral or longitudinal transport of sediment (i.e. sediment connectivity). For coarse sediment these structures can include dams, check dams, weirs and torrent controls (e.g. Boix-Fayos et al., 2007; Surian and Cisotto, 2007), whilst for fine sediment they can also include drainage ditches and artificial levées (e.g. Walter and Merritts, 2008). Depending on the catchment history, it may also be pertinent to acquire data for sediment-related activities within the channel, such as records detailing the quantity and location of sediment dredging or mining from the channel (e.g. Wishart et al., 2008; Martin-Vide et al., 2010). This inventory can be combined with information on land cover, topography, and sediment delivery collected earlier at the catchment / landscape unit and segment scales to formulate an integrated chronology of sediment flow.

Remote sensing has enormous potential for use in sediment transport estimates and sediment budgets. This includes the detection and estimation of volumetric change in bed topography (the so called "morphological approach") from aerial photos (e.g. Ham and Church, 2000) or high resolution DEMs (e.g. Wheaton et al., 2010) (see also Section 6.4.2), as well as monitoring fine sediment concentrations using aerial photography and multispectral satellite data (e.g. Ritchie et al., 2003; Kilham et al., 2012). However, the application of these techniques to studies of temporal change is limited to specific river patterns (e.g. gravel bed rivers and DEM differencing) or by methodological advancement (e.g. numerical approaches to calibrate suspended sediment concentrations from satellite data, but see Kilham et al. (2012)).

The morphological approach to estimate bed-load has been successfully used in numerous studies (Martin and Church, 1995; Ashmore and Church, 1998; McLean and Church, 1999; Ham and Church, 2000), in particular where direct measurements using samplers are difficult to carry out or where it is not possible to capture the wide spatial and temporal variability of sediment transport (e.g. in large gravel-bed rivers). Besides, it has been shown that morphological methods provide reasonably robust estimates of the time- and space-averaged bedload (Hicks and Gomez, 2003). These approaches rely on morphological changes, requiring comparison of DEMs of river channels (Brasington et al., 2003) or cross-sections (Surian and Cisotto, 2007). Considering the increasing availability of LiDAR data, but also the possibility of deriving DEMs from archival aerial photos (e.g.Lane et al., 2010), there will be more and more opportunities to apply morphological approaches for sediment transport estimation. Even in the absence of favourable conditions for estimation of bed-load transport (morphological approach requires that sediment transport is known at one cross-section within the study reach), comparison of DEMs represents the best tool for calculation of the sediment budget and, therefore, to assess the evolutionary trend of channel morphology in a given segment.

6.3.6 Riparian corridor and Wood

This section covers the analysis of riparian corridor characteristics for both the segment and reach scales. At the segment scale, these characteristics include the size, width and continuity of the riparian corridor and the potential for wood recruitment to the river; whilst at the reach scale they relate to the structure, spatial distribution and species composition of the riparian vegetation and the presence of large wood in the channel. Similar data sources and methods are used at each scale, but the level of detail required is higher for the reach scale. The primary sources of information come from remote sensing and field surveys, although detailed land survey maps can contribute to the analysis.

Remotely-sensed data is perhaps the best source of information to assess change over a decadal timescale. These include aerial photographs; multi- and hyperspectral data from airborne or satellite-based platforms; and airborne LiDAR (e.g. Beschta and Ripple, 2006; Kondolf and Piégay, 2007; Bertoldi et al., 2011; Comiti et al., 2011; Dean and Schmidt, 2011; Henshaw et al., 2013). For a general discussion of how remote sensing can be used for assessment in this present context, see the previous section on land cover characterisation at the catchment / landscape unit scales (Section 6.2.1). The choice of remotely-sensed data for a particular river segment depends upon data availability and the spatial resolution of the data in comparison to the width of the riparian corridor and the amount of change being detected. For rivers with large and continuous riparian cover, small-scale aerial photography and freely-available satellite imagery can be used to assess segment scale characteristics. For segments with narrow or patchy riparian vegetation and for all reach-level characteristics, higher resolution data is needed. For guidance on scale and resolution for vegetation identification and classification, see Table 6.3.

Classification of the riparian corridor can be done manually based on characteristics of the image (e.g. form, size, texture, spatial context) or using semi-automated (i.e. supervised) and automated techniques based on spectral characteristics. Additional information can be used to support the classification (e.g. DEM, floodplain extents, etc.). A simple approach to investigating change over time in segment-level riparian vegetation characteristics is to delineate the boundaries of the riparian vegetation and to overlay shapefiles to calculate changes in aerial coverage. A pixel-based approach can also be used, particularly with supervised and automatic classifications, which identifies change over time for individual pixels. This will yield more detailed information on vegetation structure and composition, but caution must be exercised to minimise errors associate with the position and classification of pixels. These errors arise because of the positional (in)accuracy of the data (i.e. pixels for a specific location may not overlay exactly over time) and errors in classification caused by intrinsic or extrinsic factors (e.g. leaf cover will vary with seasons; spectral characteristics of vegetation will vary with plant health or atmospheric distortion). See Section 6.5 for guidance on estimation and integration of errors from different sources in a temporal analysis.

Where available, LiDAR data is particularly useful for characterising riparian vegetation structure and spatial distribution. The point cloud data that is generated by LiDAR provides information on the presence of vegetation; vegetation height; and canopy structure, which can be used to interpret vegetation age and type; and ground topography (e.g. Antonarakis et al., 2008; Bertoldi et al., 2011). LiDAR can also be combined with other remotely-sensed data to more thoroughly characterise riparian vegetation structure (e.g. Geerling et al., 2009; Bertoldi et al., 2011). Changes over time can be investigated using height frequency distributions, DoDs or areal coverage of vegetation classes (e.g. height or species).

Box 6.3 Combining remotely-sensed data to characterise riparian vegetation

A combination of remotely-sensed datasets can yield a more detailed analysis of channel topography and vegetation structure. For example, Bertoldi et al. (2011) used LiDAR data to quantify bed elevation and tree height and aerial photography for water depths to develop a 3D model of the island-braided Tagliamento River, Italy. The analysis revealed that vegetation influenced the topography of the braid plain through sedimentation within and around vegetated patches. Frequency distributions for detrended bed elevation were used to illustrate the influences (Figure 6.8). A similar approach can be used to investigate change in bed topography or vegetation height over time.

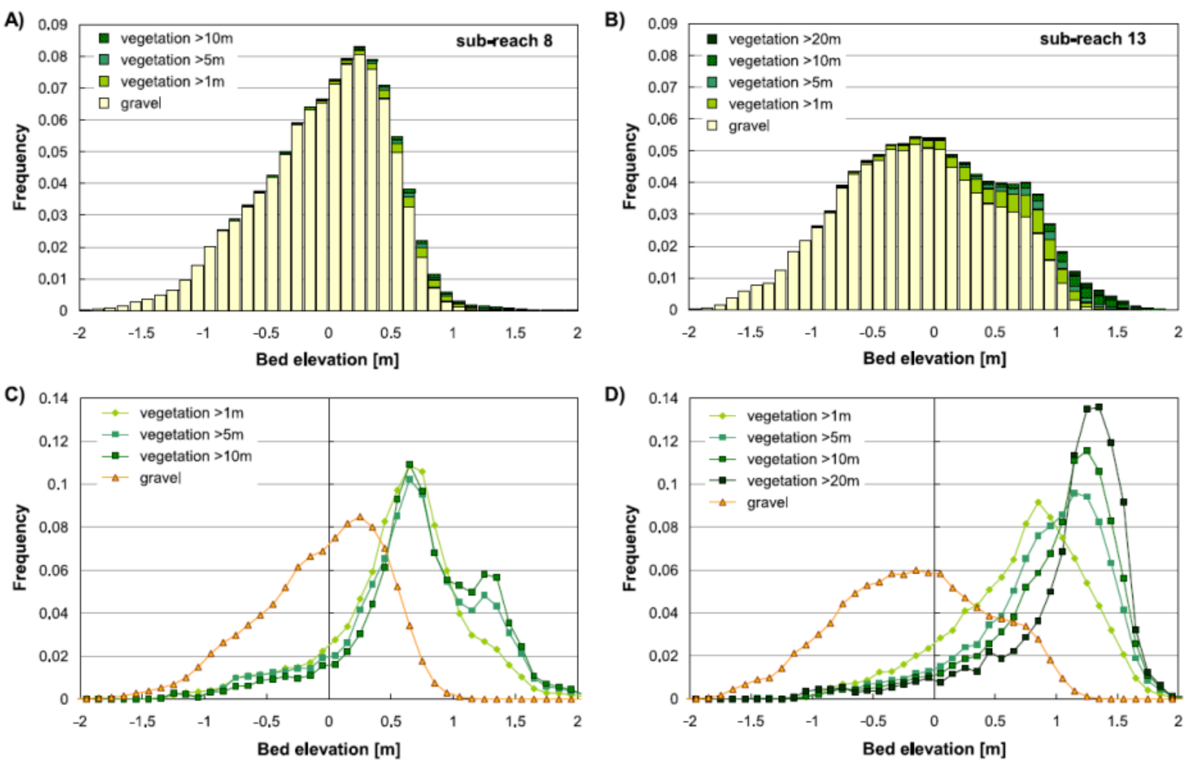

Figure 6.8 Frequency distribution of the ground surface elevation for two subreaches of the Tagliamento River, (a, b) classified according the presences and height of vegetation. (c,d) Separate frequency distributions for ground surface elevation according to the presence and height of vegetation (Bertoldi et al., 2011)

Historical maps can be a valuable resource, particularly large-scale land and tax maps that have detailed land use information associated with them. For example, Kondolf et al.

(2007) used historical cadastral maps to assess changes in the extent and composition of riparian vegetation in the Eygues River, France. This information can be paired with modern vegetation survey data to link historical channel change to current vegetation structure and species composition (Greco et al., 2007; Meitzen, 2009).

Changes in the distribution and frequency of large wood in the channel can be investigated effectively using remote sensing. For example, Lassettre et al. (2008) used vertical and oblique aerial photographs to quantify wood delivery and the frequency and distribution of large wood in the river channel. Marcus et al. (2003) used airborne hyperspectral data to map stream habitats and large wood. Bertoldi et al. (2013) used a combination of LiDAR, field surveys and oblique ground photographs to investigate wood recruitment and deposition dynamics. In small streams, or those with dense canopy cover, field surveys and photographs can be used to characterise large wood within channels. Structure from Motion (SfM) photogrammetry may be particularly useful for this purpose, particularly using ground or low-altitude aerial photography (e.g. a camera on a pole) (Westoby et al., 2012; Fonstad et al., 2013). SfM is a newly-developed technique in geomorphology that can generate DEMs from any series of overlapping digital photographs with positional accuracies as good as LiDAR. This opens up the possibility of tracking volumetric changes in large wood using DoDs from historical photos.

Finally, information on riparian vegetation and large wood can come from other historical sources such as travel accounts, ground photographs and government policy/records (Maser and Sedell, 1994; Trimble, 2008). For example, large wood may have been, and may still be, removed from channels by the local population for use as fuel or to improve drainage and reduce local flooding, and by governments to maintain channels and protect infrastructure. Any information on how the spatial extent and intensity of these practices has varied over time will help to develop an understanding of how large wood has influenced the current and past hydromorphological condition of the river.

6.4 Reach

Whilst the characteristics investigated at the larger spatial scales were largely associated with controls on geomorphology, those at the reach scale are primarily indicators of function, channel adjustment or alteration / artificiality. Geomorphological characteristics are grouped into three categories: planform morphology and channel migration; channel geometry; and bed sediment calibre. Riparian vegetation, aquatic vegetation and wood should also be assessed at the reach scale, but this has already been discussed in the segment-scale description above.

6.4.1 Planform morphology and channel migration

This section addresses changes in the 2-dimensional form of rivers over time, and includes river planform and associated characteristics (e.g. channel width and sinuosity, braiding and anabranching indices); channel migration; and geomorphic units within the channel or floodplain. This encompasses a large variety of characteristics, but they are united by the data sources and analytical techniques used to investigate temporal change. A good review of approaches and data sources is provided by Lawler (1993).

The analysis of temporal change in planform relies primarily on remotely-sensed data and historical maps. In fact, these sources are often used in combination in many studies. Aerial photographs or satellite data are frequently used to characterise planform in recent years, and historical maps extend the analyses further back in time. The basic premise of the analysis is to overlay images from multiple years and check to see if there has been a change in the position of a feature (e.g. bankline, Figure 6.9) or a change in the characteristics of a feature (e.g. channel width, Figure 6.10). Because this type of analysis is based on a comparison of geographical positions, it is crucial that the data sources are properly registered to a common coordinate system in a GIS and accuracy / uncertainty is estimated for each source and at each time point. More information on analysis methods and the assessment of accuracy / uncertainty is provided in Section 6.5. Here we provide recent examples of temporal change analyses related to planform to illustrate the range of sources and applications.

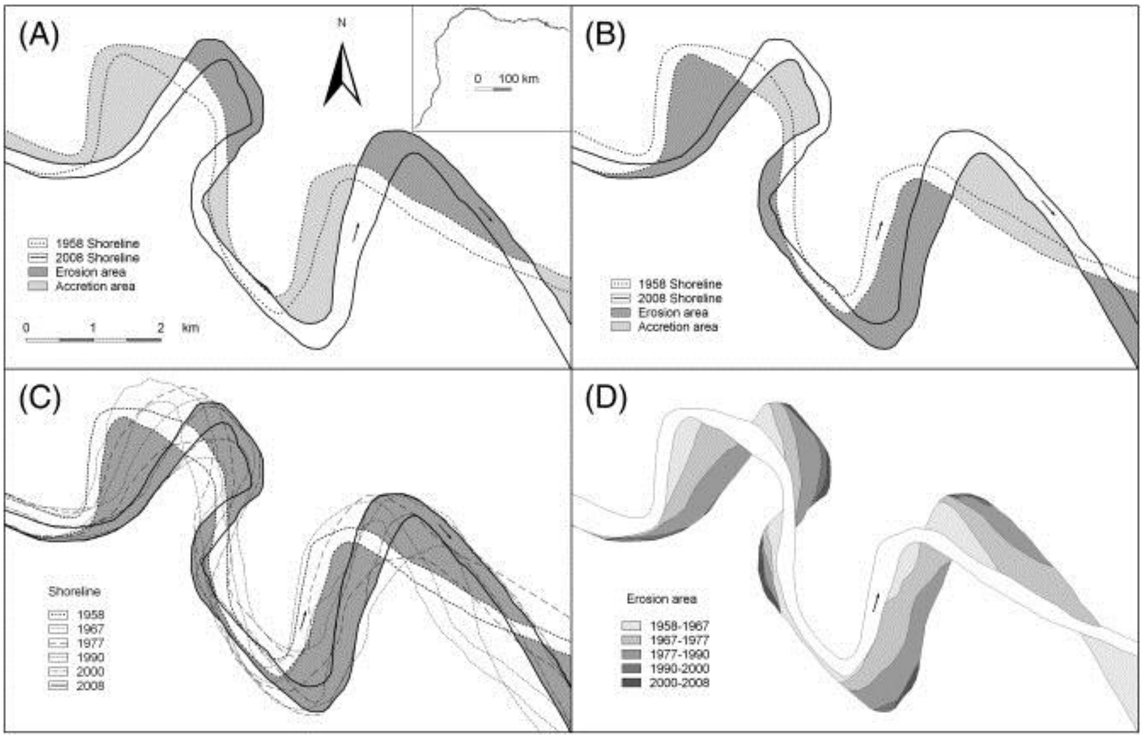

Figure 6.9 Overlaying banklines from different years to investigate the total and rates of meander migration in the Yellow River, China from 1958 to 2008 (Yao et al., 2011)

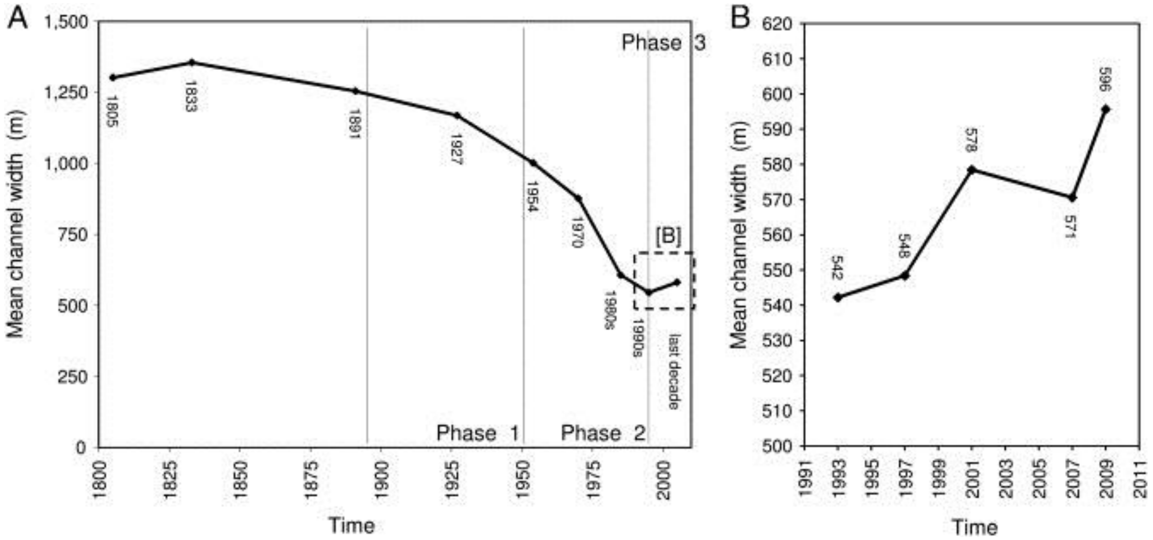

Figure 6.10 Plotting planform characteristics extracted from imagery to assess change over time. Mean channel width of a reach of the Tagliamento River, Italy. Maps were used to 1954. Aerial photographs were used thereafter (Ziliani and Surian, 2012).

Maps and aerial photography have been used to investigate temporal changes in rivers that cover the full range of sizes, patterns and dynamics. The major consideration is the scale of the data sources in relation to the size of the feature being detected (e.g. channel width) and the amount of change being detected (e.g. lateral migration). Consequently, studies of temporal change in narrow or slowly adjusting rivers need large-scale maps or aerial photographs (minimum 1:10,000 scale) (e.g. Gurnell et al., 1994; Gurnell, 1997; Hooke, 2004; Hooke, 2007). Large and dynamic rivers can be studied with smaller-scale maps and aerial photographs. For example studies of braided rivers in Italy have used a combination of 19th century military maps, regional maps and aerial photographs to describe planform changes over the last 200 years (Surian, 1999; Surian et al., 2009; Comiti et al., 2011; Ziliani and Surian, 2012). In the latter cases, these sources varied in scale from 1:5000 to 1:85,000 and had different, and often undocumented, levels of accuracy. Whilst errors in these maps were estimated to be on the order of tens of meters in a GIS (RMSE 15-20 m), the errors are small relative to the amount of change detected in the highly dynamic braided rivers that were studied (Comiti et al., 2011). Consequently, researchers could be confident that the changes in planform configuration and channel width that were observed were genuine and not solely an artefact of the survey or mapmaking process.

Satellite data is also a useful source for historical analysis. Recent studies have used the long, freely-available, Landsat archive to quantify temporal changes in planform in the Yellow River, the Ganges and the Bramaputra/Jamuna (Yao et al., 2011; Gupta et al., 2013; Mount et al., 2013), as well as the braided Tagliamento, Italy, albeit with some limitations (Henshaw et al., 2013). Infrared bands, e.g MODIS band 2 or Landsat Thematic Mapper band 5, can be used to automatically segregate water and land, based on a pixel threshold, particularly for large rivers with clear water (Pavelsky and Smith, 2008), and well-tested band ratios can be used to discriminate vegetated from unvegetated surfaces (Normalised Difference Vegetation Index, Rouse et al., 1974), and wet from drier surfaces (Modified Normalised Difference Water Index., Xu, 2006) using multispectral (e.g. Landsat) data. Smaller rivers can be studied using commercial panchromatic data; Ikonos, Quickbird, Worldview and Geoeye all have sub metre spatial resolution.

Many studies have also used remotely-sensed data to identify and monitor changes in channel and geomorphic units. White et al. (2010) used aerial photography and DEMS to investigate the location and persistence of riffle-pools in an incising river. Hook and Yorke (2011) used aerial photographs, supported by field surveys and historical maps, to study bar dynamics in a meandering river. Zanoni et al. (2008) used aerial photography and historical maps to study the temporal dynamics of islands in the braided Tagliamento River. Latrubesse et al. (2009) used Landsat imagery and aerial photography to assess changes in the frequency and size of bars and islands in the Araguaia River following catastrophic deforestation of the region.

Box 6.4 - A comprehensive example of temporal analyses using historical maps

Two recent studies have reconstructed the Danube River and its floodplain near Vienna, Austria, using a rich collection of large-scale historical maps (Hohensinner et al., 2013a; Hohensinner et al., 2013b). This detailed work has revealed that, prior to river regulation and recent land cover changes, the Danube was an anabranching river flowing through forested wetlands. The authors were able to quantify channel migration and changes in channel widths and geomorphic units (Figure 6.11).

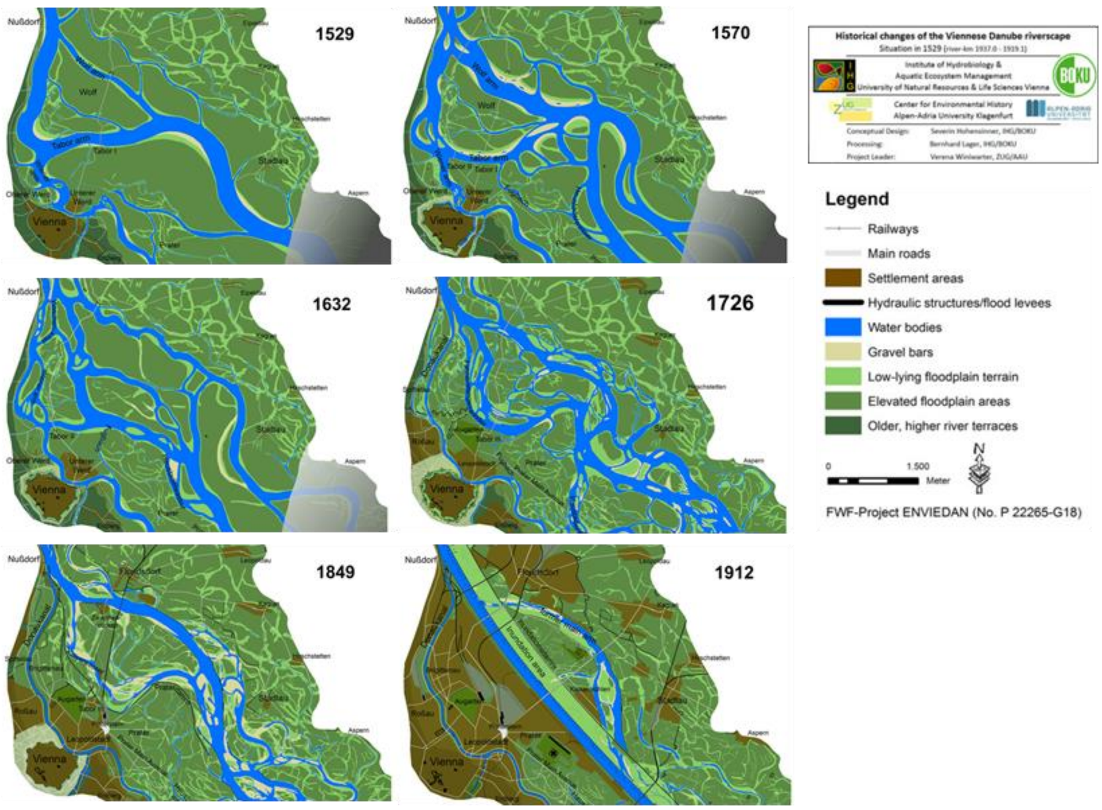

Figure 6.11 Reconstructions of the Danube "riverscape" in Vienna depicting the river planform, floodplain morphology and channel geomorphic units (Hohensinner et al., 2013a)

Geomorphological surveys can provide insights into channel migration and changes in channel width (section 5.6.2), particularly when combined with botanical, sedimentological or stratigraphic evidence (Gurnell, 1995; Hupp and Bornette, 2003). For example, channel narrowing can be identified from active accretion of sediment on opposite banks, particularly when such accretion is stabilised by vegetation encroachment. The species composition and age structure of riparian vegetation can also provide clues to the direction of channel change. For example, lateral banding in the height and ground cover of riparian vegetation due to vegetation succession can underpin estimates of lateral migration extent and rates (Perucca et al., 2006, 2007) and modes of lateral floodplain construction (Page and Nanson, 1982, Salo et al., 1986) whereas lateral and downstream changes in the species composition or morphological structure of riparian vegetation can be indicative of distinct geomorphic features, subject to contrasting inundation and soil moisture regimes (e.g. Hupp and Osterkamp, 1996). Thus changes in vegetation structure and composition can reveal channel bed incision or aggradation (e.g. Hupp and Rinaldi, 2007), through their influence on moisture conditions within the geomorphic features (e.g. Toledo and Kauffman, 2001). To go further back in time, the planform configuration of palaeochannels can be investigated based on their topographic signature in the floodplain and supported by sedimentological and stratigraphic evidence (e.g. Hoyle et al., 2008; Brown et al., 2013).

Finally, the chronology of physical pressures should be updated with the dates and extent of river realignment and channel bank and bed reinforcement. This information can come from maps, remote-sensing and government records.

6.4.2 Channel geometry

Channel geometry refers to the cross-sectional form or bed configuration of a channel. Whilst information on channel width can be gained from maps and aerial photography, additional data are essential for a full characterisation of channel geometry. The recommended data source for this analysis is topographic surveys, although several remote-sensing approaches are presented that are applicable in certain situations.

Cross-sectional surveys are the core data sources to examine changes in channel geometry over time. They are conducted across the river channel, perpendicular to the flow direction, and provide a wealth of morphometric information about the channel (bankfull and low flow channel width, bed-level, water level at the time of survey, bank profiles, etc) as well as indices used in hydraulic modelling (e.g. bankful cross-section area and hydraulic radius). In regions where a network of cross-sections has been established for regular monitoring, cross sections from different points in time can be easily overlaid to investigate changes in channel geometry (e.g. Figure 6.12). However internal checks on the surveys should still be conducted to ensure that the same reference points and start / end locations have been used and that there has not been a change in the survey approach which would affect the way the survey was conducted, the accuracy of the measurements or the interpretation of landforms.

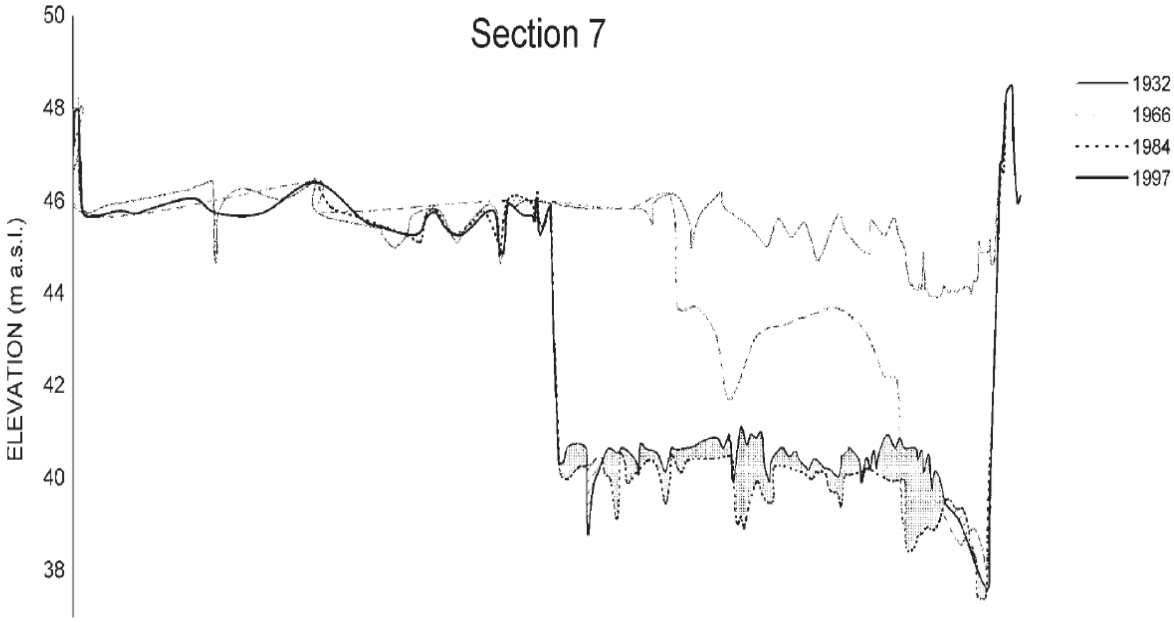

Figure 6.12 Example of changes in cross-sectional form over time for the River Brenta, Italy. Channel narrowing and incision were the dominant processes initially, but channel widening and aggradation have occurred in recent years (Surian and Cisotto, 2007).

Remote sensing approaches to characterise channel morphology fall into two categories. The first uses altimetry data from photogrammetry, LiDAR or TLS to create 3D models of the channel bed. These digital elevation models (DEMs) are then used to identify features, detect changes in the morphology over time and even calculate volumetric differences over time. This approach is most applicable to shallow, wide rivers for which a substantial portion of the bed is exposed. Large gravel bed rivers have been studied extensively using this method (e.g. Westaway et al., 2000; Lane et al., 2003; Lane et al., 2010; Wheaton et al., 2010; Moretto et al., 2013). However high resolution LiDAR and TLS have been applied to the study of bank and cliff erosion in meandering rivers in conjunction with aerial imagery (e.g. De Rose and Basher, 2011; O'Neal and Pizzuto, 2011), and recent work has demonstrated the potential for automated extraction of channel networks and bankfaces from LiDAR (Passalacqua et al., 2010; Passalacqua et al., 2012; Tarolli et al., 2012; Fisher et al., 2013). LiDAR has an additional use in bathymetric data collection. Bathymetric LiDAR can measure the bed topography of rivers up to ca. 60 m depth with high vertical accuracy. It does not suffer from problems associated with sun glint, shadows or surface disturbances like the following spectral approach; but its application is limited to waters with low suspended sediment concentrations and is not suitable for application to very shallow water (< 1.5 m deep) (Hilldale and Raff, 2008; Gao, 2009).

The second approach estimates water depths using the spectral signature of aerial photographs and multi / hyper spectral data (for a recent review, see Gao, 2009). This technique is well developed and has been used successfully to study changes in many types of water bodies, particularly coastal areas. It is used increasingly to characterise river bed topography (aerial photography (e.g. Winterbottom and Gilvear, 1997; Westaway et al., 2000; Carbonneau et al., 2006; Lane et al., 2010; Legleiter, 2013); airborne multi- and hyper spectral data; (e.g. Winterbottom and Gilvear, 1997; Roberts, 1999; Whited et al., 2002; Marcus et al., 2003); multi-spectral satellite data (Legleiter and Overstreet, 2012)). Although analysis of remotely-sensed data can provide good characterisation of spatial changes in water depth, the absolute accuracy of the depth estimates depends on calibration using synchronous water depth measurements. This has limited the use of spectrally-derived depth measurements in historical analyses (but see Lane et al., 2010 for one solution to the problem of ground-truth data for historical aerial photographs). Furthermore, spectrally-based bathymetry is limited not only to shallow water depths (typically a few metres) but also requires clear water conditions, substrate with bright and reflective surfaces, good illumination, and minimal atmospheric interference (Legleiter et al., 2009).

Whilst the focus of discussion of remote sensing techniques throughout this review is on airborne and satellite approaches, it is worth pointing out that sonar and other related acoustic devices can be used to map subsurface topography from boats. In fact most modern surveys of bathymetry are conducted using interferometric or multibeam sonar. Cserkesz-Nagaz et al. (2010) used a more advanced tool, called a sub-bed profiler, to map the bed topography of the Tisza River, Hungary. The high resolution seismic data allowed them to measure the bed-level, the thickness of the fine sediment deposits, and to identify older, consolidated deposits. This data was combined with measurements from repeat cross sections and historical maps to track changes in bed level and the evolution of scour pools and point bars.

In some circumstances, a geomorphological field survey may be the only available option to assess changes in channel geometry over time. This may be true for remote, narrow or slowly-adjusting streams which may not be represented on maps or may be subjected to high levels of uncertainty in spatial position which exceed the amount of change being detected. Field survey of channel characteristics indicative of river channel adjustment are described in section 5.6.2 and examples of indicators of temporal changes in channel bed-level are given in Section 6.3.3.

6.4.3 Bed sediment calibre

Temporal change in bed sediment calibre is often difficult to assess due to a lack of available data. However, descriptions of characteristics that may be extracted during field survey are provided in section 5.6.2 and Annex D. The use of a range of other, secondary sources is described below. Any of these sources and approaches can be used, and typically must be used in combination to characterise past sediment size and assess change over time.

As with the previous discussion of channel depths, research has demonstrated the potential for remotely-sensed characterisation of bed calibre, but at this time application is limited. Over the last decade, techniques have been developed for the extraction of bed material size from aerial photography based on image texture (Ibbeken and Schleyer, 1986; Butler et al., 2001; Carbonneau et al., 2004; Carbonneau et al., 2005; Buscombe et al., 2010; Dugdale et al., 2010). For shallow rivers with non-turbid water, these techniques offer the possibility of extracting sediment sizes from archival aerial photos to assess change over time, particularly in light of recent analytical developments that allow for automated sediment size measurement without the need for field calibration (e.g. Buscombe et al., 2010).

Airborne laser data (LiDAR) does not have the spatial or vertical resolution for all but the largest of grains, but terrestrial laser scanning has been shown to be effective in characterising the exposed gravel beds of braided rivers (Heritage and Milan, 2009; Hodge et al., 2009; Brasington et al., 2012). Backscatter information from sonar can also be used to estimate bed sediment calibre (Amiri-Simkooei et al., 2009; Eleftherakis et al., 2012).

Box 6.5 A combined approach to assessing temporal change in bed sediment calibre

Temporal changes in bed sediment calibre can be studied effectively using a combination of historical analysis using maps, geomorphological surveying and palaeo approaches. For example, Arnaud-Fassetta (2003) used historical maps to identify the location of palaeo-channels, historical topographic data conducted before and after river engineering works to examine changes in cross-sectional geometry, and a field survey to measure grain sizes in contemporary and palaeo-channels in the Rhone River delta. The study concluded that grain size increased over the last few centuries as a result of channel incision and widening following climatic changes post-Little Ice Age and river engineering works.

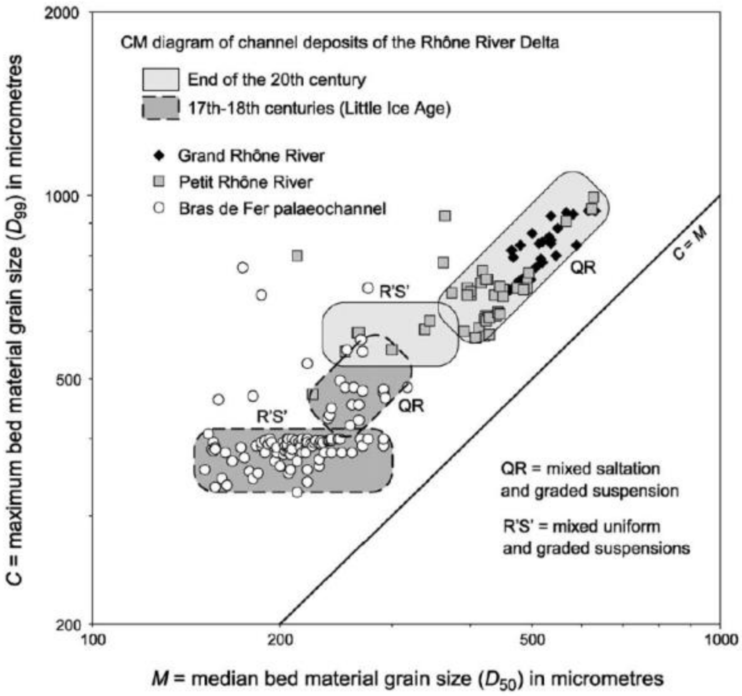

Figure 6.13 A comparison of bed sediment calibre from modern and palaeo-channels which indicates increasing flow competence over time (Arnaud-Fassetta, 2003).

The historical record has limited use for bed sediment calibre characterisation. Bed grain size might be mentioned in diaries or travel accounts, but use of this information would be limited largely to a qualitative assessment. Ground photos can offer a more reliable record of grain size as long as they include an element that can be used to provide a scale estimate. This approach would be most successful for gravel-bed braided or wandering rivers where the bed material is more likely to be visible. The most accurate evidence comes from historical scientific studies (e.g. bedload transport studies), but such datasets are rare. Overall, historical approaches are unlikely to yield much data on bed sediment calibre, and so in most cases the best options to assess changes in bed sediment calibre are a palaeo approach or a geomorphological field survey.

Palaeo and field survey approaches are closely related, and differ only in the level of detail of the analysis. A field survey would indicate if there are morphological forms and structures that are indicative of a change in bed calibre (e.g. bed armouring or extensive fine sediment deposits in a gravel bed river), but stratigraphic and sedimentological techniques can be used to quantify changes in bed sediment size or to date strata (e.g. changes in sediment size within a sequence of terraces).

6.5 Accuracy, Uncertainty, and Error

All data is subject to error, and so a careful appraisal of error is essential to scientific data analysis. As stated earlier, accuracy, error and uncertainty are related, are frequently used interchangeably, and are all associated with the reliability of the data to represent the true form or process in nature (Tucci and Giordano, 2011). The differences are subtle. When errors have been quantified for a particular data source, they are typically referred to as 'accuracy'; when they are unknown or not clearly defined, the term 'uncertainty' is used; and the term 'error' is used variously and often when it is quantified by the user. In this section, we use accuracy preferentially, and reserve uncertainty or error for the discussion of estimation methods when accuracy is not defined in advance for a dataset.

6.5.1 Types of accuracy

Accuracy can by subdivided into 3 components: position, attribute and time (Bolstad and Smith, 1992; Gurnell et al., 2003). Positional accuracy refers to the location of a feature on a graphical representation (e.g. map, photograph or remotely-sensed dataset) in relation to other features (i.e. relative accuracy) or its true location in nature (i.e. absolute accuracy). It is influenced by the methods employed to collect, interpret and display the data. For example, the absolute accuracy of a river drawn on a map is dependent on the accuracy of the original survey or the resolution of the aerial photographs it is derived from; the interpretation of a feature from those sources (e.g. banklines); the geographical projection used; and the purpose and scale of the map. Positional accuracy is routinely quoted for national/regional maps and satellite datasets. For example, a 1:10,000 scale UK Ordnance Survey map represents rivers at their true scale, with two banklines, when they are at least 5 m wide. Average positional accuracy is quoted at ±4 m (± 7 m, 95% confidence level), meaning that the channel's location on the map is on average 4 m off relative to its true position, and most points are within 7 m. Larger-scale maps typically have higher positional accuracy. A UK Ordnance Survey map at 1:2500 scale represent rivers to scale when they are 2m wide, and has an absolute accuracy of ±2.8 m. When comparing maps over time in a diachronic analysis, these measures of positional accuracy can be combined to calculate a threshold for planform change detection (see below for more information).

Attribute accuracy relates to how the identification of a feature or the characteristics of a pixel compares to its true characteristics at that location. Some degree of interpretation, simplification or classification is inherent when data is recorded, analysed and displayed graphically, whether this was done by the original surveyor and mapmaker of a historical map or a satellite-based sensor and a GIS technician, so attribute accuracy is always an issue. For example, for satellite-based multispectral data, the spectral signature of a feature is influenced by the spatial resolution of the data relative to the feature size, as well as by changes in illumination (e.g. sun angle), atmospheric conditions (e.g. clouds or haze), and viewing geometry (Lillesand et al., 2004). The spectral signature is then processed, interpreted and classified, all of which can affect attribute accuracy. If features are small relative to spatial resolution, pixels will represent more than one feature (i.e. mixed pixels), adding additional uncertainty to feature identification or classification. Techniques have been developed to help overcome this problem, e.g. classification of mixed pixels for land cover using fuzzy logic (Lillesand et al., 2004; Perez-Hoyos et al., 2012), but in general it is best to considered the spatial scale of a feature *a priori* when selecting a data source.

Temporal accuracy is concerned with the amount of time between the collection and the publication of the data. This is primarily a concern for historical data sources, such as maps and documentary evidence. The time lag between the initial field survey and the publication of a map can vary substantially. Often with historical maps, a single publication date is listed for the entire map collection, even though locations were surveyed and map sheets produced at different times. An additional problem with maps is partial resurveying, in which only a portion of an earlier map is updated and labelled with the new date. These resurveys introduce significant temporal uncertainty if the extent of the resurvey is not indicated. Temporal accuracy is less of an issue for remotely-sensing datasets, which are typically time/date stamped at collection or processing.

6.5.2 Assessing accuracy / uncertainty

A wide range of data sources can be used in the analysis of temporal change in river form and processes. These sources differ substantially in their inherent reliability and it is extremely important that sources are assessed prior to inclusion into a study. Assessment involves a series of internal and external checks that verify the positional, attribute and temporal accuracy of a source (Hooke and Kain, 1982). For example, a historical map can be checked to see if it is a partial resurvey by examining accompanying records, comparing the map against earlier or later ones from the same source, or comparing the map to other sources from the same time period (e.g. land survey records, aerial photograph). If the data sources are judged to be sufficiently reliable for the analysis, the accuracy or uncertainty of the data can be estimated and integrated with the other sources in the temporal analysis to support change detection. In the remainder of this section, we provide further information on estimating positional and attribute accuracy.

When not reported for a data source, positional accuracy can be estimated by comparing positions on the graphical representation with their true location (e.g. ground control points) or with locations on a map or digital product with higher accuracy. When using a GIS, this process takes place when the data source is registered to a geographical projection (i.e. georeferencing). To illustrate this, we provide an example using historical maps. A similar procedure would be conducted with aerial photographs, however there are additional steps that should be taken to correct for image distortion or perspective, i.e. orthorectification (for an introduction see a relevant textbook, such as Jensen, 2000). A historical map is typically registered to a coordinate system by identifying common landmarks on a modern large-scale map (Hu, 2010). Landmarks should be stable in space and time (e.g. a building), as precise as possible (e.g. the southwest corner of the building), and evenly distributed over the map. Geometric transformations are then used to alter the scale, displacement and rotation of the historical map (Manzano-Agugliaro et al., 2013). For most maps, a first-order transformation should be used, unless there is significant evidence of shrinkage and distortion of the paper map (Gurnell et al., 1994). The output of this process is an average displacement of positions on the historical map, typically represented as a root mean square error (RMSE) and often used to assess positional accuracy (Cheung and Shi, 2004; James et al., 2012). Minimum thresholds for change detection are commonly calculated by summing the RMSE; however this may not be correct in many situations as it requires several assumptions to be met (e.g. no bias, error independence) (Lane et al., 2003). See Mount and Louis (2005) for a more robust approach to error estimation and propogation that uses x,y coordinates and allows for anisotropy, and Tucci and Giordano (2011) and Manzano-Agugliaro et al. (2013) for recent spatially-explicit approaches to accuracy and feature change detection in historical maps.

This discussion of the assessment of attribute accuracy / uncertainty focuses on raster datasets. Numerous techniques are available to assess uncertainty and detect change, and the choice is dependent on the data and type of change being detected (for an introduction see Lu et al., 2004; Congalton and Green, 2009). For land cover, error mis-classification matrices are commonly used post-classification, to estimate attribute accuracy and detect change (e.g. Congalton, 1991; Fichera et al., 2012). A fuzzy logic approach is particularly appropriate when attribute classes are not standardised over time or between sources (Metternicht, 1999; Perez-Hoyos et al., 2012), and a multi-layer (GIS-based) approach can be useful when multiple data sources are integrated for the classification (Lu et al., 2004; Congalton and Green, 2009; Fichera et al., 2012). A direct comparison of pixels between years can be used, but this approach is more sensitive to positional and attribute errors.

An attribute that deserves special attention is elevation. DEMs are datasets with elevation as an attribute, and a characterisation of uncertainty in these measurements is essential for detecting changes in topography over time using DoDs. Similar to the discussion of 2D change detection, volumetric change detection can use a single threshold of change or a spatially distributed approach (Wheaton et al., 2010; Milan et al., 2011). Wheaton et al. (2010) have made their change detection software freely-available on the web as an ArcGIS extension[6].

[6] Geomorphic change detection ArcGIS extension. http://essa.com/tools/gcd/, accessed on 14-Nov-2013.

7. Extended River Typology

7.1 Introduction

In section 4.5, a simple classification of river types was presented, which was based on river channel planform character (number of threads and planform pattern) framed in the context of valley setting (degree of confinement) and was used to delineate reaches using readily-available information, mainly remotely-sensed imagery. The typology defines 7 river types (plus a type 0 for highly altered reaches) (Table 7.1, Figure 7.1).

Here, an extended typology is proposed (section 7.3), reflecting additional reach properties acquired during the characterisation phase (sections 5.5 and 5.6). The typology is followed by a description of different types of floodplain (section 7.4) and the nature of groundwater-surface water interactions (GSI, section 7.5) that may accompany the river types in the extended typology. However, before the extended typology is presented, it is important to consider how it links with the WFD river types (in their current provisional form as listed in Table 1.1), and also to stress some cautions concerning its application, these topics are discussed in section 7.2.

Although the extended typology is informed by previous geomorphological research (e.g. Schumm, 1985; Rosgen, 1994; Knighton and Nanson, 1993; Nanson and Knighton, 1996; Montgomery and Buffington, 1997; Church, 2006; Fuller et al., 2013; Nanson, 2013), it is designed for practical application by stakeholders and river managers, and it builds explicitly on the simple classification described in section 4.5. For additional information, see Thematic Annex E of Deliverable 2.1 Part 2, which provides a synthesis of the classifications proposed by Montgomery and Buffington (1997) and Church (2006). In addition, Buffington and Montgomery (2013) give a recent comprehensive review of geomorphic classifications of rivers.

7.2 The REFORM Extended River Typology: Links with the WFD River Typology and some cautions concerning Applications

As outlined in section 1.4, the provisional river typology of the WFD CIS Working Group ECOSTAT (March 2014) is a simple, high-level classification that assigns rivers to one of 14 classes according to the altitude, area, and geology of their catchment. In essence, this is a catchment rather than a river classification, and it provides a set of classes into which member states can assign more detailed river sub-classes.

In contrast, the extended typology described in this chapter is a process-based river reach typology reflecting a combination of valley confinement, river planform and bed material calibre. The typology attempts to link river reaches that possess different combinations of these three properties to the geomorphic units that the river channel and its genetic floodplain are likely to support, and also to the likely stability of the river system. It also provides an indication of the typical slope or gradient of river reaches in each of the categories and it links the different river reach types to a potential genetic floodplain type (7 classes identified as being applicable to Europe, section 7.4), and a description of likely groundwater-surface water interactions (section 7.5).

Table 7.1 Simple Classification of River Types based on Confinement and Planform

Type	Confinement	Threads	Planform	*Si* (note 1)	*Bi* (note 2)	*Ai* (note 3)
1	Confined	Single	Straight-Sinuous	n/a	approx. 1	approx. 1
2	Partly confined / Unconfined	Single	Straight	< 1.05	approx. 1	approx. 1
3	Partly confined / Unconfined	Single	Sinuous	1.05 < *Si* < 1.5 *	approx. 1	approx. 1
4	Partly confined / Unconfined	Single	Meandering	>1.5	approx. 1	approx. 1
5	Confined / Partly Confined / Unconfined	Transitional	Wandering		1 < *Bi* < 1.5	*Ai* < 1.5
6	Confined / Partly Confined / Unconfined	Multi-thread	Braided		*Bi* ≥ 1.5	Ai < 1.5
7	Confined / Partly Confined / Unconfined	Multi-thread	Anabranching		*Bi* < 1.5 or *Bi* > 1.5	Ai > 1.5

notes:
1. *Si* (sinuosity index) is the ratio between the distance measured along the (main) channel and the distance measured following the direction of the overall planimetric course (or 'meander belt axis' for single thread rivers).
2. *Bi* (braiding index) is the number of active channels separated by bars at baseflow.
3. *Ai* (anabranching index) is the number of active channels at baseflow separated by vegetated islands

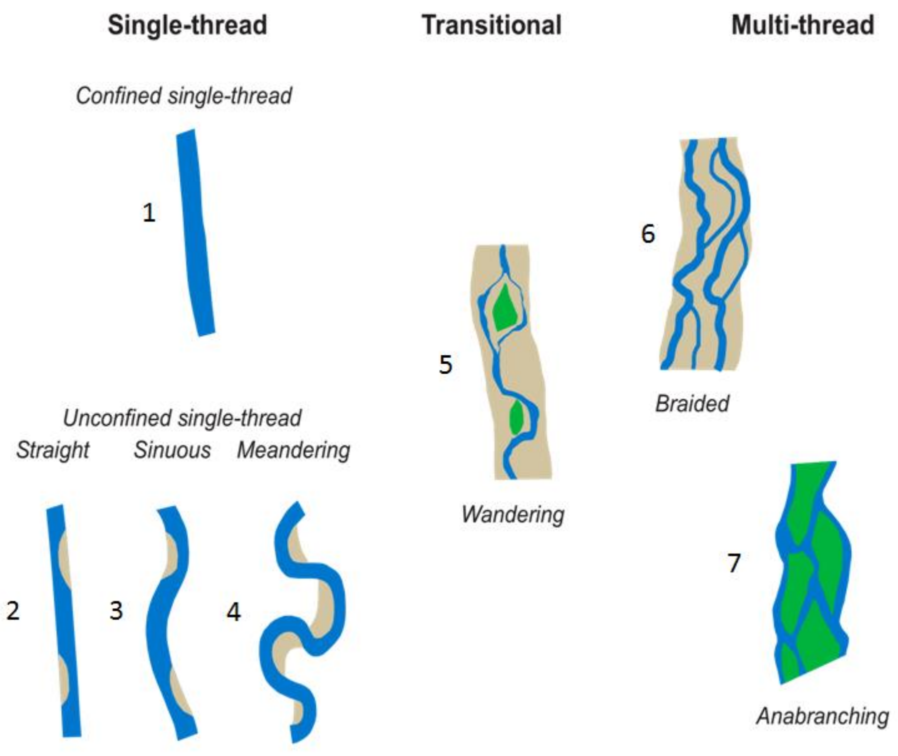

Figure 7.1 Simple River Typology based on Confinement and Planform

Despite the fact that a typology is proposed in section 7.3, it must be stressed that rivers and their floodplains do not fit into neat classes but vary continuously in response to controlling factors across space as well as time. Therefore, the extended typology is inevitably a gross simplification and should be applied with care, recognising that numerous transitional types exist and that there will be variance within and between the types. It is unlikely that any river reach will perfectly fit a single type by displaying precisely the combination of geomorphic units, bed sediment calibre, gradient or stability that are suggested. Nevertheless, it should be possible to identify a river type or transition between types that best fits a particular river reach. In addition, there is no reason why additional (sub-types) cannot be introduced for application in a particular member state, if they are felt to be important in that context. For example, a finer subdivision of sinuosity could be used to split meandering reaches into weakly meandering, meandering and strongly meandering.

The following points consider the way in which the REFORM extended typology might map onto the WFD river typology, and provide some cautions in relation to the application of these two typologies:

(i) <u>Level of confinement and gradient</u> vary with position in a catchment and so have some relationship with *catchment size* and *topography/elevation*, two of the criteria incorporated in the WFD river typology. Furthermore, as fluvial sediments are sorted and abraded along rivers, bed material tends to fine downstream. Therefore, confined, bedrock and colluvial channels (types 1 to 3) and confined, single thread, boulder-cobble-gravel channels (types 4 to 7) are most likely to be found in relatively small, steep, headwater catchments, predominantly at relatively high elevations. These river types are generally associated with confined, narrow, often discontinuous floodplains. In contrast, partly-confined or unconfined, sand and silt bed rivers (types 15 to 22) are most likely to be found in low-gradient, downstream reaches, with considerably larger catchments than types 1 to 7 and associated with quite extensive floodplains.

(ii) <u>Geology</u>. The above-described small to large, high to low altitude catchment relationship with river type is far too simple. The third factor incorporated in the WFD typology, provides a further refinement in that *geology* influences the erodibility of the rock, the typical clast sizes generated by rock weathering and erosion, and thus the upper limit to bed material calibre. Also, in the case of permeable rocks, the geology places a limit on the size of catchment required before water appears on the surface to produce streams and rivers. Thus geology is a significant confounding factor influencing the types of river that can theoretically exist in a catchment: if the bedrock is a young, friable sandstone, then only bedrock, or sand and finer river types are feasible.

(iii) <u>Roughness elements and river size</u>. Channel form and dynamics are also scaled to the roughness elements that form their boundaries. While the fundamental roughness elements are the particles of the bed and bank material, plants and wood also form important roughness elements. The effect of a tree, a large log or a boulder on river form and dynamics changes with river size. The extended typology incorporates the influence of bed material size to some extent, but it does not explicitly consider the variations that may occur among rivers of different size with similar bed material, and it does not consider the impact of plants and wood at all (although this is a central theme in Deliverable 2.2). Church (1992) suggested that ‘small’, ’medium’ and ‘large’ rivers should be identified according to the relative roughness of bed material grain diameter (D) and channel depth (d), with small channels showing an approximate D/d ratio of > 1; intermediate channels showing 1.0 > D/d > 0.1, and large channels showing D/d < 0.1. Similarly, Gurnell (2003) suggested that forest rivers are small when they are narrower than the typical wood piece length; medium when they are slightly narrower than the larger wood pieces (or tree height) present and large when they are wider than the length of the wood pieces (or tree height) delivered to them. These examples illustrate that there are many ways to express river size apart from the area of the catchment or the channel width. If channels are small with respect to the size of riparian or aquatic plants or wood pieces, then the latter are likely to have an overriding influence on channel morphology, which is likely to be very irregular, and on the particular geomorphic units that are present in and around the channel. Medium sized channels, with respect to the size of riparian or aquatic plants or wood pieces, would be expected to map quite well onto the proposed typology but would nevertheless show some significant morphological deviations associated with a very significant presence of the wood- and vegetation-related geomorphic units described in table 5.7. Large-sized channels, if they are relatively unmanaged, may also show a significant presence of the wood-and vegetation-related geomorphic units described in table 5.7, but these units would not impact on the broad morphological type or style of the river.

(iv) Assemblages of river types. Overall, it is important to recognise that the extended river types described in this chapter vary both within and between catchments of different size, but a typical assemblage of types is expected to be present within different segments or landscape units, and this assemblage of types will reflect the controlling factors presented in Table 7.3 coupled with the vegetation, flow regime and human interventions. Thus the extended typology can be loosely linked to the WFD typology, but, as intended by the latter, the nature of rivers falling within each WFD type are highly variable across space and through time.

(v) Linking ecology with hydromorphology. The REFORM extended typology has been developed as a key for reading fluvial systems through survey units, at different spatial scales, that could be relatively homogeneous with respect to river geomorphological processses. A multi-scale hierarchical approach, as that used in the REFORM multi-scale framework, is fundamental for many management applications, for example for selecting sampling and monitoring sites, and for interpreting and extrapolating the information gathered at specific sites to other sites of the same typology. This is an essential step in trying to find the right space and time scales for relating the hydromorphological aspects to the ecological ones (Frissel et al., 1986). This approach is also very respectful of the rationale behind the WFD system of classification, in that the reference conditions for biology assume an almost unaltered hydomorphological condition and biological status and must be consistent with those hydromorphological conditions.

7.3 Extended River Typology

The extended typology represents typical associations between channel planform, bed sediment calibre and geomorphic units, framed in the context of different valley settings. This typology is built directly onto the simple typology, providing more detailed information on reach character. However, several of the simple types are subdivided when there is a clear distinction within the same simple morphological type, reflecting different bed material calibre and/or morphological units (e.g. different bed material or bed configuration sub-types of confined single thread reaches; a change from a straight / sinuous channel with continuous bars to a straight / sinuous channel with sporadic to absent bars).

Twenty-two extended morphological types are identified (Table 7.2, Figures 7.2 and 7.3) and described (Table 7.3) according to their confinement (confined, partly confined, unconfined), dominant bed material calibre (bedrock, boulder, cobble, gravel, sand, silt) and planform (straight-sinuous, meandering, pseudo-meandering, wandering, braided, island-braided, anabranching). The following points should be noted:

(i) The extended types are intended as 'naturally-functioning' types. Therefore type 0 (highly altered reaches) from the simple typology is retained in the extended typology, and any reach with a predominantly artificial bed is allocated to this type.

(ii) Straight and sinuous types are combined in the definitions and descriptions of the extended typology (Tables 7.2 and 7.3), because both planform types are related to similar morphological units when they possess similar bed material and level of confinement. However, to avoid inconsistency between the simple and extended classifications, the combination of, for example, a 'straight' channel (simple classification) with a 'straight-sinuous with alternate bars' (extended classification) should lead to a 'straight with alternate bars' extended type.

(iii) A new transitional type is added to the extended classification: 'pseudo-meandering'. This describes straight or sinuous channels that display large, alternate bars at low flow. While the bankfull channel conforms to a straight or sinuous channel, the low flow channel is so heavily affected by the exposure of alternate bars that it would be defined as meandering if its Si index were to be calculated for the inundated channel at low flow.

The 22 extended types are not an exhaustive list of possible combinations of planform, morphological units, valley setting and sediment size, but rather an indicative, general framework for identifying catchment- or region-specific ranges of morphologies. This is because river characteristics cannot be neatly divided into classes, they vary continuously and thus transitional types are likely to be encountered quite frequently. Furthermore, the set of distinguishing morphological attributes may vary between biogeographical regions, but a check-list of the units that may be present within the channel and its floodplain is provided in Table 7.3 as a starting point.

Table 7.2 Index of the 22 morphological types in the extended classification

BED MATERIAL CALIBRE **(dominant type in bold)**	PLANFORM							
	Braided	Island Braided	Anabranching (high energy)	Wandering	Pseudo-meandering (sinuous with alternate bars)	Sinuous - Straight	Meandering	Anabranching[1] (low energy)
	No exposed bed material							
Entirely artificial bed	0							
	Bedrock and Colluvial Channels							
Bedrock	1							
Coarse - Mixed	2							
Mixed	3							
	Alluvial (confined single-thread)							
Boulder - Cobble	4 (Cascade)							
Boulder - Cobble	5 (Step-pool)							
Boulder - **Cobble** – Gravel	6 (Plane Bed)							
Cobble - **Gravel**	7 (Riffle-pool)							
	Alluvial (partly-confined / unconfined single thread; confined / partly-confined / unconfined transitional / multi-thread)							
Cobble - **Gravel** - Sand (gravel-bed rivers)	8	9	10	11	12	13	14	
Fine Gravel - **Sand** (sand-bed rivers)	15				16	17	18	19
Fine Sand - **Silt** - Clay (cohesive)						20	21	22

[1] The term *anastomosing* is often used to describe low energy *anabranching* rivers that are very stable, showing negligible lateral migration or exposed (unvegetated) sediment above the limits of the low flow channel (i.e. types 19 and 22).

Table 7.3 Descriptions of the 22 morphological types in the extended classification

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope ($m.m^{-1}$)	Potential Morphological (Geomorphic) Units	Stability	Description
HEAVILY ARTIFICIAL							
0 (0)	Confined / Partly confined / Unconfined	Artificial	Any	Any	Some superficial bars may be present	Very Stable	Highly modified reaches
BEDROCK AND COLLUVIAL CHANNELS							
1 (1)	Confined	**Bedrock**	Straight-sinuous	Usually steep	Rock steps Cascades Rapids	Usually strongly confined and highly stable because of the low erodibility of the bedrock bed and bank material	These, sediment supply-limited channels exhibit no continuous alluvial bed, but some alluvial material may be stored in scour holes, or behind flow obstructions such as large boulders.
2 (1)	Confined	**Coarse mixed**	Straight-sinuous	Steep	Boulder levées Cascades Sand splays Abandoned channels	Can be highly unstable as water is diverted around and across very coarse bed deposits supplied from hillslopes.	Small, steep channels at the extremities of the stream network. Very coarse bed sediment and large wood pieces delivered by debris falls, slides and flows accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows.
3 (1)	Confined	**Mixed**	Straight-sinuous	Lower gradient than types 1 and 2	Poorly defined, featureless channels.	Very stable, shallow (often ephemeral) channels	Small, relatively low gradient channels at the extremities of the stream network. Mixed bed sediments delivered by less catastrophic hillslope processes than the steep subtype accumulate as colluvial valley fill to form the channel bed. Very low and variable fluvial transport limited by shallow flows.

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope (m.m^{-1})	Potential Morphological (Geomorphic) Units	Stability / Capacity for Adjustment	Description
ALLUVIAL CHANNELS							
4 (1)	Confined	**Boulder**	Straight-sinuous	> > 0.04	Cascades Small pools (do not span the channel, often less than a channel width apart).	Stable for long periods but occasional catastrophic destabilisation during debris flows.	Very steep with coarse bed material consisting mainly of boulders and local exposures of bedrock that split the flow and allow throughput of bed material finer than the large clasts dominating the bed structure.
5 (1)	Confined	**Boulder** - Cobble	Straight-sinuous	> 0.04	Step-pools (alternating, channel-spanning, steep sections and pools)	Stable for long periods but occasional catastrophic destabilisation during debris flows.	Sequence of channel spanning accumulations of boulders and cobbles (steps) support broken, fast-flowing, turbulent, shallow flow threads,separated by pools that frequently span the channel, are usually lined with finer, cobble-sized, material, and support deeper, slower flowing water that is also often turbulent..
6 (1)	Confined	Boulder - **Cobble** - Gravel	Straight-sinuous	> 0.02	Relatively featureless plane bed. Forced bars Forced pools induced by obstructions (boulders, large wood). Occasional: Rapids. Abandoned / active side-channels	Relatively stable for long periods, but floods can induce lateral instability and avulsions, with secondary channels that may be periodically reoccupied, and some channels can be destabilised by debris flows.	Predominantly single thread but secondary channels are sometimes present. Plane bed, composed of predominantly cobble and gravel sized material with occasional boulders or sand patches. Flows are fairly uniform, comprised of glides and runs with occasional rapids. Total sediment transport is low and is supplied mainly by bank erosion / failure and fluvial transport from upstream, but debris flows may occur in some locations.

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope (m.m^{-1})	Potential Morphological (Geomorphic) Units	Stability / Capacity for Adjustment	Description
ALLUVIAL CHANNELS (ctd.)							
7 (1)	Confined	Cobble - **Gravel**	Straight-sinuous	> 0.01	Pools Riffles Lateral bars	Subject to frequent shifting of bars.	Coarse cobble-gravel sediments are sorted to reflect the flow pattern and bed morphology. Total sediment transport is low and is supplied mainly by fluvial transport from upstream and some debris flows.
8 (6)	Confined / Partly confined / Unconfined	**Gravel** - Sand	Braided	<0.04	Mid channel bars Riffle-pools (particularly noticeable in large braid channels).	Usually highly unstable both laterally and vertically	Occur where sediment supply is relatively higher and/or slopes are steeper and / or sediment is coarser than types 9 and 10. Bed material is supplied predominantly by bank erosion / failure and fluvial transport from upstream reaches, but debris flows may occur in confined and partly-confined locations.
9 (6)	Confined / Partly confined / Unconfined	**Gravel** - Sand	Island-braided	<0.04	Islands Mid channel bars Riffle-pools (particularly noticeable in large channels)	Usually unstable both laterally and vertically	Island braided channels are distinguished from type 11 by > 20% area of active tract covered by islands of established vegetation. Bed material is supplied predominantly by bank erosion / failure and fluvial transport from upstream reaches, but debris flows may occur in confined and partly-confined locations.
10 (7)	Confined / Partly confined / Unconfined	**Gravel** - Sand	Anabranching (high energy)	<0.01	Islands Riffle-pools (particularly noticeable in large channels)	Most stable of the gravel-sand channel types but some lateral instability usually present	Islands covered by mature vegetation extend between channels with only occasional exposured sediment bars Bed material is supplied predominantly by bank erosion / failure and fluvial transport from upstream reaches.

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope (m.m^{-1})	Potential Morphological (Geomorphic) Units	Stability/ Capacity for Adjustment	Description
ALLUVIAL CHANNELS (ctd.)							
11 (5)	Confined / Partly confined / Unconfined	**Gravel** - Sand	Wandering	<0.04	Islands Mid channel bars Marginal bars Riffles Pools	Usually highly unstable both laterally (but not when confined) and vertically.	Exhibit switching from single to multi-thread reflecting local changes in slope and/ or sediment supply / calibre. Bed material is supplied predominantly by bank erosion / failure and fluvial transport from upstream reaches, but debris flows may occur in confined and partly-confined locations.
12 (3)	Confined / Partly confined / Unconfined	**Gravel** - Sand	Pseudo-meandering	<0.04	Large, continuous alternate bars Riffles Pools	Usually highly unstable both vertically, and also when not confined.	Differs from type 11 in its lower sinuosity and very pronounced alternating lateral bar development. Undulating thalweg reflects alternating sequence of pools, riffles and bars.
13 (2 or 3)	Partly Confined / Unconfined	**Gravel** - Sand	Straight-sinuous	< 0.02	Pools Riffles Large alternate (continuous) point bars closely confining the low flow channel	Subject to frequent shifting of bars.	Although dominated by gravel, bed material of varying size in the sand to cobble range may be present. Sediments are usually well sorted to reflect the flow pattern and bed morphology. Total sediment transport is low and is supplied mainly by bank erosion / failure and fluvial transport from upstream, but debris flows may occur in some locations.

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope ($m.m^{-1}$)	Potential Morphological (Geomorphic) Units	Stability/ Capacity for Adjustment	Description
ALLUVIAL CHANNELS (ctd.)							
14 (4)	Partly Confined / Unconfined	**Gravel** - Sand	Meandering	< 0.02	Pools Riffles Point bars Chutes (on point bars) Cutoffsand abandoned channels (across floodplain) Scroll bars Point benches	Laterally unstable sinuous channels subject to lateral and/or progressive migration	Undulating thalweg reflecting an alternating longitudinal and lateral sequence of pools, riffles and bars. Lateral instability often reflected in sequences of landforms such as point benches and scroll bars, which extend across the floodplain
15 (6)	Confined / Partly confined / Unconfined	Fine gravel - **Sand**	Braided	<0.02	Bars Ripples (and Dunes)	Unstable both laterally and vertically	Vegetation critical in limiting the lateral extent of the bar-braided channel.
16 (3)	Confined / Partly confined / Unconfined	Fine gravel - **Sand**	Pseudo-meandering	<0.02	Continuous, large alternate bars Pools Ripples (and Dunes)	Vertically unstable due to bar movement and sometimes migrate laterally.	Continuous, extensive, highly sinuous, bar development within a straight to sinuous channel

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope (m.m^{-1})	Potential Morphological (Geomorphic) Units	Stability/ Capacity for Adjustment	Description
ALLUVIAL CHANNELS (ctd.)							
17 (1or 2)	Partly confined / Unconfined	Fine gravel - **Sand**	Straight-sinuous	<0.02	Riffles Pools Point bars Ripples (and Dunes) Occasional: Benches Scroll bars Leveés Backswamps	Laterally unstable sinuous channels sometimes subject to lateral and/or progressive migration	Undulating thalweg reflecting an alternating longitudinal and lateral sequence of pools, riffles and bars.
18 (4)	Partly confined / Unconfined	Fine gravel - **Sand**	Meandering	<0.02	Pools Point bars Ripples (and Dunes) Scrolls Leveés Ridges and Swales Backswamps Abandoned channels	Laterally unstable sinuous channels subject to lateral and/or progressive meander loop progression and extension with cutoffs	Undulating thalweg reflecting an alternating longitudinal and lateral sequence of pools and bars. Lateral instability often reflected in sequences of landforms such as highly sinuous meander bends, point benches and scroll bars, which extend across the floodplain as oxbows, ridges and swales with pronounced wetland development around oxbows, in swales and at the outer extermities of the floodplain

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope ($m.m^{-1}$)	Potential Morphological (Geomorphic) Units	Stability/ Capacity for Adjustment	Description
ALLUVIAL CHANNELS (ctd.)							
19 (7)	Confined / Partly confined / Unconfined	Fine gravel - **Sand**	Anabranching	<0.005	Islands Ripples (and Dunes) Leveés Vegetation-induced bar and bench forms Ripples Abandoned channels	Stable	Vegetation is critical in stabilising bars between channel threads, forming islands that develop by vertical accretion of fine sediment. Little channel bedform development unless stabilised by vegetation
20 (2 / 3)	Partly confined / Unconfined	Fine sand - **Silt** - Clay	Straight-sinuous	<0.005	Levées Backswamps	Very stable	Silt to silt-clay banks often with high organic content are highly cohesive. Little channel bedform development. Bed material is very fine, dominated by silt-sized particles but may also include coarser material, particularly sand. Sediment supply is abundant relative to transport capacity. Little channel bedform development unless stabilised by vegetation
21 (4)	Confined / Partly confined / Unconfined	Fine sand - **Silt** - Clay	Meandering	<0.005	Levées Backswamps Point and counterpoint organic benches	Very stable	Silt to silt-clay banks often with high organic content are highly cohesive. Bed material is very fine, dominated by silt-sized particles but may also include coarser material, particularly sand. Sediment supply is abundant relative to transport capacity. Little channel bedform development unless stabilised by vegetation

Extended Channel Type (Simple Channel Type)	Confined / Partly confined / Unconfined	Bed Material Calibre	Planform	Approximate /Typical Slope (m.m^{-1})	Potential Morphological (Geomorphic) Units	Stability / Capacity for Adjustment	Description
ALLUVIAL CHANNELS (ctd.)							
22 (7)	Confined / Partly confined / Unconfined	Fine sand - **Silt** - Clay	Anabranching	<0.005	Islands containing peat swamps, levées crevasse channels, crevasse splays, ponds. Vegetation-induced bar and bench forms Abandoned channels Backswamps	Very stable	Silt to silt-clay banks often with high organic content are highly cohesive. Extensive islands covered by wetland vegetation and separated by multiple stable channels. Little channel bedform development unless stabilised by vegetation. Bed material is very fine, dominated by silt-sized particles but may also include coarser material, particularly sand. Sediment supply is abundant relative to transport capacity. Little channel bedform development unless stabilised by vegetation

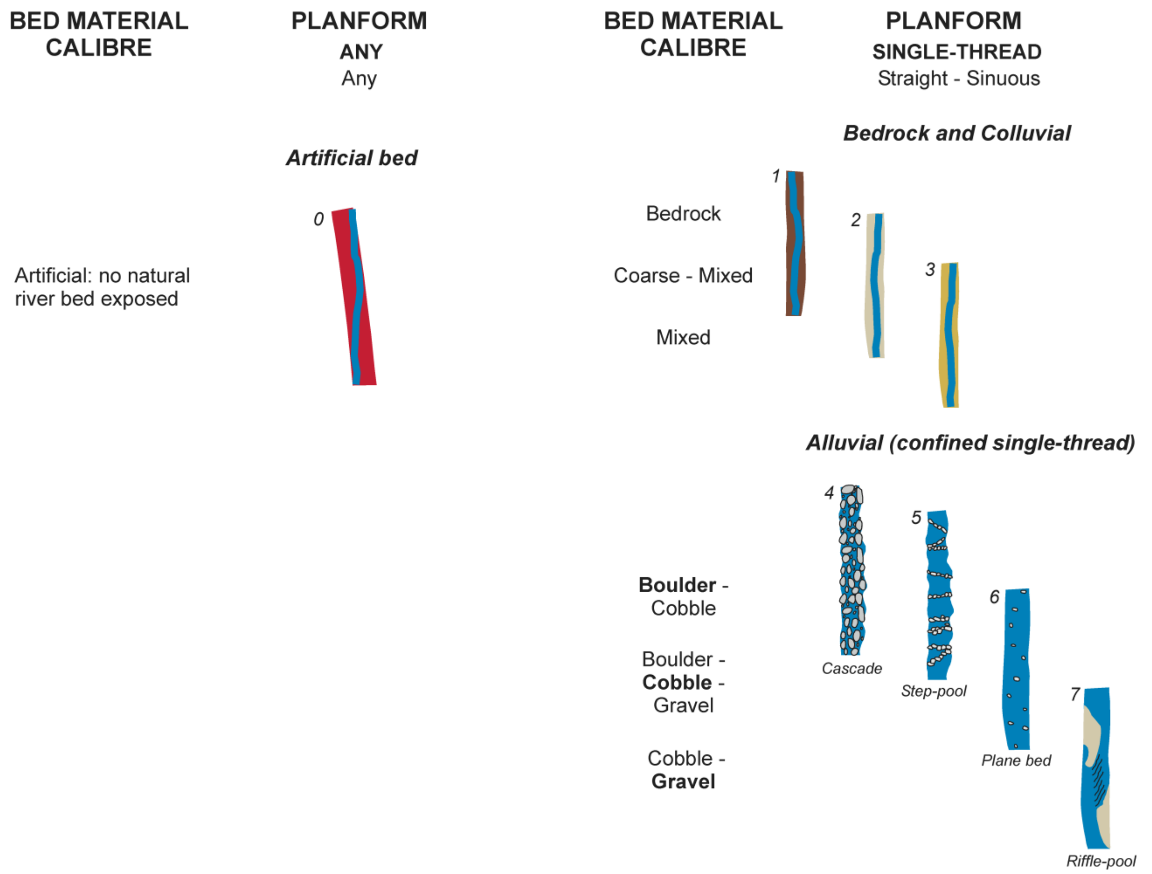

Figure 7.2 Sketches of river types 0 to 6 in the extended typology

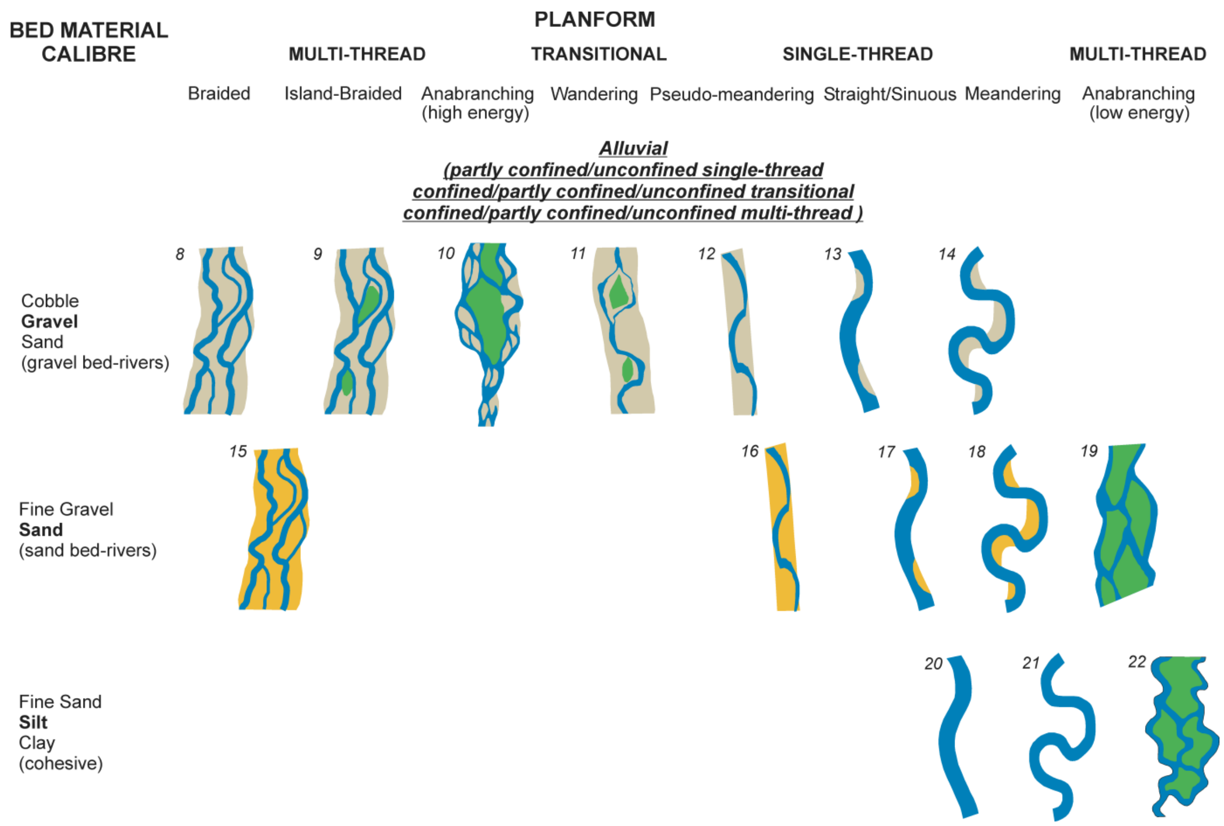

Figure 7.3 Sketches of river types 7 to 21 in the extended typology

7.4 Indicative Floodplain Characteristics associated with the Extended River Types

The extended classification of river types is designed to provide a simple means for managers to allocate a river reach to a type. In many cases the observed planform may be an artifact of human modifications to the reach or to larger spatial units that influence the reach. However, the presence of geomorphic units, bed sediment calibre and apparent channel stability that are appropriate to the river type (Table 7.3) provide evidence that a particular reach is functioning in accordance with its type. Since alluvial rivers provide the sediments to build their flood plains, the characteristics of the floodplain provide further evidence that the river is functioning in an appropriate way for its type. In addition, for rivers that have been subject to significant human-modification, floodplain features and the associated floodplain type provide an indication of the river type that may have existed prior to human modification. Furthermore, where there has been an historical change in the river type, the floodplain type provides an indication of the past character and trajectory of change experienced by the river.

Nanson and Croke (1992) proposed a genetic classification of floodplains based on river energy (bankfull unit stream power) and floodplain sediments (non-cohesive or cohesive), that is a relatively simple tool suited to the present management-oriented applications. Therefore, this classification has been adapted to provide a tool for recognising broad categories of floodplain and linking them to the extended river types that may have constructed them. Table 7.4 describes 10 broad types of floodplain that are likely to be encountered widely across Europe, and a further three types (described by Nanson and Croke for semi-arid environments), which may have some relevance to the driest parts of Europe. Figure 7.4 illustrates 7 of the 10 main floodplain types that are most likely to be encountered. Type D (wandering) is excluded because this represents a mixture of other types. Types E and F are excluded because these floodplain types are relatively featureless (see Table 7.4).

In relation to Table 7.4, the following points should be noted:

(i) the term 'floodplain' is used quite loosely, since confined or partly-confined rivers may only show patchy marginal sediment accumulations or disconnected pieces of floodplain.

(ii) the river types listed in bold in the first column are indicative types: in some cases other (adjacent) types (Table 7.3) may be associated with similar floodplain features.

(iii) the channel planform description in the first column is broader than for the individual river types listed in Table 7.3.

(iv) the values given for bankfull unit stream power in the first column should be taken as indicative rather than as strict envelope values.

(v) the floodplain sediment size classes (gravel, sand, etc.) listed in the last column are generally finer than the bed material size listed for the river types in Table 7.3, reflecting the nature of the floodplain sediments rather than the river bed sediments.

(vi) the geomorphic units listed in the last column of table 7.4 are exclusively floodplain units, whereas those in Table 7.3 are mainly channel and channel margin units.

Examples of the application of the extended typology are provided in the Case Studies of Deliverable 2.1 Parts 3 and 4.

Table 7.4 A classification of floodplains (developed from Nanson and croke, 1992)

EXTENDED CHANNEL TYPE(S) FORMING FLOODPLAIN 1. Channel planform description, 2. Environment context, 3. Bankfull unit stream power (W m-2)	**FLOODPLAIN CLASS**	**FLOODPLAIN TYPE (index letter, name)**	**FLOODPLAIN SEDIMENTS AND GEOMORPHIC UNITS**
(1), 2, 4, 5 1. single-thread straight or sinuous 2. steep confined bedrock valleys and narrow gorges 3. >1000	High energy, non-cohesive floodplains	**A.** Confined, coarse textured	*Sediments:* Poorly sorted boulders and gravel with some sand and buried soils *Geomorphic units:* boulder levées, sand / gravel splays; back / abandoned channels, scour holes, usually covered with a thin overbank deposit of fine alluvium.
3, 6, 7 1. single-thread straight or sinuous 2. upland headwater valleys 3. 300 – 1000		**B.** Confined, vertical accretion	*Sediments:* basal gravels with an overburden of abundant sand with silt. *Geomorphic units:* large levées, deep back channels, scour holes.
8, 9,15 1. multi-thread braided 2. abundant sediment load (in tectonically and glacially active areas) 3. 50 – 300	Medium energy, non-cohesive	**C.** Braided	*Sediments:* gravels with sand and occasional silt usually showing a fining-upwards sequence *Geomorphic units:* undulating floodplain comprised of the aggrading surfaces of abandoned channels, bars, and islands.
10, 11 1. transitional, wandering with possibility of some single-thread and multi-thread anabranching sections 2. abundant sediment load (alternating sedimentation zones in tectonically and glacially active areas) 3. 30 - ~200		**D.** Wandering, gravel-bed	*Sediments:* gravels, sands, silts and organic sediments *Geomorphic units:* complex undulating floodplains comprised of the aggrading surfaces of features associated with both braided and single thread river floodplains including abandoned channels; point, lateral and medial bars; and islands.

EXTENDED CHANNEL TYPE(S) FORMING FLOODPLAIN 1. Channel planform description, 2. Environment context, 3. Bankfull unit stream power (W m-2)	**FLOODPLAIN CLASS**	**FLOODPLAIN TYPE (index letter, name)**	**FLOODPLAIN SEDIMENTS AND GEOMORPHIC UNITS**
12, 13 1. single-thread sinuous / meandering 2. middle to lower valley reaches 3. 10 – 60	Medium energy, non-cohesive (ctd.)	**E.** (Sinuous / meandering) lateral migration, non-scrolled	*Sediments:* gravels, sands and silts *Geomorphic units:* gently undulating, smooth floodplain surface, sometimes with abandoned channels.
13, 14 1. single-thread sinuous / meandering 2. middle to lower reaches 3. 10 – 60		**F.** (Sinuous / meandering) lateral migration, scrolled	*Sediments:* sands with some gravels *Geomorphic units:* undulating floodplain surface incorporating distinct parallel scrolls or ridges with intervening swales and occasional backswamps in lower lying areas.
16, 17, 18 1. large single-thread sinuous / meandering rivers with insufficient power to rework more than a part of the valley fill 2. middle to lower reaches 3. 10 – 60		**G.** (Sinuous / meandering) lateral migration, backswamp	*Sediments:* sands, silts and organic sediments *Geomorphic units:* flat to undulating floodplain surface featuring ridge and swale topography close to the active channel with extensive smooth areas of vertically accreted fine sediments often associated with extensive backswamps and ponding on distal areas of the floodplain

EXTENDED CHANNEL TYPE(S) FORMING FLOODPLAIN 1. Channel planform description, 2. Environment context, 3. Bankfull unit stream power (W m-2)	**FLOODPLAIN CLASS**	**FLOODPLAIN TYPE (index letter, name)**	**FLOODPLAIN SEDIMENTS AND GEOMORPHIC UNITS**
17, 18 1. partly-confined sections of single-thread meandering, forced to reduce their normal curvature because of valley side obstruction 2. middle to lower reaches 3. 10 – 60	Medium energy, non-cohesive (ctd.)	**H.** (Partly-confined, sinuous / meandering) lateral migration, counterpoint.	*Sediments:* sands, abundant silts and organic sediments *Geomorphic units:* series of parallel ridges arranged upstream of and parallel to tightly curving meander bends, illustrating the downstream migration of the bends. The low areas between the ridges are often poorly drained and so may contain linear wetland areas.
20, 21 1. single-thread straight, sinuous or meandering 2. abundant fine sediment load, middle to lower reaches 3. < 10	Low energy cohesive	**I.** Laterally stable.	*Sediments:* silts, clays and organic material *Geomorphic units:* flat floodplains with low levées, sand splays and sometimes backswamps indicative of poor drainage
19, 22 1. multi-thread anabranching (low energy) 2. very low gradient (<0.0002) in humid environments 3. < 10		**J.** Anabranching (low energy), organic rich.	*Sediments:* abundant silts and clays with some sands and gravels and abundant organic / lacustrine deposits *Geomorphic units:* flat floodplains with extensive islands, often bordered by levées; crevasse-channels and splays, lakes and peat swamps.

EXTENDED CHANNEL TYPE(S) FORMING FLOODPLAIN 1. Channel planform description, 2. Environment context, 3. Bankfull unit stream power (W m-2)	**FLOODPLAIN CLASS**	**FLOODPLAIN TYPE (index letter, name)**	**FLOODPLAIN SEDIMENTS AND GEOMORPHIC UNITS**
FLOODPLAINS SPECIFIC TO SEMI-ARID ENVIRONMENTS			
20 (semi-arid) 1. single-thread to transitional wandering 2. semi-arid open valleys 3. 300 – 600	High energy, non-cohesive floodplains	**K.** Unconfined, vertical accretion, sandy	*Sediments:* predominantly sands with interbedded muds *Geomorphic units:* flat floodplain surface lacking major levées around channels. Channels alternate between wide relatively straight and narrow sinuous states.
16 (semi-arid) 1. single-thread straight or sinuous 2. semi-arid alluvial-filled valleys 3. ~ 300		**L.** Cut and fill	*Sediments:* sands, silts and organic sediments *Geomorphic units:* flat floodplain surface with little surface relief around channels that oscillate between shallow sinuous channels and deeply incised flat-bedded gullies.
19, 22 (semi-arid) 1. multi-thread anabranching (low energy) 2. very low gradient (<0.0002) in semi-arid environments 3. < 10	Low energy cohesive	**M.** Anabranching (low energy), inorganic.	*Sediments:* abundant silts and clays with some sands and gravels and little organic matter *Geomorphic units:* flat floodplains with extensive levees, islands and flood basins, crevasse-channels and splays. Vegetation is relatively sparse although the anabranching channels are often tree-lined, have low width/depth ratios, transport little sand and are incised into very cohesive mud. The floodplain braid-channels are free of trees, very broad and shallow and may initiate at, terminate at or cross over the anabranching channels.

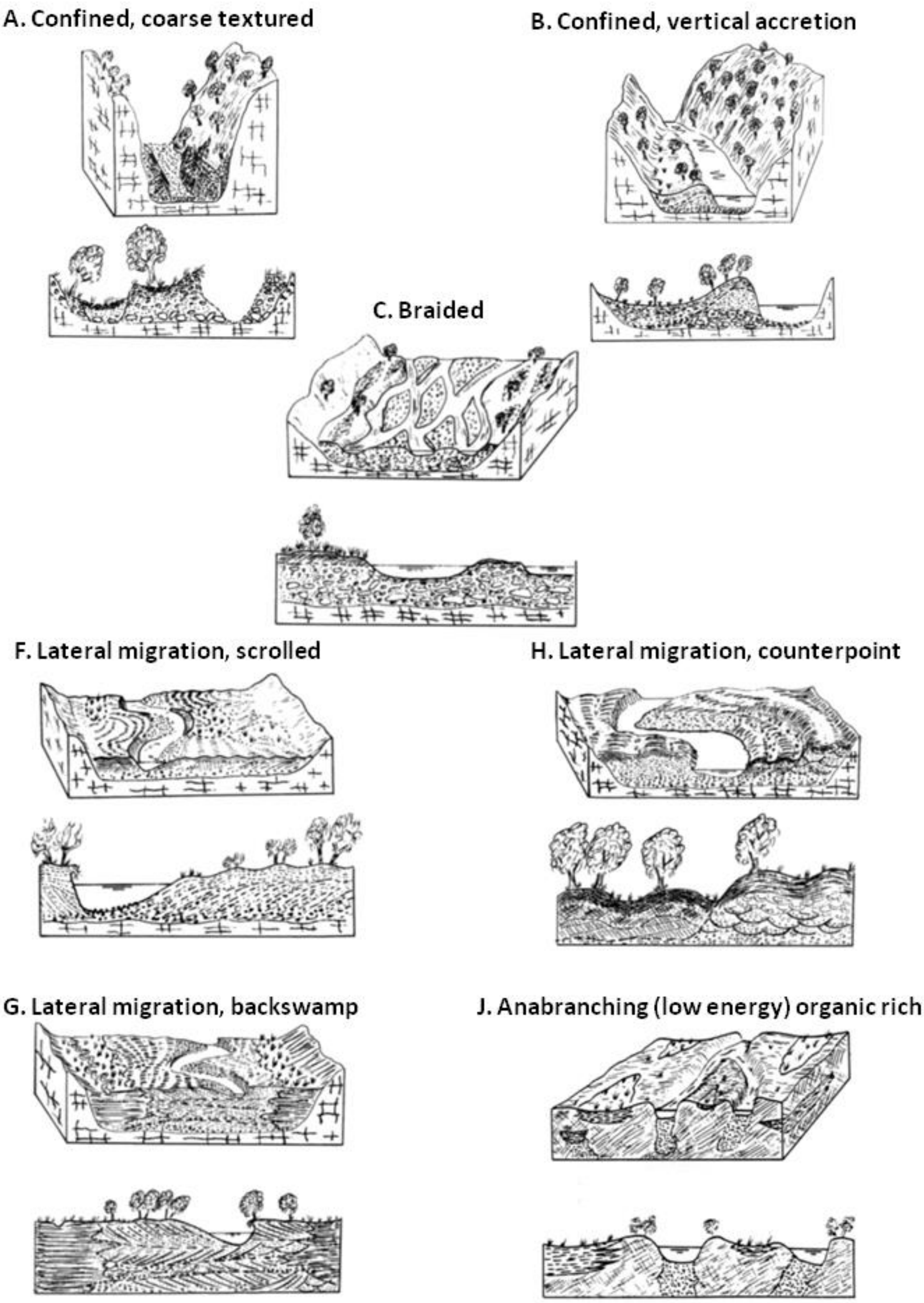

Figure 7.4 Seven of the ten floodplain types listed in Table 7.4 that are likely to be widely encountered across Europe (three types are excluded: type D – wandering is excluded because it is a mixture of other types; types E and I are excluded because these floodplains are relatively featureless) (Diagrams from Nanson and Croke, 1992)

7.5 Groundwater-Surface Water Interactions (GSI)

A critical hydrological aspect of the 22 river types that strongly affects their ecology is the nature and extent of any groundwater-surface water interactions. This section illustrates and provides a description of such interactions, depending upon the geological and climatic setting of each river type. The interactions fall into four main groups, depending upon whether the channel beds are predominantly (i) bedrock or colluvial, (ii) coarse, (iii) intermediate, or (iv) fine (significant quantity of clay) and whether they are predominantly confined or unconfined. A set of tables and schematic diagrams indicate the likely locations, directions and strengths of GSI water movements.

7.5.1 Types 1 to 3: Confined Bedrock and Colluvial Channels

Table 7.5 describes the typical GSIs found in channel types 1 to 3, and Figure 7.5 illustrates these interactions in different structural and bed sediment conditions.

Table 7.5: Typical GSI in Confined Bedrock and Colluvial Channels

Extended Channel Type	Confined / Partly confined / Unconfined	Bed Material Calibre	Typical Groundwater -Surface Water Interactions (GSI)
1	Confined	**Bedrock**	In general none, or very little vertical GSI. However, in the case of permeable faults or fracture zones there can be more vertical GSI (possibly strong GSI locally).
2	Confined	**Coarse mixed**	In general none, or very little vertical GSI with deep groundwater bodies. If coase sediment forms a thick layer, this might form some sort of groundwater body. In that case shallow vertical GSI. Additonally, in case of permeable faults or fracture zones there can be more vertical GSI (possibly strong GSI locally).
3	Confined	**Mixed**	

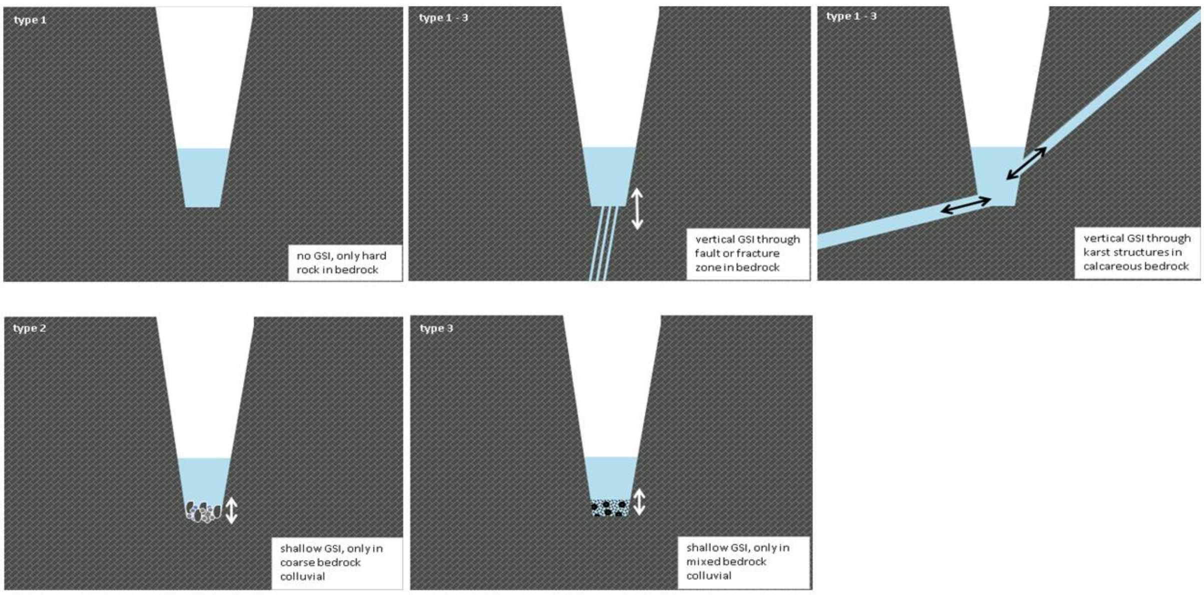

Figure 7.5 GSI in confined bedrock and colluvial channels associated with different local structural and river bed conditions.

7.5.2 Types 4 to 7: Confined Alluvial Channels on Coarse (Boulder-Cobble-Gravel) Substrates

Table 7.6 describes the typical GSIs found in channel types 4 to 7, and Figure 7.6 illustrates these interactions for temperate and dry regions in wet and dry seasons.

Table 7.6: Typical GSI in Confined Alluvial Channels on Coarse Substrates

Extended Channel Type	Confined / Partly confined / Unconfined	Bed Material Calibre	Typical Groundwater -Surface Water Interactions (GSI)
4	Confined	**Boulder**	GSI with phreatic groundwater (local and regional) GSI with deep semi-confined groundwater
5	Confined	**Boulder** - Cobble	
6	Confined	Boulder - **Cobble** - Gravel	
7	Confined	Cobble - **Gravel**	

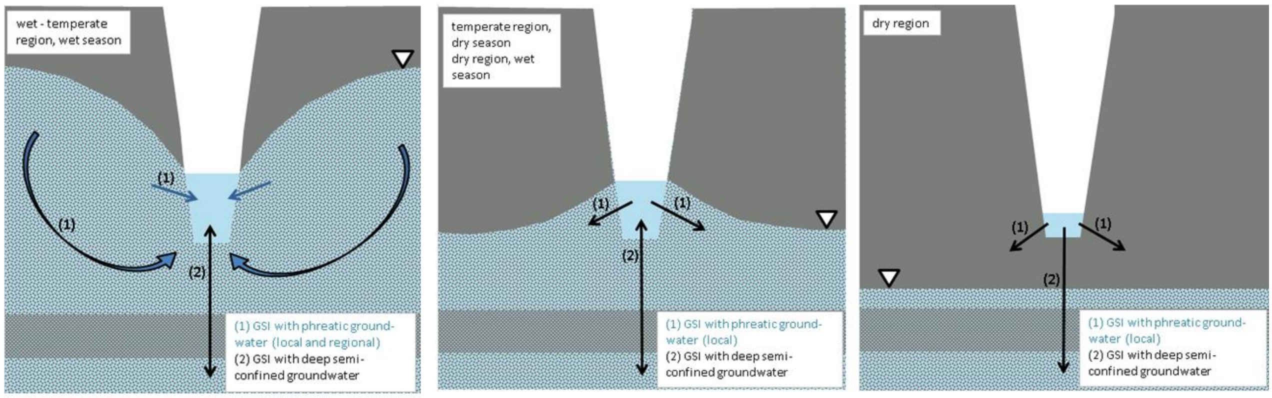

Figure 7.6 GSI in confined alluvial channels of intermediate to coarse particle size (no significant clay).Interactions may be with local and regional phreatic groundwater (blue arrows) and/ or with deep semi-confined groundwater (black arrows), depending on the local structure, and their nature varies in temperate regions in the wet season (left), temperate regions in the dry season or dry regions in the wet season (centre) and in dry regions under typical dry conditions (right).

7.5.3 Types 8 to 19: (Partly) Confined / Unconfined Alluvial Channels on Intermediate (Gravel-Sand) Substrates

Table 7.7 describes the typical GSIs found in channel types 8 to 19, Figure 7.6 illustrates GSI in (partly) confined situations and Figure 7.7 illustrates these interactions for unconfined situations in temperate and dry regions in wet and dry seasons.

Table 7.7 Typical GSI in (Partly) Confined and Unconfined Alluvial Channels on Intermediate (Gravel-Sand) Substrates

Extended Channel Type	Confined / Partly confined / Unconfined	Bed Material Calibre	Typical Groundwater -Surface Water Interactions (GSI)
8	Confined / Partly confined / Unconfined	**Gravel** - Sand	GSI in riparian zone (only unconfined segments) GSI with phreatic groundwater (local and regional) GSI with deep semi-confined groundwater
9	Confined / Partly confined / Unconfined	**Gravel** - Sand	
10	Confined / Partly confined / Unconfined	**Gravel** - Sand	
11	Confined / Partly confined / Unconfined	**Gravel** - Sand	
12	Partly Confined / Unconfined	**Gravel** - Sand	
13	Partly Confined / Unconfined	**Gravel** - Sand	
14	Partly confined / Unconfined	Fine gravel - **Sand**	
15	Confined / Partly confined / Unconfined	Fine gravel - **Sand**	
16	Partly confined / Unconfined	Fine gravel - **Sand**	
17	Partly confined / Unconfined	Fine gravel - **Sand**	
18	Partly confined / Unconfined	Fine gravel - **Sand**	
19	Confined / Partly onfined / Unconfined	Fine gravel - **Sand**	

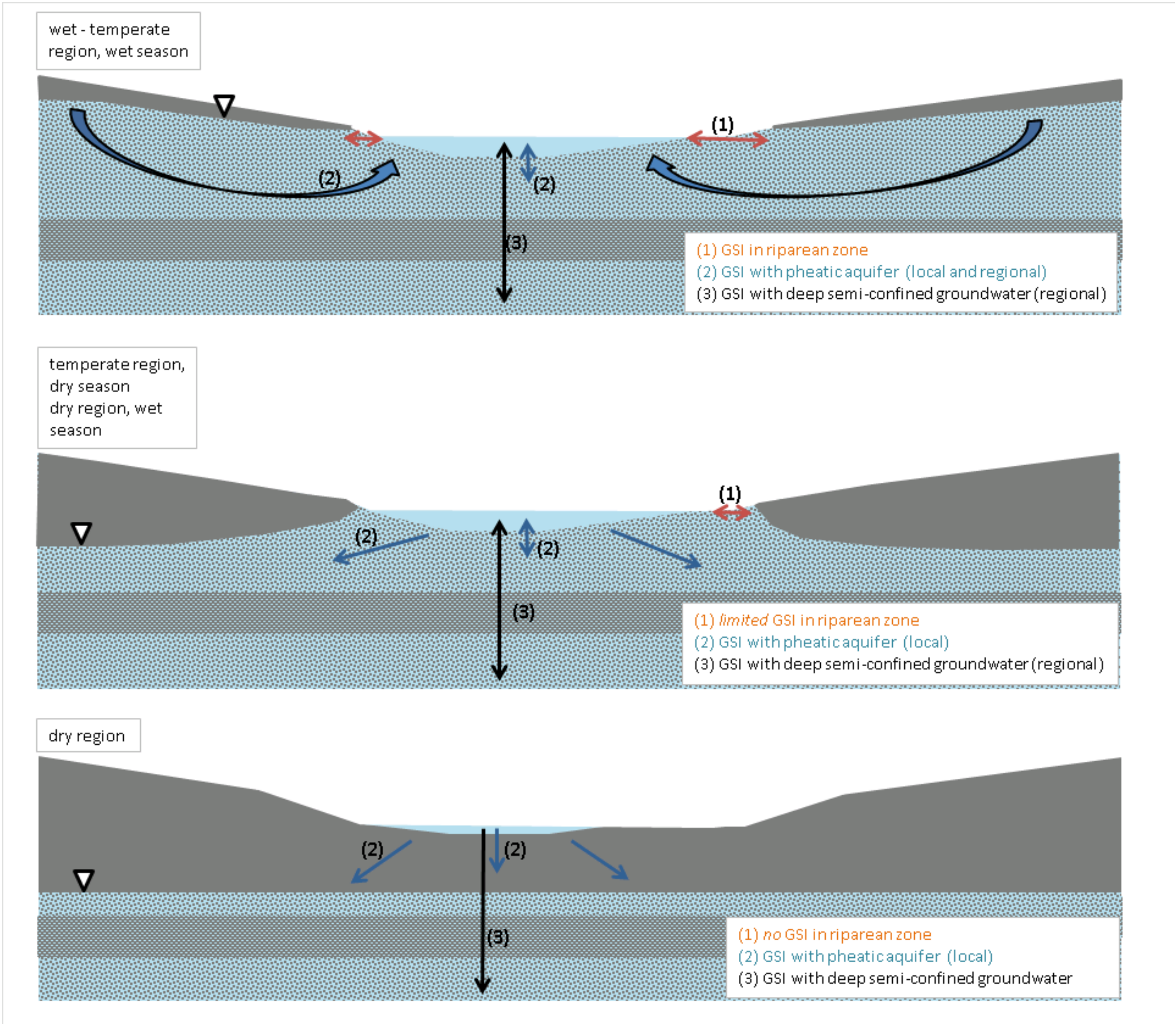

Figure 7.7 GSI in unconfined alluvial channels of intermediate to coarse particle size (no significant clay). Interactions may be in te riparian zone (orange arrows), with the local and regional phreatic groundwater (blue arrows) and/ or with deep semi-confined groundwater (black arrows), depending on the local sediment / rock structure, and their nature varies in temperate regions in the wet season (top), temperate regions in the dry season or dry regions in the wet season (centre) and in dry regions under typical dry conditions (bottom).

7.5.4 Types 20 to 22: Partly Confined / Unconfined Alluvial Channels on Fine (Silt-Clay) Substrates

Table 7.8 describes the typical GSIs found in channel types 20 to 22, Figures 7.8 and 7.9 illustrate GSI for confined and unconfined situations, respectively.

Table 7.8 Typical GSI in (Partly) Confined and Unconfined Alluvial Channels on Fine (Silt-Clay) Substrates

Extended Channel Type	Confined / Partly confined / Unconfined	Bed Material Calibre	Typical Groundwater -Surface Water Interactions (GSI)
20	Partly confined / Unconfined	Fine sand - **Silt** - Clay	*limited or localized* GSI in riparian zone (only unconfined segments)
21	Partly confined / Unconfined	Fine sand - **Silt** - Clay	*limited or localized* GSI with phreatic groundwater (local and regional)
22	Confined / Partly confined / Unconfined	Fine sand - **Silt** - Clay	*limited or localized* GSI with deep semi-confined groundwater

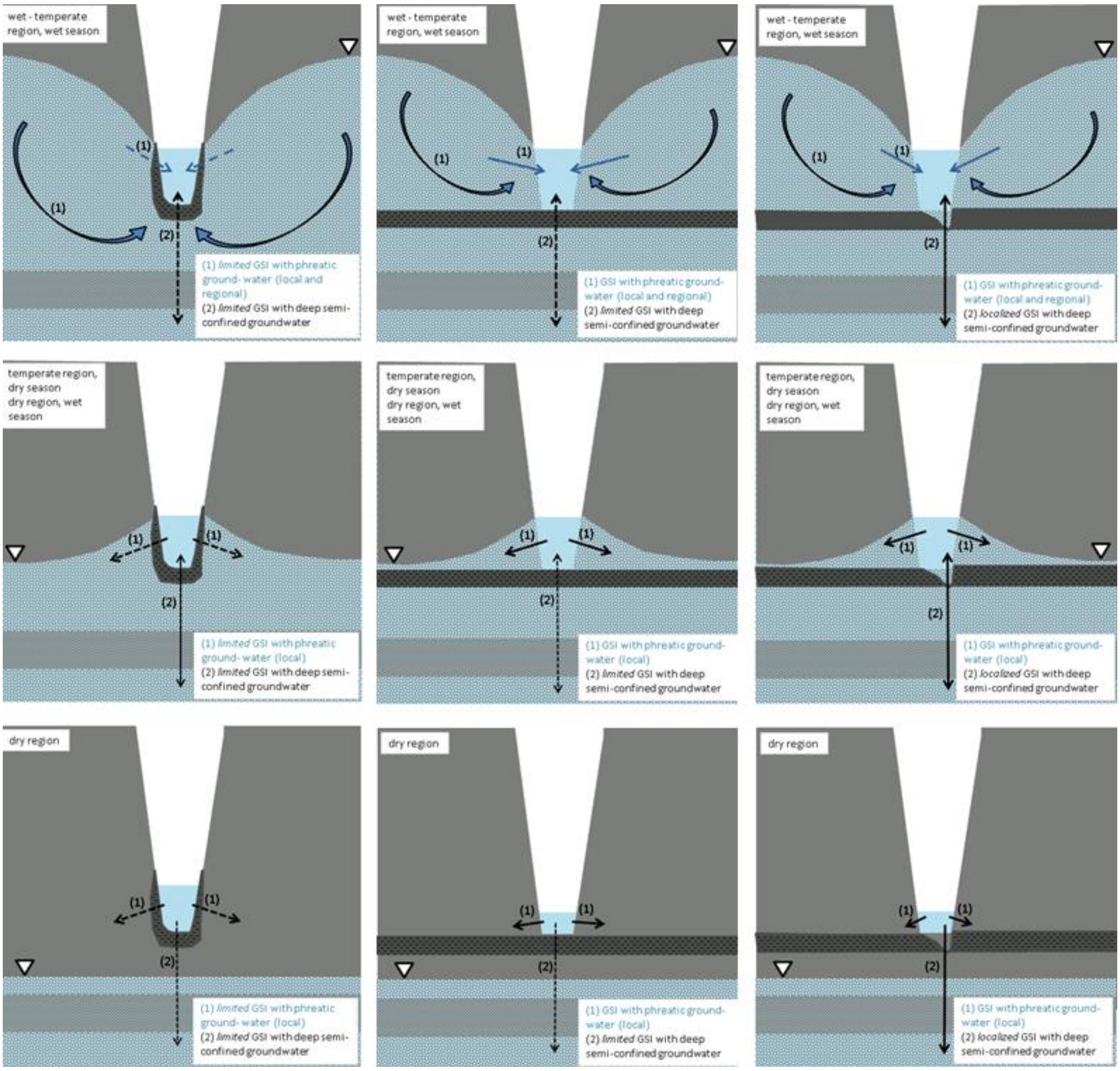

Figure 7.8 (caption on following page)

Figure 7.8 GSI in confined alluvial channels of fine particle size (significant clay). Interactions may be with the local and regional phreatic groundwater (blue arrows) and/ or with deep semi-confined groundwater (black arrows), depending on the local sediment / rock structure (confined (clay) river bed (left), confining clay layer (centre) or discontinuous confining (clay) layer) and their nature varies in temperate regions in the wet season (top), temperate regions in the dry season or dry regions in the wet season (centre) and in dry regions under typical dry conditions (bottom).

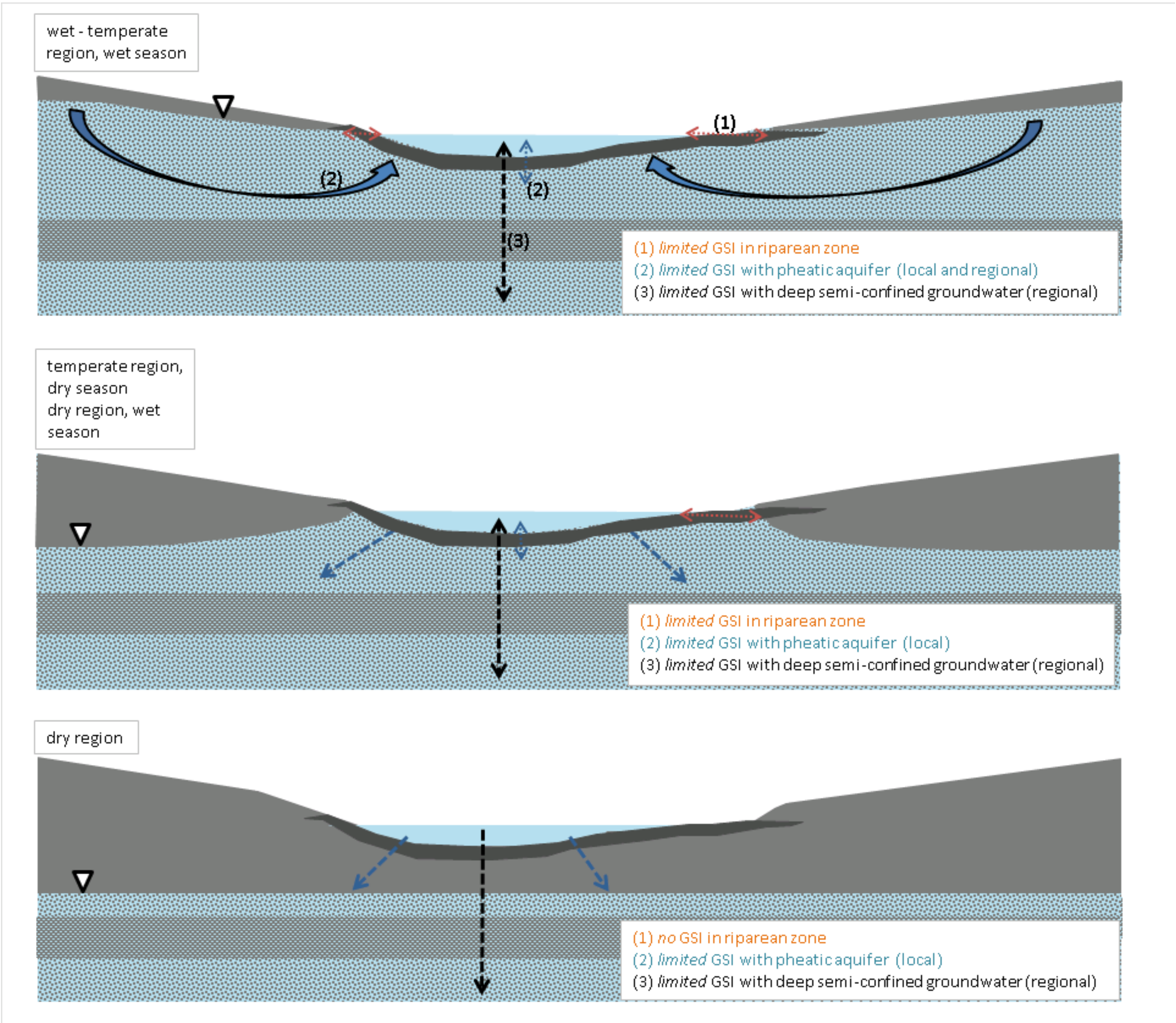

Figure 7.9 GSI in unconfined alluvial channels of fine particle size (significant clay). Interactions may be in the riparian zone (orange arrows), with the local and regional phreatic groundwater (blue arrows) and/ or with deep semi-confined groundwater (black arrows), and their nature varies in temperate regions in the wet season (top), temperate regions in the dry season or dry regions in the wet season (centre) and in dry regions under typical dry conditions (bottom).

8. Indicators of Present and Past Condition

8.1 Introduction

The information assembled during the characterisation phases (chapters 5, 6 and 7) supports a list of indicators of the current and past condition of a catchment and its spatial units. These key indicators, which are presented in this chapter, provide an overview of current and past functioning of the catchment and its spatial units. However, interpretations of catchment functioning can incorporate as many of the characteristics from chapters 5, 6 and 7 as have been assembled for a particular catchment and, where information is unavailable for a particular catchment, alternative indicators can be developed from other characteristics that have been quantified. Examples of the evaluation of indicators are provided in the full Catchment Case Studies of Deliverable 2.1 Part 3.

Here the term 'condition' is used to reflect the degree to which observed hydrogeomorphological characteristics conform to what would be expected in a naturally-functioning situation, and thus how far the properties have deviated from that naturally-function state.

Although the reach scale is often the main focus of interest, indicators representative of other spatial scales, particularly of the segment and landscape units in which the reaches are situated, provide important contextual information for interpreting reach scale indicators. Multi-scale indicators can provide much management-relevant information including:

(i) Assessment of current reach condition and degree of alteration

(ii) An understanding of associations between landscape unit, segment and reach properties. In other words, what types of naturally functioning reach are sustainable and feasible within particular segment and landscape unit conditions and how do degraded conditions at the reach scale reflect processes or factors operating at the segment or landscape unit scales?

(iii) Assessment of potential reach condition in the context of its segment and landscape unit setting. In other words, to what extent and in what ways is the reach altered from the naturally-functioning reach types that are feasible in the segment and landscape unit setting, and to what extent does the condition of a reach conform to or differ from the condition of the segment in which it is situated?

(iv) Establishment of the spatial structure and condition of the river network. In other words, an analysis of the distribution of reaches of different style and condition throughout the network to assess (a) the presence and spacing of reaches that are in good condition, and (b) the degree of alteration of intervening reaches.

These types of information can feed into:

(i) identification of the best condition reaches so that they may be protected.

(ii) selection of the most effective locations for restoration and the balance of expenditure on reaches that are in better condition or the linking reaches in between (according to both hydromorphological and ecological criteria).

(iii) selection of appropriate styles of restoration for the segment and landscape unit context of reaches.

Figure 8.1 illustrates the broad concept of processes being represented by indicators across time and space and Table 8.1 lists a range of indicators that can be extracted from the information assembled during the characterisation phase (chapters 5, 6 and 7) from the catchment to reach scales. Table 8.1 identifies the key processes that influence hydromorphology at each spatial scale. For each of these processes, the main criteria or factors are identified which could indicate the status or condition of each process, and then, several indicators (variables, metrics) are listed that assess the criteria or indicate the condition of the process. The last column shows the types of pressures that may alter the value of the indicators or modify the criteria and processes. For example, if the key process is flooding, the criteria could be peak river flows (m^3/s), flooded area (m^2, ha), flooding duration (hours, days), etc. If peak flow is selected as the criterion, an indicator could be the 2-year maximum flow (m^3/s). Pressures that could alter this indicator include flow regulation, groundwater abstraction, or hydropeaking.

In the following descriptions, the selected indicators are underlined, and are presented in the order in which they are listed in Table 8.1. In each case, the purpose of the indicator is described, relevant parts of chapters 5, 6 and 7 are referenced to guide assessment of the current (and, where appropriate, past) status of the indicators; and then some guidance is given on interpretation of the indicators. The description of many indicators inevitably overlaps with descriptions presented in chapters 5, 6 and 7, but it is included in each case for completeness.

In relation to assessments of the indicators under past conditions, the timescale is flexible and can be selected to suit local circumstances. However, high quality data sets are usually available from the mid-20th century, so this provides a good baseline for tracking recent (decadal scale) changes. One very important point to note is that the past should not be viewed as providing 'reference' conditions. Indeed, it is likely that across much of Europe, the mid-20th century was a time of even more intense human impacts on catchments and rivers than the present. Neverthless, to understand current river and floodplain properties, knowledge of changes from catchment to reach scale over the last 50-100 years is crucial. The changing intensity and nature of human interventions over that period will have strongly influenced water and sediment production, river flow and sediment dynamics, and river channel dynamics. Furthermore, as there is a temporal lag between cause and effect, particularly as the effects are transmitted from larger (e.g. landscape unit) to smaller (e.g. reach) spatial units, historical conditions within a catchment over a period of 50 to 100 years (or more) are likely to continue to affect river systems significantly at the present time.

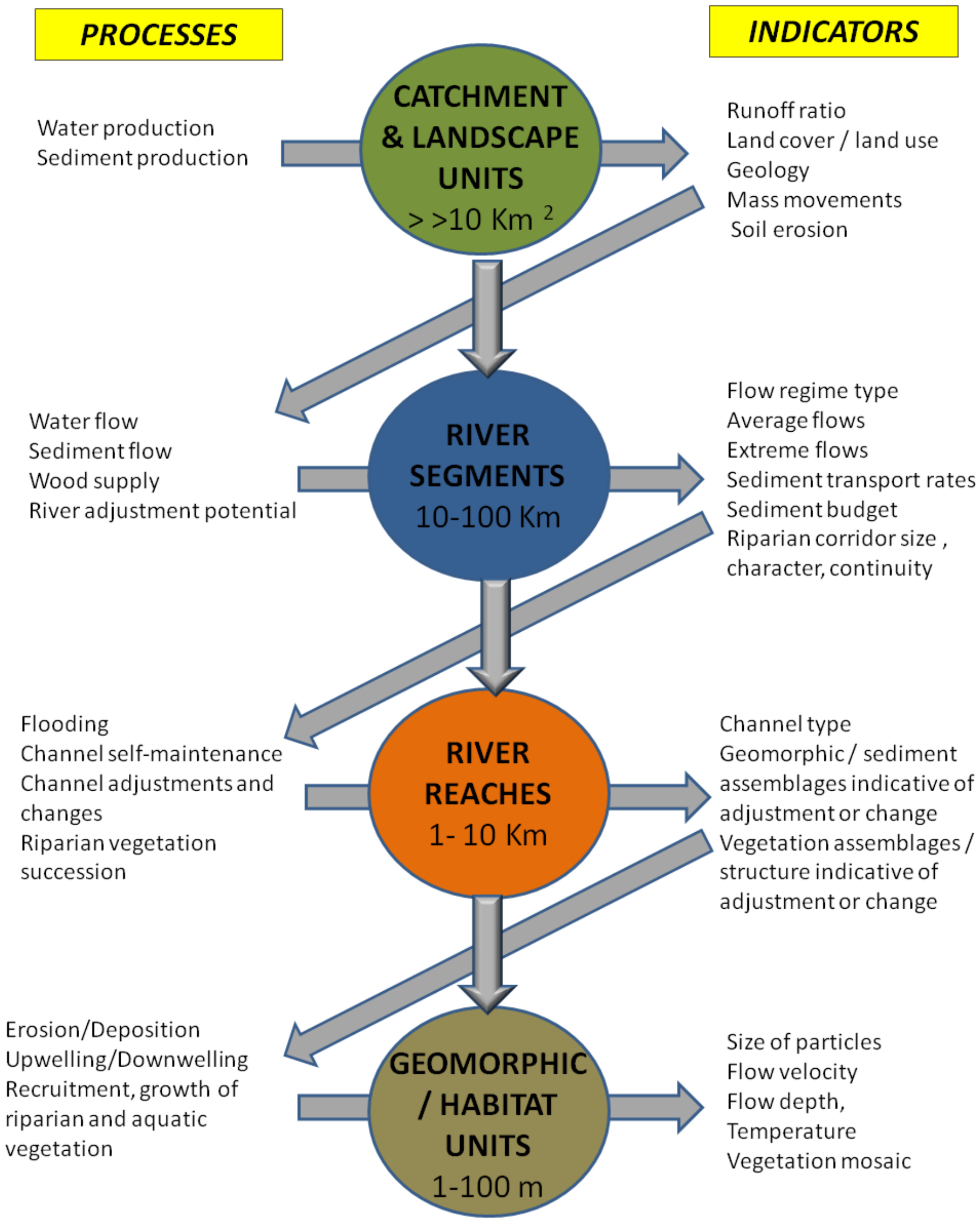

Figure 8.1 Indicators represent processes at each spatial scale. They provide indications of how the catchment is functioning at each scale, how the functioning may change through time and how processes at one scale influence processes at smaller scales across space and time

Table 8.1 List of indicators of current and past condition according to the relevant spatial scale, the key processes and criteria that they represent, and the human pressures that influence them.

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
CATCHMENT	Water Yield	Catchment area Runoff ratio (coefficient) Geology Land cover	Drainage area (km^2) Water yield (mm) Annual runoff ratio (coefficient) Geology (WFD types) % silicious, % calcareous % organic, % mixed /other Land cover (CORINE level 1) % artificial surfaces % agricultural areas % forest and semi-natural areas % wetlands	Water transfers De/Afforestation Agriculture / grazing abandonment Major land cover change (e.g. urbanization)
LANDSCAPE UNIT	Water Production	Rapid runoff production (low infiltration areas, potential saturated areas) Delayed runoff production (high infiltration areas, deep drainage areas)	% area of exposed aquifers % area of permeability classes % glaciers and perpetual snow % large surface water bodies Land cover (CORINE level 2) % area of rapid runoff production (paved or compacted area, urban fabric, industrial, commercial, transport units, open spaces with little or no vegetation) % area of intermediate runoff production (arable land, perm. crops, pastures, shrub and/or herbaceous vegetation) % area of delayed runoff production (forests, wetlands)	Changes in groundwater exploitation / abstraction Changes in land cover / use Changes in ice / snow storage

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
LANDSCAPE UNIT (ctd.)	Sediment production	Fine sediment production Coarse sediment production	Soil erosion rate (t. ha^{-1}. y^{-1}) % area with potential sources of coarse sediment	Changes in land cover / use De/Afforestation Intensification of use of agricultural soils Changes in soil conservation practices, buffer strips, natural barriers to soil movement Torrent control
SEGMENT	Water flow	River flow regime[1*]	Flow regime type[1*] Average annual flow ($m^3.s^{-1}$) [1*] Average monthly flow ($m^3.s^{-1}$, seasonal pattern) [1*] Baseflow index (BFI) Morphologically meaningful discharges (Qp_{median}, Qp_2, Qp_{10}, $m^3.s^{-1}$) [1*] Extremes: median, LQ, UQ of 1- and 30-day maximum and minimum flows ($m^3.s^{-1}$ and month of most frequent occurrence) [1*] Hydropeak frequency (number / year) [1*]	Dams, flow regulation, water transfers, hydropower development Groundwater exploitation
	Sediment flow	Sediment supplied to the channel Sediment transport and storage[2*]	Eroded soil delivered to channel Land surface instabilities conn. to channel Measured / estimated suspended sediment load ($t.y^{-1}$) [2*] Measured / estimated bedload ($t.y^{-1}$) [2*] Sediment budget (+ve / -ve channel sediment storage) [2*] Number of high channel blocking structures Number of medium channel blocking structs. Number of high spanning / crossing structures Number of medium spanning / crossing structures .	Dams, flow regulation Major changes in land cover / use Removal of riparian vegetation

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
SEGMENT (ctd.)	River morphology adjustments	Valley controls on channel dynamics Riparian corridor features	Average valley gradient (m.m^{-1}) Valley confinement River confinement (alluvial plain width / bankfull river width) Average riparian corridor width Proportion of riparian corridor under functioning riparian vegetation Riparian corridor continuity Riparian corridor vegetation cover / structure	Effective valley width can be reduced by human activities but these lateral constraints are assessed at the reach scale Dams, flow regulation Groundwater abstraction Channelisation, dredging / gravel mining Floodplain occupation Riparian forest exploitation / management
	Wood production	Potential wood Delivery	% active channel edge bordered by living / dead trees	Flow regulation / groundwater abstraction Dams, weirs and other blocking structures Channelization, bank reinforcement / protection Beavers Wood removal
REACH	Flooding	Flood area	% floodplain accessible by floodwater	Flow regulation / groundwater abstraction Channelization, embanking Channel incision / aggradation
	Channel self-maintenance / reshaping	Flow energy Sediment size Channel dimensions, type and features	Specific stream power (at current mean bankfull width and morphologically meaningful discharge). Bed sediment size (D_{50}, dominant size) Bank sediment size (D_{50}, dominant size) Channel gradient Bankfull channel width Average bankfull channel depth Bankfull channel width:depth ratio Bankfull sinuosity index	Dams, flow regulation Channelization (gradient changes, blocking structures, reinforcement) Sediment dredging / mining Vegetation encroachment Accelerated soil erosion, torrent control

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
REACH (ctd.)	Channel self-maintenance / reshaping (ctd.)	Channel dimensions, type and features (ctd.)	Braiding index Anabranching index River type (see Tables 7.2 and 7.3) Presence of channel and floodplain Geomorphic features / units typical of river type (see Tables 7.3 and 7.4) Bars, benches, islands (% area of bankfull channel	
	Channel Change / Adjustments	Lateral migration, planform change	Eroding banks (% active channel bank length) Laterally aggrading banks (% active channel bank length) Retention of in-channel sediment (% area of bankfull channel) Lateral channel migration rate ($m.y^{-1}$) Changes in (i) sinuosity index, (ii) braiding index, (iii) anabranching index	Flow regulation / groundwater abstraction Bed incision Embanking, revetments Floodplain land occupation Vegetation encroachment
		Narrowing / widening Bed Incision / aggradation Vegetation encroachment	Changes in active channel (i) width, (ii) depth, (iii) width:depth ratio Presence of geomorphic features / units indicative of (i) narrowing (ii) widening Presence of geomorphic features / units indicative of (i) bed incision, (ii) aggradation Changes in bed sediment structure indicating (i) incision, (ii) aggradation Aquatic / riparian encroachment	Dams, flow regulation Groundwater abstraction Channelization Dredging and gravel extraction (sediment deficit) Accelerated soil erosion (sediment surplus) Urbanization

Spatial Unit	Key Process	Assessed Criteria	Indicators	Alteration Pressures
REACH (ctd.)	Channel adjustments (ctd.)	Constraints on channel adjustment	Width of erodible corridor Proportion of potentially erodible channel margin Proportion of river bed that is artificially reinforced Number of high, medium, low blocking or spanning/crossing structures	
	Vegetation succession	Aquatic vegetation	Aquatic plant (i) extent, (ii) patchiness, (iii) species / morphotypes Presence of aquatic-plant-dependent Geomorphic units / features	Flow regulation Groundwater abstraction Channelization Riparian corridor occupation / management Accelerated soil erosion and delivery Invasive species
		Riparian vegetation	Proportion of riparian corridor under mainly mature trees, shrubs, shorter vegetation and bare (recruitment sites) (i) Lateral gradient and (ii) patchiness in riparian vegetation cover classes Dominant riparian tree species Presence / abundance of large wood Presence of wood- or riparian tree-dependent geomorphic units / Features	
	Wood delivery	Large wood and organic debris	Abundance of (i) isolated wood pieces, (ii) in-channel wood accumulations (iii) channel-blocking jams, (iv) wood in the riparian corridor	Vegetation and wood management Dams, flow regulation, flood control Beaver control

[1*] Flow properties are estimated at the segment level to maximise the likelihood of having suitable flow gauging stationrecords, but could also be estimated at the reach level if suitable flow series are available.

[2*] Sediment transport is estimated at the segment scale to link with discharge measurements. However, the measurements or estimates are equally applicable at the reach scale where good information may be available segment level, where on bed material particle size, local channel gradient and width to support modelling.

8.2 Catchment

At the catchment scale, indicators aim to identify broad properties of runoff production by the catchment and, in some cases, how these may have changed.

8.2.1 Catchment Area (section 5.2.1)

Catchment area is a primary control on hydrological behaviour. The actual catchment area (in km^2 to a gauged point) is the key indicator. However, where major water diversions are present, alteration is indicated by the current functioning catchment area (in km^2 to the same gauged point). Comparison of the catchment area and functioning catchment area, plus information of when the latter area changed, provides a first indication of alteration to the catchment's hydrological regime, which will affect river channel dimensions and dynamics throughout the catchment.

8.2.2 Water Yield and Runoff Ratio / Coefficient (section 5.2.1)

Water yield (mm) and the runoff ratio or coefficient over a standard period (section 5.2.1) give average catchment indicators of the effectiveness with which the catchment converts rainfall to runoff. These provide a first indication of runoff magnitude, which is a major control on river channel dimensions and dynamics. These are indicators of current condition: indicators of water production (runoff) and river flow alteration are investigated at the landscape unit (section 8.3.2) and segment (8.4.1) scales.

8.2.3 Geology and Land Cover (sections 5.2.2, 5.2.3, 6.2.1)

These two groups of properties affect the rates and pathways of runoff (and sediment) production, and so some simple indicators are important at a catchment scale, followed by a more detailed analysis in relation to the various landscape units present within the catchment (8.3.2).

At the catchment scale, the simplest geological indicators of water yield are the percentage cover of each of the four WFD types (% siliceous, % calcareous, % organic, % mixed/other), which indicate hydrological properties of the catvhment including water retention capacity.

Land cover is represented at the catchment scale by the % cover of the four CORINE level 1 classes. Percentage cover of CORINE level 1 classes indicative of the potential amount and responsiveness of runoff are % artificial surfaces, % agricultural areas, % forest and semi-natural areas, and % wetlands. For estimates of temporal change, CORINE data are available for different dates, or alternatively national mapping and censuses may allow historical estimates of these cover types (e.g. estimates for past decades) (see 6.2.1). Such estimates provide an initial indication of likely alteration in runoff, and thus potential changes in channel-modifying high flows (leading to channel enlargement) or more reliable baseflows (leading to improved growing conditions for channel-stabilising riparian vegetation). These are revisited at the landscape unit scale to provide indicators of where runoff changes are occurring within the catchment and thus how they may affect different areas of the river networkdownstream of the changes.

8.3 Landscape Unit

At the landscape unit scale, indicators focus on water and sediment production so that locations of high production within the catchment can be recognised to aid spatial (and temporal) interpretation of likely impacts on river form and dynamics.

8.3.1 Exposed Aquifers and Soil / Bedrock Permeability (section 5.3.1)

Exposed aquifers and permeable soils absorb and attenuate runoff and also minimise runoff pathways associated with soil erosion. Thus the minimum indicator required is % area of exposed aquifers since this highlights the area of high rainfall acceptance / infiltration. Where possible, this can be complemented by indicators of % area of (soil and rock) permeability classes, such as the five rainfall acceptance classes mapped in the UK, which give a detailed pattern of rainfall acceptance from high to low across the landscape unit. These indicators allow an assessment of the most important landscape units for rapid or delayed runoff production and so start to indicate how runoff quantity and variability might be distributed across the catchment and thus affect river size and dynamics differentially.

8.3.2 Land cover (sections 5.3.1, 6.2.1)

Land cover is superimposed on soils and geology and varies greatly through time. It moderates rainfall acceptance / infiltration and runoff production very significantly.

In some landscape units, large storages of surface water have a very strong influence on the river flow regime by greatly delaying runoff (section 5.3.1). These large water stores are indicated for frozen water by % glaciers and perpetual snow (e.g. CORINE level 3, cover class 3.3.5) and for liquid water by % large surface water bodies. The latter also influence sediment transfer by trapping most of the suspended and bed sediment that are transported into them.

Other land cover types (section 5.3.1) have highly variable impacts on runoff production. The % cover of the following 10 CORINE, level 2, land cover classes indicate a gradient from very rapid to very delayed runoff production: % paved or compacted area, % urban fabric, % industrial, commercial, transport units, % open spaces with little or no vegetation, % arable land; % permanent crops, % pastures, % shrub and/or herbaceous vegetation, % forests, % wetlands.

The percentage cover of the above 12 indicators illustrates how land cover may be affecting runoff production (and so three aggregate cover assessments are also useful indicators).

(i) The following are indicative of % area of delayed runoff production: % glaciers and perpetual snow, % large surface water bodies, % forests, % wetlands.

(ii) The following are indicative of % area of rapid runoff production: % paved or compacted area, % urban fabric, % industrial, commercial, transport units, % open spaces with little or no vegetation.

(iii) The following are indicative of % area of intermediate runoff production: % arable land; % permanent crops, % pastures, % shrub and/or herbaceous vegetation. However, some arable land, depending upon the crop, land gradient and management, may generate very rapid runoff and arable land is usually a very important area for fine sediment production.

Historical changes in the % cover of the above cover types will have strongly influenced runoff (and sediment) production from the landscape unit and their transfer through downstream segments and reaches of the river network. Therefore, it is important to assemble historical estimates for a minimum of one or two periods over the last 50+ years for at least the most influential cover classes (e.g. % urban fabric + % industrial, commercial, transport units, % arable land; % forests + % wetlands, % large surface water bodies, % glaciers and perpetual snow). Section 6.2.1 describes relevant information sources and methods.

8.3.3 Sediment Production (section 5.3.2)

Fine sediment production: Land cover and land cover change indicators give an indication of likely production of sediment that may eventually reach the river network, particularly when they are combined with information on soil properties and land surface slope. There are many sources and methods for estimating fine sediment production across the landscape unit (section 5.3.2) from which the spatial pattern and average soil erosion rate (t. ha^{-1}. y^{-1}) can be calculated.

At the spatial resolution of the Pan-European PESERA maps (1 km^2), local (pixel) values of soil erosion rate can be interpreted as follows: 1 = < 0.5 t.ha^{-1}.yr^{-1} (Low), 0.5 – <1.0 (Moderate); 1.0 – <5.0 (Substantial); 5.0 – <10.0 (High); > 10.0 (Extremely high). This gives a firm basis for interpreting the location and severity of the major fine sediment sources. Comparison of historical assessments of the spatial pattern and average soil erosion rate (t. ha^{-1}. y^{-1}) (or changes in land cover to infer changes in sediment production, section 6.2.1) with contemporary assessments are crucial for understanding how and why fine sediment may be accumulating or being scoured from the river and floodplain network, since there is usually a lag of several decades or more between (historical) sediment production and the current status of sediment storage within downstream river segments and reaches.

Coarse sediment production: At the landscape unit scale, the simplest indicator of potential coarse sediment production is an assessment of the % area with potential sources of coarse sediment (i.e. area covered by exposed rock debris, earth or mud - falls, slumps, slides or flows, major gullies, section 5.3.2). Where appropriate historical and map data are available (section 6.2.2) changes in the extent and distribution of areas of coarse sediment production can be recognised, which may be influencing the current status of sediment storage within downstream segments and reaches. Connectivity of these potential source areas with the channel is assessed at the segment scale (see 8.4.2).

Note: Where a comprehensive assessment is not to be undertaken for every segment within a catchment (e.g., where the focus is on a single reach, with a minimum assessment of the larger spatial units within which the reach is located), the number of high and intermediate channel blocking structures needs to be assessed across the entire landscape unit using the methods and indicators described in sections 8.4.2 and 5.4.5. This is particularly important in mountainous areas, where such structures are numerous and can have a massive effect on coarse sediment transfer through the river network to particular segments and reaches.

8.4 Segment

At the segment scale, indicators highlight the properties of the river and its floodplain rather than the surrounding areas of the catchment, notably indicators of flows of water, sediment and wood, and indicators of space for and constraints upon river channel adjustments within the river corridor.

8.4.1 Water Flow (section 5.4.1, 6.3.1)

The typical regime of river flows and its variability is crucial for determining river channel size, dynamics and planform and floodplain development, and it is also an important influence on river ecology. Numerous flow indicators can be calculated from flow records (see section 5.4.1 and Deliverable 2.1 Part 2 Annex C), but a minimal list of indicators follows that should be estimated from a minimum 20 year record:

Flow regime type indicates the overall pattern of flow, including its intermittancy, interaction with groundwater and the likely contributing water sources.

Average annual flow ($m^3.s^{-1}$) indicates the long term average flow at the segment, which can be compared with estimates for upstream and downstream segments to identify how flow accumulates downstream through the river network

Average monthly flows ($m^3.s^{-1}$) complements the flow regime type, by illustrating the typical annual sequence of monthly flows, including the typical highest and lowest flow months. The annual pattern is important for river ecology.

Baseflow index (BFI) complements the flow regime type by emphasising the reliable flow component.

Morphologically meaningful discharges (Qp_{median}, Qp_2, Qp_{10} in $m^3.s^{-1}$) are the discharges to which the channel size often corresponds (i.e. the approximate the bankfull discharge, with Qp_{median} or Qp_2 usually selected for rivers with reliable flow regimes, and longer return period flows such as Qp_{10} or Qp_5 selected for rivers with very flashy and more ephemeral regimes). This is a very important indicator of potential channel size and feeds into estimates of bankfull flow energy.

(Four) Extreme flows: Median, lower and upper quartile and month of most frequent occurrence of the annual maximum and minimum 1-day and 30-day flows.

High flows are important for sediment transport and low flows affect maintenance of and encroachment by riparian vegetation, so both impact on channel size and form.

Hydropeak frequency: The number of abrupt increases in flow per year due to hydropeaking. When frequent, these scour the channel, removing vegetation and finer sediment, and severely disturb macroinvertebrates and fish.

Where long-term records are available, a similar analysis can be conducted on a historical 20 year record, or where information is available to 'naturalise' the contemporary 20 year flow record, all of the above indicators can be re-calculated to identify changes in flow properties from free-flowing conditions (see section 5.4.1). In addition, a variety of sources can be used to at least extend records of flood events back through historical and even pre-historical times (section 6.3.1). All of these indicators allow an assessment of how river flows have changed from some past historical condition.

8.4.2 Sediment Flow (section 5.4.3, 5.4.5, 6.3.5)

The characterisation of segment sediment size and dynamics are described in section 5.4.3 with suggestions on estimation of changes through time presented in section 6.3.5. As noted in section 5.4.3, characterisation of these properties can be conducted at the segment or reach scale according to the properties of the river under study and the information that is available. Here, the assessment of all sediment dynamics indicators are presented at the segment scale.

At the segment scale, simple indicators of fine and coarse sediment delivery to the river, sediment transport and storage, and obstacles (high and intermediate blocking structures) to the downstream transfer of sediment are included. Sediment transport and retention / storage within a reach has an enormous impact on the character and dynamics of the river channel.

As discussed in section 5.4.3, estimating sediment delivery to rivers and sediment transport within river channels is an inexact science, and direct measurements are rarely available and often imprecise. Where direct measurements of suspended and bedload transport are available, these should be used. Alternatively transport may be estimated using models. The simplest sediment transport equations use information on river flow energy and sediment size to estimate the transport of grains of different size. For example, Bagnold's (1980) stream power function incorporates specific stream power, channel / water dimensions (width, depth, slope), discharge and D_{50} of the bed material to estimate a bedload transport rate per unit channel width. However, these simple methods do not take account of sediment supply (availability) and do not handle mixed grain sizes well. Slightly more sophisticated methods incorporate inputs of sediment of different grain sizes, allowing inputs and outputs from segments / reaches to be compared and thus sediment budgets to be estimated for different sediment components within individual segments / reaches. More advanced modelling approaches are reviewed in chapter 9. One model – the Sediment Impact Asset Method (SIAM), which is freely available online (http://www.hec.usace.army.mil/software/hec-ras/) as part of the 1-D modelling software HEC-RAS and supports estimation of the transport and storage of different grain sizes - is fully described and applied in Annex I.1 (Deliverable 2.1 Part 2) and is used in Catchment Case Study 1 (Deliverable 2.1 Part 3). Whichever of the many approaches is used, some attempt should be made to quantify sediment transport and the sediment budget of segments or reaches since these have a fundamental impact on channel morphodynamics and bed sediment characteristics.

The following seven indicators allow the broad segment scale pattern of potential sediment flow into the river network, sediment transport and storage, and sediment flow obstructions within the river network, to be recognised and key sediment source, transfer and obstruction segments within the river network to be identified:

Eroded soil delivered to channel (section 5.5.3) indicates the total soil erosion per year estimated within a 500m zone bordering the river channel within the segment and divided by the length of bankfull channel margin (fine sediment delivery in $t.yr^{-1}.km^{-1}$ river edge)

Land surface instabilities connected to channel (section 5.5.3) indicates the total unstable area (landslides, other mass movements, torrents, gullies) connected to the river channel, divided by the length of the bankfull channel margin.

Measured / estimated suspended sediment load ($t.y^{-1}$)

Measured / estimated bedload ($t.y^{-1}$)

Sediment budget (at a minimum, whether sediment storage within the segment is positive or negative and thus indicative of change, or in quasi-equilibrium).

Number and severity of channel blocking structures that interrupt sediment (flow and wood) continuity through the segment is represented by two separate indicators:

Number of high blocking structures; Number of medium blocking structures (section 5.4.5). Wood transfer is additionally interrupted by spanning / crossing structures. These are indicated by Number of high (impact) spanning / crossing structures; Number of medium (impact) spanning / crossing structures (section 5.4.5).

Recent changes in the above indicators can also be estimated (section 6.3.4) to provide some understanding of how past changes may have and may continue to influence current river segment (and reach) condition.

8.4.2 River Morphology Adjustments (sections 4.4, 5.4.2, 5.4.4, 6.3.2, 6.3.3, 6.3.6)

At the segment scale, indicators represent constraints on and evidence for recent river dynamics represented by broad features of the valley (5.4.2, 6.3.2, 6.3.3) and riparian corridor (5.4.4, 6.3.6).

Three indicators represent constraints on river channel dynamics (section 5.4.2) within the segment, since they relate to the energy of the river: Average valley gradient (in $m.m^{-1}$); the lateral confinement of the river by its valley: Valley confinement (confined, partly-confined, unconfined, section 4.4); and the size of the river in relation to its valley: River confinement (alluvial plain width divided by typical river bankfull width – high river confinement (ratio = 1 to 1.5), medium (1.5 to 5 for single thread rivers, 1.5 to 2 for multithread rivers), low (> 5 for single thread, > 2 for multi thread rivers).

Four indicators represent the historical (decadal scale) lateral river dynamics as reflected by the extent and vegetation cover of any naturally-functioning riparian corridor (defined in section 5.4.4).

Average riparian corridor width (m) indicates the width of potential riparian corridor, including that under agriculture (see 5.4.4 for detailed definition)

Proportion of riparian corridor under functioning riparian vegetation (%)

Riparian corridor continuity (%) – proportion of the length of the bankfull channel margin abutting naturally functioning riparian vegetation

Riparian corridor vegetation cover / structure – this assesses the degree to which there is balanced interaction between fluvial and riparian vegetation dynamics as indicated by whether the naturally-functioning riparian vegetation coverage is mature (limited interaction), balanced (a balanced interaction is occurring), immature (riparian vegetation is heavily disturbed). The assessment of whether the vegetation coverage is mature, balanced or immature is based on the proportions of the corridor under patches of predominantly mature trees, shrubs, shorter vegetation, and bare soil:

mature = negligible (~0%) bare ground and shorter vegetation patches, mainly (> 80%) mature trees;

immature = negligible (~0%) mature trees, few if any shrubs, mainly (> 80%) bare ground and shorter vegetation patches;

balanced = intermediate between young and mature, with some representation of all patch types: mature trees, shrubs, shorter vegetation and bare soil patches.

8.4.4 Wood production (section 5.4.4)

Potential wood delivery (%) is indicated by the proportion of the active / bankfull river channel edge (bank top and island margins) covered by mature (living or dead) trees

8.5 Reach

All of the above indicators describe sources and production of runoff, sediment and wood, within the catchment; their transfer from landscape units into and to some extent through segments of the river network; and, where appropriate, how these may have changed over past decades. At the reach scale, indicators provide evidence of the current form and functioning of the river channel and its margins and how these may be changing. Indicators from the larger spatial scales should identify the larger-scale processes that govern present and past forms and dynamics at the reach scale.

8.5.1 Flooding (section 5.5.5)

Even where space remains for lateral channel movements, reaches of many European rivers have restrictions on the area of the natural floodplain that can actually be flooded. Such restrictions lead to hydraulic pressures within the area that can be flooded (river channel and riparian zone) and hydrological pressures on areas that can no longer be flooded. Therefore a simple indicator of these pressures is % floodplain accessible by floodwater (section 5.5.5).

8.5.2 Channel self-maintenance / reshaping (5.5.1, 5.5.2, 5.5.3, 5.6.2, 6.4.1, 6.4.2, 7)

Several indicators have a heavy influence on the potential type of river and level of dynamics that may be present:

Flow energy can be represented by Specific stream power (ω – stream power at appropriate morphologically meaningful discharge - Qp_{median}, Qp_{2}, Qp_{10} - per unit bankfull channel width in $W.m^{-2}$) (section 5.5.2)

Sediment size needs to be described separately for the river bed and banks and provides an indication of their respective structure and erodibility:

Bed sediment size Dominant calibre (bedrock, boulders, cobbles, gravel, sand and silt, clay) or D_{50} (median particle size) (5.5.3 and Annex C)

Bank sediment size Dominant calibre (bedrock, boulders, cobbles, gravel, sand and silt, clay) or D_{50} (median particle size) (5.5.3 and Annex C)

River channel dimensions both control and respond to river flows, sediment transport, and in many cases, the type and growth performance of riparian and aquatic vegetation. Seven river channel dimensions are important indicators of river channel character (for definitions of each underlined term see sections 5.5.1, 5.6.2):

Channel gradient (in $m.m^{-1}$) (based on the bankfull channel centre line).

Mean bankfull channel width (m)

Mean average bankfull channel depth (m)

Bankfull channel width:depth ratio

Bankfull sinuosity index

Braiding Index

Anabranching Index

When coupled with bed material size, the above indicators are sufficient to identify the river type for the reach (chapter 7 - see Table 7.1 for indicator thresholds and Table 7.3 for the 22 river channel types). Table 7.3 also lists some typical geomorphic units / features for each river channel type, from which an indicator of the natural functioning of the reach can be defined: Presence of channel and floodplain geomorphic units / features typical of the river type (negligible = no / few unit / feature types in low abundance, some = some unit / feature types or many unit / feature types in low abundance, many = many unit / feature types and in abundance). A final indicator of self-maintenance and reshaping is the % area of the bankfull channel occupied by bars, benches and islands, since this indicates dynamic in-channel sediment storage (section 5.6.2).

8.5.3 Channel Change / Adjustments (sections 5.5.5, 5.6.2, 6.4.1, 6.4.2)

The identification of channel changes or adjustments and the causes of such adjustments is fundamental to understanding the current condition and status of a reach and its response to particular pressures (see section 9.1). Identification of these changes is based on a combination of contemporary and historical evidence.

Lateral channel changes / adjustments can be identified from both contemporary and historical evidence.

Contemporary assessments of lateral channel adjustments are based on the spatial extent of particular geomorphic units / features (Table 5.7). Although these can be recognised from aerial imagery, their abundance / extent is best estimated from field surveys, to avoid their presence being obscured by overhanging vegetation or high water levels at the time of the imagery. Three indicators summarise current channel adjustments:

Eroding banks (% active channel bank length). This indicator is quantified using the extent of the active channel bank length showing natural (unreinforced) vertical, vertical/undercut, and vertical with toe bank profiles (section 5.6.2).

Laterally aggrading banks (% active channel bank length). This indicator is quantified using the extent of the active channel bank length showing stabilising (vegetating) marginal bar and bench features (Table 5.7, section 5.6.2)

In-channel retention of sediment (% area of bankfull channel). This indicator represents the proportion of the channel occupied by stabilising (vegetating) mid-channel bars and islands (Table 5.7, section 5.6.2).

The above contemporary indicators may only be indicative of very short term channel adjustments. Longer-term (decadal scale) lateral adjustments can be inferred from historical imagery and maps (Section 6.4.1). Active, channel boundary positions can be extracted from these historical sources and then overlain within a GIS to calculate average rates of bank erosion or accretion, and thus decadal scale lateral channel migration rates. Similarly bankfull channel mid-line lengths, numbers of channels separated by bars, and numbers of channels separated by islands can be extracted (the latter two require historical photograph sources), to estimate changes in channel planform through three indicators:

changes in sinuosity index,

changes in braiding index,

changes in anabranching index.

Changes in channel cross-sectional dimensions (narrowing / widening, bed incision-deepening / bed aggradation-shallowing, vegetation encroachment), can also be investigated through contemporary and historical information sources. Repeat (historical) surveys of channel cross profiles (6.4.2) can be used to quantify three indicators:

changes in channel width,

changes in channel depth,

changes in channel width:depth ratio.

The above longer-term indicators of channel change are complemented by seven contemporary indicators of channel widening, channel narrowing, bed incision and bed aggradation:

Presence of geomorphic units / features indicative of narrowing. This indicator is the proportion of the active channel length where active lateral channel accretion is observed on opposing banks (stabilizing, vegetated bars or benches on both banks, or presence of wide benches (> 25% channel width) opposite non-eroding banks (vegetated profiles other than vertical, vertical-undercut, vertical with toe), section 5.6.2, Table 5.7). Presence of geomorphic units / features indicative of widening. This indicator is the proportion of the active channel length along which active channel erosion (unreinforced banks with vertical, vertical-undercut, vertical with toe profiles, section 5.6.2, Table 5.7) is observed on both (opposing) banks

Presence of geomorphic units / features indicative of deepening

This indicator is the proportion of the active channel length where one or more of the following are observed - bank failures on both banks, bed sediments (e.g. gravel, overlain by finer true bank material) exposed in banks above current bed level, trees collapsing / leaning into channel on both banks, exposed foundations of structures such as bridge piers (section 5.6.2)

Presence of geomorphic units / features indicative of shallowing

This indicator is the proportion of the active channel length where one or more of the following are observed - buried soils revealed in bank profiles, burial of structures and contracted channels relative to bridge openings, partial burial of established vegetation (section 5.6.2)

Changes in bed sediment structure indicating incision (bed deepening) indicated by a severely armoured bed (D_{50} surface >> 3 times D_{50} subsurface across >50% of the bed - see section 5.5.5).

Changes in bed sediment structure indicating shallowing / bed aggradation (accumulation of sediment on bed). Two bed properties support an assessment of significant shallowing / aggradation: (i) a coarse river bed that has become very severely clogged and buried by finer sediments (sand and finer sediment layer completely burying > 90% of the gravel river bed - see section 5.5.5), (ii) a coarse bed characterized by very loose, uncompacted bars (surveyor's feet sink into the bar surface easily).

A vegetation indicator that supports the presence of very active channel narrowing is vegetation encroachment. All the geomorphic features / units indicative of channel narrowing are stabilised by vegetation (see above). Where narrowing is very marked, these features are heavily vegetated and their leading (inner) edge is completely covered by riparian or aquatic vegetation that is trapping sediment (vertically and laterally) and is encroaching into the active channel.

Constraints on channel adjustments arise from a variety of human activities. They prevent some of the lateral dynamics described by the above indicators and also influence whether vertical dynamics can occur. Therefore, their extent indicates the degree to which natural dynamics are prevented or constrained by current human interventions within the channel and close to its margins:

Width of the erodible corridor. The erodible corridor is the floodplain or, where a true floodplain is absent, the extent of erodible sediment adjacent to the river that is not protected from erosion by flood or transport infrastructure embankments, or bank reinforcement (bedrock channels would generally have no erodible corridor). Although appropriate indicators may vary with river style and environmental conditions, an indicator of erodible corridor width (including the channel width), which is suitable for single thread rivers in humid climates, could be recorded as absent; narrow (< 2 bankfull widths); moderate (up to 10 bankfull widths); wide (> 10 bankfull widths) (section 5.5.5).

Proportion of potentially erodible channel margin. The proportion not subject to the five types of immobilisation listed in section 5.5.5 (i.e. Proportion of bank length with 'hard'-reinforcement (concrete, stone, bricks, metal, gabions etc); with 'soft'-reinforcement (bioengineered banks); with artificial levées / embankments at the bank top; with set-back levées / embankments within 0.5 channel width of bank top; with infrastructure (buildings, roads etc) within 0.5 channel width of bank top). Thus bedrock channel margin would count as 'potentially erodible')

Proportion of river bed that is artificially reinforced. (section 5.5.5).

Number of high blocking structures. (section 5.5.5).

Number of medium blocking structures. (section 5.5.5).

Number of low blocking structures. (section 5.5.5).

Number of high spanning/crossing structures. (section 5.5.5).

Number of medium spanning/crossing structures. (section 5.5.5).

Number of low spanning/crossing structures. (section 5.5.5).

8.5.4 Vegetation Succession (Section 5.5.4)

Vegetation is not only an important component of river ecology and biodiversity, but its properties provide important indicators of the potential morphodynamics of the river and its corridor, particularly the degree to which fluvial processes and vegetation are interacting. Aquatic and riparian vegetation are assessed separately because in low-energy, baseflow-dominated rivers, aquatic vegetation underpins the most important indicators of natural plant-river interactions, whereas in higher-energy systems, little aquatic vegetation is present (Gurnell et al., 2010), except occasionally in lower energy side channels, and thus riparian vegetation underpins indicators of natural plant-river interactions (Gurnell, 2013).

There are four aquatic vegetation indicators. Each of which assesses the degree to which aquatic vegetation is influencing channel properties:

Aquatic vegetation extent. This indicator is recorded as absent; occasional patches; abundant along the channel margins; abundant across > 50% baseflow channel area (section 5.4.4).

Aquatic vegetation patchiness. (i) numerous (small) patches; (ii) a moderate number of (medium / large) patches; or (iii) a few very large, quasi-continuous, patches (section 5.4.4).

Aquatic vegetation species. the number of aquatic plant species or plant morphotypes (Gurnell et al., 2010) present (section 5.4.4).

Presence of aquatic-plant-dependent geomorphic units / features.

This index identifies the presence and abundance of these features on a scale of none; occasional; frequent small features; extensive large features (> 25% channel bed area).

These features occur where aquatic vegetation (usually emergent plants) trap and reinforce sediment inducing bar, bench and island development (Table 5.7) in low energy channels often with unstable (sand-silt) beds.

The following indicators of riparian vegetation, represent the degree to which vegetation-river interactions are active:

Proportion of the riparian corridor under mature trees, shrubs and shorter vegetation, and bare soil. A functioning riparian zone shows a mix of cover classes across areas of riparian vegetation, indicative of vegetation stands of different age including mature trees, shrubs / young trees, shorter vegetation, and bare areas that are essential for riparian tree recruitment. Where tree age classes are available, the cover classes can relate to tree growth stage such as bare, pioneer (1-2 yr), early growth (< 5 yr), juvenile (5-15 yr), mature (15-50 yr), and old tree patches (> 50yr)). As with the segment scale, this indicator describes whether the vegetation coverage is mature, balanced or immature. Based on the simple cover classes, mature = negligible (~0%) bare ground and shorter vegetation patches, mainly (> 80%) mature trees; immature = negligible (~0%) mature trees, few if any shrubs, mainly (> 80%) bare ground and shorter vegetation patches; balanced = intermediate between young and mature, with some representation of all patch types: mature trees, shrubs, shorter vegetation and bare soil patches (section 5.4.4). The same cover types are also used in the other two indicators:

Lateral gradient in riparian vegetation cover classes across the riparian corridor (suggesting lateral connectivity between the river and the areas of functioning riparian vegetation within the riparian corridor). The indicator records whether the lateral gradient is 'strong', 'subdued' or 'absent', where this refers to a lateral change in the proportion of the corridor under bare soil, shrubs and shorter vegetation, or mature trees with distance from the river channel (section 5.4.4).

Patchiness in riparian vegetation cover types across the riparian corridor (suggesting natural disturbance and interaction between vegetation and fluvial processes *within* the naturally functiong areas of riparian vegetation, including potential to retain large wood). The indicator assesses the degree to which discrete patches of mature trees, shrubs and shorter vegetation, and bare soil are present *within areas of functioning riparian vegetation* according to a scale of 'strongly patchy' (frequent changes in cover type and numerous small patches); 'some patchiness' (relatively large patches present but showing a clear mosaic effect); 'no patchiness' (predominantly consists of large areas of similar vegetation cover) (section 5.5.4).

In agricultural floodplains, only discrete areas of naturally-functioning riparian vegetation are present but is there patchiness within these areas that is indicative of interaction between vegetation and fluvial processes?

In a naturally-functioning riparian zone, all age classes should be represented, and thus the proportion indicator should be 'balanced', the lateral gradient indicator should be 'subdued' or 'strong', and the patchiness indicator should be 'strongly patchy' or 'some patchiness', with variations partly reflecting the river type, tree species and their growth performance within a particular reach.

The dominant riparian tree species is / are representative of the potential strength and style of tree-river interactions. In particular, some trees species (willows and poplars) sprout freely from wood pieces and uprooted trees, providing additional root anchorage to support tree-river interactions, whereas others produce predominantly dead wood.

Tree-river interactions are indicated by the presence of wood- or riparian tree- dependent geomorphic units / features. A list of such features is provided in Table 5.7. The indicator describes whether such geomorphic units are 'absent', 'occasional', 'frequent', 'abundant', or 'abundant and diverse'.

8.5.5 Wood Delivery (Section 5.5.4)

The delivery of large wood (both dead and regenerating pieces) to a reach is very important for driving interactions between the river and riparian vegetation (through the creation of wood- and tree- dependent geomorphic units / features). Wood delivery is affected by both spanning and blocking structures. Indicators of blocking and spanning/crossing structures are listed above in section 8.5.3 (i.e. Number of high blocking structures, Number of intermediate blocking structures, Number of low blocking structures, Number of high (impact) spanning/crossing structures; Number of medium (impact) spanning/crossing structures).

Wood retention is represented by four indicators (see section 5.4.4):

Abundance of isolated large wood pieces in the active channel.

Abundance of accumulations of large wood pieces in the active channel.

Abundance of channel-blocking jams of wood in the active channel.

Abundance of large wood in the riparian corridor.

In each case, abundance is recorded as 'negligible', 'present' (but in low abundance), 'extensive'.

9. Interpreting Condition and Trajectories of Change

9.1 Introduction

In chapter 9, the indicators assembled in chapter 8 are used to build understanding of river characteristics, condition, past dynamics, sensitivity, and potential future changes. For specific applications of the process of interpreting condition and trajectories of change, see the full Catchment Case study applications in Deliverable 2.1 Part 3.

Before embarking on detailed descriptions of how these themes can be approached, the meaning of the terms 'condition', 'trajectories of change' and 'sensitivity' are considered.

9.1.1 'Condition'

The term 'condition' is used to capture the degree to which observed hydrogeomorphological properties conform to what would be expected in a naturally-functioning situation, and thus how far the properties have deviated from that naturally-functioning state. However, the degree to which such a deviation is seen to be small or large depends upon the biogeographical, socio-economic, and cultural context. What might be considered to be a small deviation from natural function that is of no concern in some contexts, might be seen to be a considerable and notable deviation in other contexts.

9.1.2 'Trajectories of Change'

The identification of 'channel changes', 'channel adjustments', related 'trajectories of change' and their causes is fundamental to understanding the current condition and status of a reach and its response (adjustment and trajectories of change) to particular pressures. Therefore, the following paragraphs provide the broad context in which reach 'condition', 'adjustment' and 'change' need to be considered.

Identification of reach adjustments is based on a combination of contemporary and historical evidence and is initially investigated at the reach scale. However, such reach scale evidence more often than not reflects processes operating beyond the reach, and under such circumstances, it is crucial to consider what the processes and pressures might be that are inducing current condition and associated adjustments.

Channel adjustments are most frequently induced by a distinct change in the discharge regime or the quantity of sediment supplied to the reach. Such changes may result in (i) too much sediment being supplied for river flows to move the sediment on through the reach, leading to the accumulation of sediment within the reach; or (ii) insufficient sediment being supplied to satisfy the sediment transport ability of the river flows, resulting in erosion of the bed or banks within the reach.

Where sediment supply exceeds the transporting ability of the flows, then sediment is deposited within the reach. The particular type of adjustment within the reach depends on the quantity and particle size of the sediment that is delivered and the extent to which these exceed the ability of the flow to transport the sediment. If the supplied sediment is finer than the channel bed material, the early phases of channel adjustment often involve clogging of the pre-existing bed material prior to aggradation and burial of the pre-existing bed surface. Whatever the size of the supplied sediment, bed aggradation is likely to occur, coupled with bar and bench development, and often stabilisation of the deposited sedment by vegetation. Ultimately, the reduction in the size of the channel (shallowing / narrowing) increases over-bank flood frequency, aggradation of the floodplain, and the likelihood of channel avulsion or a change in channel type (e.g. from single thread to braided, see Deliverable 2.1, Part 2, Annex G), as the original river channel becomes choked with sediment.

An increase in sediment supply relative to flow often reflects changes in land cover in the upstream catchment, or the dumping of sediment into the channel (e.g. mining waste). Sometimes these changes persist in the medium to long term, as in the case of sediment delivered in response to agricultural instensification. However, sediment dumping often occurs for a specific time period, leading to a distinct period of increased sediment supply that generates the movement of a slug of sediment downstream and the downstream propagation of cycles of aggradation followed by degradation, as the slug transfers downstream, in affected reaches. The increase in sediment supply relative to flow may also reflect a reduction in flow, change in flow regime, or reduction in channel gradient and thus in flow energy. A reduction in the overall quantity or magnitude-frequency of high flows usually accompanies water abstractions or the manipulation of water resources by reservoir development. A reduction in channel gradient may result from downstream pressures such as the installation of reservoirs, weirs, or channel training structures that induce sediment retention and an increase in bed level downstream, followed by propagation of raised bed levels in an upstream direction. A reduction in channel gradient is also a consequence of increasing stream sinuosity.

Where sediment supply is insufficient to satisfy the ability of the flows to transport sediment, then the result is sediment erosion within the reach (unless the reach is fully reinforced, in which case the eroson is displaced downstream). Likely channel adjustments include bed armouring (as the river mobilises all particle sizes it is able to mobilise and remove from the bed), bed incision (where the river is able to move all particle sizes on the bed), and bank undercutting and erosion. These lead to channel enlargement; in the case of incision, a reduction of the connectivity between the river and its floodplain; and in the case of lateral erosion, destabilisation of banks, lateral channel dynamics and widening, and the potential undermining of infrastructure on the river banks. In any of these cases, the channel type may change (see Deliverable 2.1, Part 2, Annex G), and where there is bed incision, inset floodplains and terraces may develop along the margins of the deepened channel.

A decrease in sediment supply relative to flow arises either because the supply of sediment is reduced, flows are increased (particularly high flows), or the reach gradient and thus flow energy is increased. Reduced sediment supply can result from the installation of storage structures upstream, such as reservoirs and drop structures, or the removal of sediment from the channel (e.g. gravel mining). Increased flows can be associated with land use change, particularly urban development. Urban development usually leads to an increase in percentage runoff from rainfall, increased frequency of floods of moderate size, as well as a reduction of sediment supply as a result of channel reinforcement and sealing of the land surface under roads and buildings. Hydropower development that involves hydropeaking, may also lead to channel scour as a result of the frequent occurrence of bankfull flows. A less obvious but potentially widespread impact is the increase in channel gradients that are attributable to channel straightening and deepening. Where such changes in gradient occur, they can lead to bed scour and head-cutting or the upstream propagation of a knick point (sharp drop in bed level) for considerable distances through the channel network, affecting numerous reaches upstream.

Thus, recognising poor condition or changes occurring within a reach should be coupled with a detailed consideration of the causes of the degraded condition and associated changes. These can be evidenced by information from upstream and downstream reaches (are they adjust in a similar way and over a similar time period) and from the segments, landscape units and catchments within which the reaches are located. Knowledge gained from this process also helps to forecast likely future responses of river reaches to specific scenarios of change.

9.1.3 'Sensitivity'

A final element of this description of the context in which section 9 should be placed, is the concept of 'sensitivity'. The term is used to describe the likelihood of a particular river reach adjusting to imposed changes (e.g. in flow or sediment supply). In some cases negligible adjustments to imposed changes may occur, and the reach 'accommodates' the changes and so has negligible 'sensitivity' to those changes. In other cases, quite small changes in controlling processes may result in major adjustments and thus the reach is deemed 'highly sensitive'. This is often the case when a reach is close to a threshold condition where it may change from one river type to another (see Deliverable 2.1, Part 2, Annex G for some empirical methods for estimating proximity to threshold conditions). This highly sensitive, near-threshold condition has been described by some researchers as high 'vulnerability'.

Channel adjustments may be expressed in the form of increased lateral dynamics (channel migration / widening / narrowing), vertical dynamics (channel incision / shallowing), or changes in bed structure (coarsening / armouring / fine sediment retention – infiltration - burial of the bed). Whether any of these adjustments imply significant 'sensitivity' depends upon their magnitude in the context of the river type considered. For example, if the river is actively meandering (as in the case of many gravel-cobble meandering rivers) then a lateral displacement of ten or more meters to a particular change in processes would not indicate a high sensitivity, whereas if the river was stable meandering (as is the case of most silty meandering rivers) then such a displacement could be interpreted as a high sensitivity to the change in processes.

To some extent, the assessment of 'sensitivity' is also economically, socially and culturally constrained. For example, significant bed siltation on an economically important salmonid river could be deemed an expression of high sensitivity to a change in processes, even if no channel movement or change in channel dimensions occurred.

9.1.4 Logic and Structure of Section 9

As with all previous chapters, the approach that is described is open-ended and can be adapted to local circumstances. Thus, additional indicators could be incorporated to expand the detail of any assessments (e.g. chapters 5 and 6 suggest many characteristics that are not incorporated as indicators in chapter 8), and different interpretations or weightings of indicators could be made to suit local environmental conditions. The rationale underlying chapters 8 and 9 is to present a short list of key indicators and to explain how these can be used to interpret condition and change across spatial scales.

Throughout chapter 9, the names of indicators are underlined to clarify when specific indicators are being cited. Understanding is built through four stages of analysis:

Stage 1. In section 9.2, the current condition of reaches within a study area is assessed. The assessment concerns the river types and riparian corridor that are present, the degree to which they possess features indicative of natural function and dynamics, direct (within reach) human alteration, and any contemporary evidence of a trajectory of change.

Stage 2. In section 9.3, a temporal perspective is introduced and the contemporary and historical, indirect (beyond reach) controls on reach-scale changes are assessed at the catchment, landscape unit and segment scales to construct a space-time inventory of changes, focusing particularly on human alterations that indirectly affect river reaches.

Stage 3. In section 9.4, the sensitivity of individual reaches to change is assessed. Sensitivity assessment is based upon (i) compiling evidence for historical adjustment within reaches and comparing it with (ii) contemporary condition and adjustment, already identified at the reach scale in section 9.2, to provide an overall picture of adjustment and then (iii) placing this information in the context of direct / local (identified at stage 1, section 9.2) and indirect (identified at stage 2, section 9.3) human-induced and other changes that may have influenced the adjustments.

Stage 4. In section 9.5, potential future trajectories of change are considered for different reach contexts (river type and condition, landscape unit / segment context), emphasising the use of local information from application of the hierarchical framework described in this report to underpin assessments. Trajectories are based on a small number of scenarios relevant to the river in question, with the aim of informing management recommendations.

Chapter 9 ends with a discussion of the use of models at different spatial and temporal scales (section 9.6). Models are invaluable tools that can complement and extend many of the approaches suggested in this report, particularly in chapter 9. They can help to make the most effective use of contemporary and historical data in building an integrated picture of system functioning, and, based upon this improved understanding of functioning, they are invaluable in considering scenarios of future change. However, the value of modelling depends upon the expertise of the modeller. Furthermore, the accuracy of model outputs reflects the availability of sufficient, good quality information for reliable model calibration and application. Thus, the use of models within this multi-scale framework depends upon information collected during the characterisation and indicator estimation phases (chapters 5 to 8) and can contribute to delivering stages 1 to 4 (sections 9.2 to 9.5), when relevant data sets and modelling expertise are available.

For modelling applications to particular Case Study catchments see section I in Deliverable 2.1, Part 2.

9.2 STAGE 1: Assess Current Reach Condition

This stage aims to produce a catchment-wide synthesis of the types of river reach that are present within the catchment, their current condition and how reach types and condition vary within the catchment using the set of reach-scale indicators listed in Table 9.1. Where indicators are combined, suggestions are made about their relative significance and weighting, but precise, quantitative or semi-quantitative weightings should be considered carefully by the user and adjusted to suit local circumstances, since it is unlikely that a single approach would be suited to application across the whole of Europe.

In this section, 3 to 7 category assessments are suggested, because this level of detail is usually sufficient in a management context and it lends itself to clear catchment-scale mapping. The following reach-scale assessments of current condition are described:

(i) reach type

(ii) hydromorphological function (good intermediate, poor);

(iii) hydromorphological alteration / artificiality (severely artificial, artificial, some significant artificial elements, low artificiality)

(iv) hydromorphological adjustment (narrowing, bed aggradation, widening, bed incision,channel enlargement, channel reduction, no indicators of significant change)

(v) riparian corridor function (functioning riparian vegetation structure, functioning wood budget)

(vi) riparian corridor alteration, artificiality (riparian vegetation structure excessively disturbed / exploited, riparian vegetation structure shows little or no natural disturbance or excessive managementance / alteration, excessive riparian wood removal, riparian corridor not functioning as a sufficient supplier of large wood).

Table 9.1 groups the reach scale indicators from Table 8.1 according whether they are *predominantly* descriptors of reach character (D) or fundamental controls on that character (C) (i.e.controls on channel morphology and dynamics), and whether they are predominantly indicators of hydromorphological or ecological function (F), alteration / artificiality (A) and / or channel adjustment (CA). The table also identifies whether each indicator is *mainly relevant* to describing and assessing the channel (CH) or the riparian corridor (RC). Since the river type synthesises the bankfull sinuosity index, braiding index and anabranching index, these latter indicators are not listed in Table 9.1, but they are revisited in section 9.3 in the context of historical channel change and sensitivity.

First, the control and descriptor indicators for each reach are assessed to allocate each reach to a type. The river type reflects the combination of bed sediment size, planform and level of confinement (Table 7.2) and should be concordant with the channel gradient. Specific stream power is also a determinant / control of river type, whereas total stream power (i.e. unit stream power x channel bankfull width) is a control on channel size.

Assessments of hydromorphological functionality, alteration/artificiality and adjustment of the channel are made based on the contemporary condition indicators (Table 9.1).

(i) **Hydromorphological function** of the river can be conveniently assessed for all river types as good, intermediate or poor. This assessment is made initially using Presence of channel and floodplain geomorphic features/units typical of river type. For example, functionality could be assessed as good if this indicator is 'many', intermediate if the indicator is 'some' and poor if the indicator is 'negligible' (section 8.5.2).

Channel types 1 to 7 are all confined types and so not laterally mobile. However, each type possesses a set of potential geomorphic units which are sufficiently distinct to apply the above single criterion and allocate these reaches a good, intermediate or poor assessment. Other channel types, when in a confined setting, can also be assessed using mainly this single indicator.

For channel types 8 to 18, which are expected to be laterally mobile when not fully confined (see stability column in Table 7.3), the initial assessment could be raised if such lateral mobility is apparent. For example, an initial assessment of intermediate could be raised to good and a poor assessment could be raised to intermediate if the % area of bankfull channel occupied by bars, benches, islands is greater than 20% or if the total of Eroding banks and Laterally aggrading banks (section 8.5.2) is more than 20%. (Note that high values may also indicate channel adjustment, but this is revisited in subsection (iii) below)

In many environmental contexts, less mobile, low gradient, fine sediment channel types 19 to 22, support a significant cover of aquatic vegetation. Where this is the case, a value of 'frequent' or 'extensive' in the indicator, Presence of aquatic-plant-dependent geomorphic units / features (section 8.5.4), could justify raising a poor assessment to intermediate.

Lastly, where the reach is located below the tree line, another indication of natural function that could contribute to raising the initial assessment is the Presence of wood / riparian tree-dependent geomorphic units / features (section 8.5.4). This indicator describes whether such geomorphic units are 'absent', 'occasional', 'frequent', 'abundant', or 'abundant and diverse' and illustrates that wood is being retained in the reach in sufficient quantities and for sufficient time to interact with fluvial processes to create landforms and habitats. Indicator values of frequent, abundant, or abundant and diverse could be used to raise the initial assessment based on Presence of channel and floodplain geomorphic features/units typical of river type from intermediate to good or poor to intermediate.

(ii) **Hydromorphological alteration/artificiality** of a reach can be assessed in relation to longitudinal continuity, lateral continuity, and level of reinforcement.

Alteration of the longitudinal continuity through the reach for water, sediment, wood and other organic material is indicated by Number of high, intermediate, low blocking structures (section 8.5.3). Longitudinal continuity could be assessed as poor if a single high or intermediate blocking structure is present, intermediate if more than one minor blocking structure is present, and good if no blocking structures are present.

Table 9.1 Reach scale indicators of contemporary condition, grouped according to whether they are descriptors (D), controls on hydromorphology (C), and whether they are indicators of function (F), alteration / artificiality (A), or channel adjustment (CA). Their spatial relevance to predominantly the river channel (CH) or the river's riparian corridor (RC) is also indicated.

Indicator	Type[1]	Spatial Relevance[2]
Specific stream power	C	CH
Bed sediment size	C, D	CH
Bank sediment size	C, D	CH, RC
Channel gradient	C, D	CH
Bankfull channel width	D	CH
Bankfull channel depth	D	CH
Width:depth ratio	D	CH
River type	D	CH, RC
Dominant riparian tree species	D	RC
Presence of channel and floodplain geomorphic features/units typical of river type	F	CH, RC
% area of bankfull channel occupied by bars, benches, islands	F	CH
Eroding banks	F	CH
Laterally aggrading banks	F	CH, RC
Aquatic plant extent	F	CH
Aquatic plant patchiness	F	CH
Aquatic plant species / morphotypes	F	CH
Presence of aquatic-plant-dependent geomorphic units / features	F	CH
Proportion of riparian corridor under mature trees, shrubs, shorter vegetation, bare	F	RC
Lateral gradient in riparian vegetation cover classes	F	RC
Patchiness in riparian vegetation cover classes	F	RC
Presence of wood / riparian tree-dependent geomorphic units / features	F	RC
Abundance of isolated wood pieces,	F	RC
Abundance of in-channel wood accumulations	F	RC
Abundance of channel-blocking jams,	F	RC
Abundance of large wood in the riparian corridor	F	RC
% floodplain accessible by floodwater	A	CH[3]
Width of erodible corridor	A	RC
Proportion of potentially erodible channel margin	A	CH, RC
Proportion of river bed artificially reinforced	A	CH
Number of high, intermediate, low blocking structures	A	CH
In-channel retention of sediment	CA	CH
Presence of geomorphic units / features indicative of narrowing	CA	CH
Presence of geomorphic units / features indicative of widening	CA	CH
Presence of geomorphic units / features indicative of incision	CA	CH
Presence of geomorphic units / features indicative of aggradation	CA	CH
Changes in bed sediment structure indicating incision	CA	CH
Changes in bed sediment structure indicating aggradation	CA	CH
Aquatic / riparian vegetation encroachment	CA	CH, RC

[1] D=descriptor, C=Control, F= Function, A=Alteration/Artificiality, CA=Channel adjustment
[2] CH=River Channel, RC=Riparian corridor
[3] RC not included because by definition the riparian corridor is subject to inundation

Alteration of lateral continuity within the reach for water, sediment, wood and other organic material is indicated by % floodplain accessible by floodwater (for a description and definition see sections 5.5.5, and 8.5.1) and Width of erodible corridor (section 8.5.3), and can only be assessed for partly-confined and unconfined reaches. The following recommendations for assessment are probably applicable to most single thread rivers, but may be too restrictive for multi-thread rivers. In this context, lateral continuity could be assessed as poor if the total width of the erodible corridor on both sides of the channel is less than one bankfull channel width or if the % floodplain accessible by flood water is less than 5%; good if the total width of the erodible corridor on both sides of the channel is greater than 10 bankfull channel widths and the % floodplain accessible by flood water is greater than 75%; and intermediate if it falls between these bounds.

Alteration of the potential of the channel to adjust laterally or vertically is indicated by Proportion of potentially erodible channel margin and Proportion of river bed artificially reinforced (section 8.5.3). Adjustment potential could be assessed as low if the total of the proportion of non-erodible channel margin (inverse of Proportion of potentially erodible channel margin) and the Proportion of river bed artificially reinforced exceeds 100%; high if this total is less than 5% and intermediate if it falls between 5 and 100%.

The above assessments can be integrated into an overall hydromorphological alteration / artificiality assessment. For example, if a poor/low assessment is scored 3, intermediate is scored 2, and good/high is scored 1, then partly confined or unconfined channels could be assessed as severely artificial (total score = 8-9), artificial (total score = 5-7), some significant artificial elements (total score = 4), or low artificiality (total score = 3) according to their total score on the three elements. For confined channels, the scoring could be severely artificial (total score = 6), artificial (total score = 4-5), some significant artificial elements (total present, the nature of change / trajectory that it appears to be following, using the indicators described in section 8.5.3.

Channel narrowing is indicated by Presence of geomorphic units / features indicative of narrowing and In-channel retention of sediment. For example, if more than 80% bank length is affected by Presence of geomorphic units / features indicative of narrowing and / or if more than 50% of the bed is affected by vegetation-stabilised accumulations of sediment (In-channel retention of sediment), significant narrowing of the channel is indicated. A further vegetation indicator that supports the presence of very active channel narrowing is vegetation encroachment along the margins of the channel

Channel bed aggradation / shallowing is indicated by In-channel retention of sediment and Changes in bed sediment structure indicating bed aggradation. The former illustrates sufficient accumulation of sediment for distinct landform development, while the latter indicates an earlier stage in the process of bed aggradation. In either case, if more than two-thirds (66%) of the bed is affected, this could be interpreted as significant channel bed aggradation.

Channel widening is indicated by Presence of geomorphic units / features indicative of widening. If more than 80% channel bank length is affected by Presence of geomorphic units / features indicative of widening, then significant widening is likely to be occurring.

Channel incision is indicated by Presence of geomorphic units / features indicative of incision, and Changes in bed sediment structure indicating incision. If Presence of geomorphic units / features indicative of incision affects more than 80% of the channel length or Changes in bed sediment structure indicating incision indicate a severely armoured bed then significant incision is likely to be occurring. Further confirmation of the severity of bed incision is provided by the channel Width:depth ratio. A ratio of $\leq$ 1 is usually taken to be indicative of an incising channel.

Channel narrowing and bed aggradation often accompany one another, indicating that the capacity of the channel is reducing. All the geomorphic features / units indicative of channel narrowing are stabilised by vegetation. Conversely, bed incision and widening often occur together indicating channel enlargement. Bed incision and narrowing can also occur together where there is a decrease in bed material supply.

The extent to which widening, narrowing, lateral movement, shallowing and deepening, and accompanying changes in channel gradient, stability, and sediment storage have occurred in the longer term, extracted from historical plan, long profile and cross profile evidence include, from plan information, changes in sinuosity index (reflects change in channel gradient), changes in anabranching index (reflects changes in the stability of stored sediment), and from long profile and cross sectional information, changes in channel width, changes in channel depth, changes in channel width:depth ratio, changes in channel gradient.

Assessments of the riparian corridor (corridor of naturally-functioning riparian vegetation cover, where the vegetation is subject to inundation, physical disturbance and material exchange from the river) uses contemporary condition indicators (Table 9.1) to assess function and alteration/artificiality.

(i) **Riparian corridor function** is assessed using the vegetation succession and wood delivery indicators (section 8.5.4). Because the corridor is defined as being subject to inundation, remnant areas of the corridor that are no longer accessible by flood water are not assessed.

Vegetation structure: Three indicators (Proportion of riparian corridor under mature trees, shrubs, shorter vegetation, bare, Lateral gradient in riparian vegetation cover classes, Patchiness in riparian vegetation cover classes) support an assessment of whether the vegetation structure of the riparian corridor is indicative of natural successional processes and an active fluvial disturbance regime. Although the absolute proportions and detailed structure of the different cover types vary with river type and moisture availability (particularly groundwater levels / dynamics), a naturally functioning riparian corridor possesses a mix of different cover types that is spatially patchy and also shows a broad increase in the later successional stages with distance from the river channel. Therefore, if Proportion of riparian corridor under mature trees, shrubs, shorter vegetation, bare is 'balanced' and Patchiness in riparian vegetation cover classes is 'some patchiness' or Lateral gradient in riparian vegetation cover classes is 'strong' or 'subdued', then it is likely that the areas of the riparian corridor under riparian vegetation are functioning well.

Wood budget: Four indicators assess elements of the wood budget of a reach (Abundance of isolated wood pieces, Abundance of in-channel wood accumulations, Abundance of channel-blocking jams, Abundance of large wood in the riparian corridor) and are indicative of riparian corridor function and river-riparian connectivity within or immediately upstream of the reach. Therefore, if Abundance of large wood in the riparian corridor is 'extensive' and at least one of the other three indicators is also 'extensive' (their relative abundance varies with river type and size), the riparian corridor can be assessed as a functioning, connected, producer and supplier of large wood.

(ii) **Riparian corridor alteration / artificiality.** The most extreme artificiality assessment occurs where no riparian corridor is present.

Where a riparian corridor is present, its alteration / artificiality can be assessed indirectly from the same indicators as were used for assessing function.

Vegetation structure could be deemed to be altered if Proportion of riparian corridor under mature trees, shrubs, shorter vegetation, bare is 'immature' (suggesting excessive disturbance or exploitation) or 'mature' (little or no natural disturbance), Patchiness in riparian vegetation cover classes is 'strongly patchy' (suggesting excessive disturbance or exploitation) or 'no patchiness' (little or no natural disturbance), Lateral gradient in riparian vegetation cover classes is 'absent' (suggesting little or no natural disturbance or intensive management).

Severe degradation of the wood budget (e.g. excessive wood removal or very poor supply of wood by the corridor vegetation) is indicated if Abundance of large wood in the riparian corridor is 'negligible'. Furthermore, the riparian corridor can be assessed as disconnected, or not functioning as a sufficient supplier of large wood (i.e. wood not reaching the river or is being removed from the river at a rate that exceeds supply), if the other three indicators are all recorded as 'negligible'.

9.3 STAGE 2: Controls on Change

In this section, the catchment to segment contexts for river reaches are considered, including both their current and historical condition. These assessments help to explain the current hydromorphological condition of reaches (section 9.2), and also the past sensitivity of individual reaches to changes at larger spatial scales (sections 9.4).

Tables 9.2 to 9.4 group, respectively, the catchment to segment scale indicators from Table 8.1 and categorise them according whether they are predominantly descriptors (D) or fundamental controls on channel morphology and dynamics (C), and whether they are indicators of natural function (F), or alteration / artificiality (A) at the particular spatial scale

9.3.1 Catchment

Table 9.2 lists the catchment scale indicators from Table 8.1.

As described in chapter 6, assessment of change is dependent upon the availability of historical information. Therefore, we recommend the assessment of historical change in as many indicators as possible. Many indicators throw light on similar hydromorphological processes and forms, and so the assembly of as thorough a set of historical values and dates as is feasible, will provide the most robust basis for constructing an inventory of change (section 9.3.4). Since air photograph cover is available for most areas of Europe from the mid 20th century, and is complemented since the 1980s by multi-spectral satellite data, we suggest that for those indicators that can be estimated from these sources, at least three evaluations should be attempted. Ideally these could focus on the 1940s to 1950s, the 1980s to 1990s, and the present, to describe a basic trajectory of change over the last 60-80 years. As with all stages of this procedure, the approach is open-ended and so can be simplified, adjusted or expanded to suit local circumstances of data and time availability, as we illustrate in the full Catchment Case studies (Deliverable 2.1 Part 3).

Table 9.2 Catchment scale indicators grouped according to whether they are descriptors (D), act as controls (C) on hydromorphology, and whether they are indicators of hydromorphological function (F) or alteration / artificiality (A). Those indicators that have the potential to change significantly through time are also indicated by Y in the Change? column.

Indicators	Type[1]	Change?
Drainage area (km^2)	D, C	Y
Geology (WFD types)		
% silicious	D, C	
% calcareous	D, C	
% organic	D, C, F	Y
% mixed /other	D, C	
Land cover (CORINE level 1)		
% forest and semi-natural areas	C, F	Y
% wetlands	C, F	Y
% artificial surfaces	C, A	Y
% agricultural areas	C, A	Y
Water yield (mm)	C	Y
Annual runoff ratio (coefficient)	C	Y

[1] D=descriptor, C=Control, F= Function, A=Alteration/Artificiality

Of the indicators in Table 9.2, drainage area and the four geology indicators (% silicious, % calcareous, % organic, % mixed /other) provide the main descriptors of a catchment in the context of hydromorphology, since they affect the area over which precipitation is collected and the potential importance of subsurface water storage and different drainage pathways, and thus the amount and timing of runoff through the river network.

In most catchments, drainage area, although a fundamental control on runoff production, can be considered to be a fixed descriptor. However, in basins that lose or receive water as a result of inter-basin transfers, it is crucial to know when the effective catchment area changed, the size of the natural (topographic) catchment area and the size of the effective catchment area as a result of the transfer scheme. Indicators of elevation and catchment morphology (see section 5.2.1) are also catchment descriptors, but these properties are absorbed into other indicators at the landscape unit and segment scales, and so can be considered optional at this scale.

In relation to geology, while the hydromorphogical impact of % silicious and % calcareous can be considered to remain essentially the same through time, the other two geological indicators, particularly % organic, may be susceptible to change as a result of their exploitation by humans. Organic material (e.g. peat) has a very important influence on hydrological processes, including both quality and quantity of water retention / delivery to the river network. Therefore, significant historical changes in its extent and volume are potentially important for the functioning of the fluvial system downstream and so require assessment

Land cover in Europe is highly dynamic and is a fundamental control on the water balance, runoff responsiveness and sediment production within a catchment. Therefore, it is important to determine current and past cover of the four land cover indicators (% forest and semi-natural areas, % wetlands, % artificial surfaces, % agricultural areas), which should provide sufficient context for interpreting catchment trends in land cover that may have had a significant hydromorphological impact.

Where flow records permit, similarly-spaced estimates (e.g. 20 year averages spread through 1950 – present) or a twenty year running mean plot of water yield and annual runoff ratio, provide an initial basis for unravelling impacts of changes in effective catchment area, land cover change, and climate-related hydrological changes on river flows and thus hydromorphology.

9.3.2 Landscape units

Indicators at the landscape unit scale (table 9.3), provide information on the distribution of some of the catchment-scale controls, emphasising soil and bedrock permeability, land cover and sediment production.

Only a single assessment of % area of exposed aquifers and % area of permeability classes is necessary as these can be viewed as unchanging.

All other indicators are subject to significant change through time, so assessment at a minimum of three different dates is recommended. Change in % glaciers and perpetual snow is indicative of climate change and has a very significant impact on the river flow regime. Change in % large surface water bodies also has a very significant impact on the river flow regime and change is usually indicative of reservoir development. In this case, locations, dates of implementation and volumes of water stored are crucial to developing an informative inventory (section 9.3.4). Land cover change affects both water and sediment delivery to the river network, and so once again, assessment at three different dates is the minimum that is needed. CORINE can provide some of this data, but some attempt to quantify cover according to the four listed indicators (% area of rapid runoff production, % area of intermediate runoff production, % area of delayed runoff production, % area with potential sources of coarse sediment) for earlier dates is strongly recommended.

Soil erosion rate (t. ha^{-1}. y^{-1}) for the landscape unit can be estimated from existing maps for at least one date. For other dates, a modelling approach could be adopted (section 5.3.2) or at a minimum, the changes in land cover already estimated above, provide an indication of likely changes in erosion rates through time.

Table 9.3 Landscape unit scale indicators that act as controls (C) on hydromorphology and, in some cases are indicators of alteration / artificiality (A). Those indicators that have the potential to change significantly through time are also indicated by Y in the Change? column.

Indicators	Type[1]	Change?
% area of exposed aquifers	C	
% area of permeability classes	C	
% glaciers and perpetual snow	C	Y
% large surface water bodies	C, A	Y
Land cover (CORINE level 2)		
% area of rapid runoff production (paved or compacted area, urban fabric, industrial, commercial, transport units, open spaces with little or no vegetation)	C, A	Y
% area of intermediate runoff production (arable land, permanent crops, pastures, shrub and/or herbaceous vegetation)	C, A	Y
% area of delayed runoff production (forests, wetlands)	C	Y
Soil erosion rate (t. ha^{-1}. y^{-1})	C	Y
% area with potential sources of coarse sediment	C	Y

[1] C=Control, A=Alteration/Artificiality

9.3.3 Segments

Indicators at the segment scale (Table 9.4), provide information on the valley setting, water and sediment flow through the river network, and the valley and corridor constraints on river adjustments.

Average valley gradient and valley confinement are both generally unchanging controls on the range of river types that are feasible within the segment (although both may change following extreme events such as earthquakes or glacier surges). River confinement is also generally unchanging, although major changes in river width (in response to large changes in flow, sediment transport and/or marginal vegetation) could significantly alter this ratio, and can be assessed for at least three dates from air photographs.

The flow regime type and baseflow index both summarise the type of flow regime that is present. As such they are regime descriptors and are very unlikely to change without significant human interventions. As a part of the flow analysis, it is strongly recommended that temporal changes in these descriptor indicators are investigated. For example a change in the flow regime type will be reflected in major hydromorphological changes within and downstream of the segment. All of the remaining five flow indicators (average annual flow, average monthly flows, morphologically meaningful discharges, extremes, hydropeak frequency) can be estimated from flow records to depict the present, past or naturalised conditions as described in section 5.4.1 and Annex C of Deliverable 2.1 Part 2. Changes in any of these indicators through time or in comparison with naturalised conditions will be accompanied by hydromorphological changes within the segment and, in most cases will affect downstream segments as well. Whilst small shifts may be attributable to climate change, major shifts usually reflect human interventions, with hydropeaking being a distinct indicator of artificiality in the flow regime.

Table 9.4 Segment scale indicators of condition, grouped according to whether they are descriptors (D), controls on hydromorphology (C), and whether they are indicators of hydromorphological function (F) or alteration / artificiality (A). Those indicators that have the potential to change significantly through time are also indicated by Y in the Change? column.

Indicators	Type[1]	Change?
Average valley gradient ($m.m^{-1}$)	C	
Valley confinement	C	
River confinement (alluvial plain width / bankfull river width)	C	Y
Flow regime type	D	Y
Baseflow index (BFI)	D	Y
Average annual flow ($m^3.s^{-1}$)	C, F	Y
Average monthly flows ($m^3.s^{-1}$, seasonal pattern)	C, F	Y
Morphologically meaningful discharges (Qp_{median}, Qp_2, Qp_{10}, $m^3.s^{-1}$)	C, F	Y
Extremes: 1- and 30-day maximum and minimum flows	C, F	Y
($m^3.s^{-1}$ and month of most frequent occurrence)		Y
Hydropeak frequency (number / year)	C, A	Y
Eroded soil delivered to channel	C	Y
Land surface instabilities connected to channel	C	Y
Measured / estimated suspended sediment load ($t.y^{-1}$)	C	Y
Measured / estimated bedload ($t.y^{-1}$)	C	Y
Sediment budget (+ve / -ve channel sediment storage)	C	Y
Number of high channel blocking structures	C, A	Y
Number of intermediate channel blocking structures	C, A	Y
Riparian corridor width	C, F	Y
Riparian corridor continuity	C, F	Y
Riparian corridor vegetation cover / structure	C, F	Y
% active channel edge bordered by living / dead trees	C, F	Y

[1] D=descriptor, C=Control, F= Function, A=Alteration/Artificiality

Four indicators reflect sediment delivery and transport dynamics within a segment (eroded soil delivered to channel, land surface instabilities connected to channel, measured / estimated suspended sediment load, measured / estimated bedload) and all are subject to temporal change. The first two indicators are relatively easily obtained from historical and contemporary information assembled at the landscape unit scale. For the last two indicators, any measurements or estimates should be treated with caution because they are subject to considerable error. However, estimates based on formulae may be informative because they provide an idea of the potential of the river within the segment to transport sediment of different grain sizes based on flow and channel properties. Therefore, a comparison of historical and contemporary estimates will provide an indication of the extent to which any changes in the flow regime may have influenced the quantity and grain sizes of sediment that can be transported through the segment, with these changes being reflected in hydromorphological adjustments within and downstream from the segment.

Two indicators reflect the degree to which artificial influences are likely to affect transfer of water and sediment through the segment (number of high channel blocking structures, number of intermediate channel blocking structures). Historical and contemporary estimates of these (preferably gained from design documents, which will give date of installation, dimensions and water / sediment storage estimates, but alternatively extracted from air photo sources) provide a crucial assessment of changes that will have affected hydromorphology of the segment and all segments downstream.

The sediment budget indicator synthesises the above indicators relating to sediment delivery, transport and storage within the segment. At its simplest an assessment of whether the present (and if possible past) budget indicates approximate equilibrium, a net gain or a net loss of sediment in each segment, is extremely informative in the context of explaining reach-scale morphological adjustments.

The final four indicators (riparian corridor width, riparian corridor continuity, riparian corridor vegetation cover / structure, % active channel edge bordered by living / dead trees) relate to the riparian corridor and the degree to which its continuity, structure and connection to the river channel imply active interaction with the river including the potential to supply wood to the active channel. Historical changes in these indicators can be extracted from air photographs and satellite imagery. Changes in these indicators will be associated with significant hydromorphological change, both in morphology and function.

9.3.4 Space-Time Inventory

The inventory attempts to synthesise aspects of change at catchment, landscape unit and segment scales so that key patterns can be identified. It consists of a description of what has been found (sections 9.3.1 - 9.3.3), supported by summary diagrams for some of the key indicators. The most appropriate diagrams will vary between catchments, so that the particular properties of individual catchments are highlighted, but should include the following:

(i) A summary of temporal changes in the indicators of artificiality at:

a. catchment scale: % artificial surfaces, % agricultural areas:

b. landscape unit scale: % large surface water bodies, % area of rapid runoff production, % area of intermediate runoff production;

c. segment scale: number of high channel blocking structures, number of intermediate channel blocking structures, hydropeak frequency.

These provide a picture of when, where and with what severity human interventions are impacting on longitudinal flows of water and sediment through the fluvial system, including potential initiation and upstream propagation of head-cutting or bed aggradation (see section 9.1 for a broad description of likely causes).

(ii) A summary of temporal changes in runoff and sediment production and transfer at;

a. catchment scale: water yield, annual runoff ratio;

b. landscape unit scale: % glaciers and perpetual snow, soil erosion rate, % area with potential sources of coarse sediment;

c. segment scale: flow indicators relevant to the particular catchment, at a minimum - average annual flow, average monthly flows, morphologically meaningful discharge(s); sediment indicators, particularly - eroded soil delivered to channel, land surface instabilities connected to channel, sediment budget.

These provide a picture of the spatial and temporal distribution of the key longitudinal flow and sediment processes that are controlling the fluvial system, and whose temporal dynamics can be interpreted in relation to the artificiality indicators

(iii) A summary of temporal changes in riparian corridor dimensions and condition at the segment scale: riparian corridor width , riparian corridor continuity , riparian corridor vegetation cover / structure, % active channel edge bordered by living / dead trees. This provides an indication of the lateral space within which river-floodplain interactions have been and are active.

(iv) A summary of temporal changes in channel characteristics at the reach scale: changes in sinuosity index, changes in channel gradient (both reflect change in channel gradient), changes in anabranching index (reflects changes in the stability of stored sediment), changes in channel width, changes in channel depth, changes in channel width:depth ratio, (direct changes in channel capacity and dimensions). These direct measures of change may indicate responses to some of the above factors ((i) to (iii)) but may also reflect the local impact of channel modifications and the upstream propagation of head cutting or aggradation as a result of adjustments occurring in downstream reaches.

9.4 STAGE 3: Assess Reach Sensitivity

This stage involves a detailed and potentially time-consuming historical assessment of reaches, and so, at least in the first instance, should only be applied to selected reaches. For example, the focus might be on reaches that are deemed to be of conservation importance; for which changed management is proposed; or which are 'representative' of particular segments or landscape units. Preference should also be given to reaches where detailed field surveys have been undertaken (giving a complete and well-defined set of contemporary reach-scale indicators) or where such surveys are to be undertaken to accompany the sensitivity analysis

The aim of this stage is to diagnose the condition and sensitivity of specific reaches to changes in the fluvial system at all spatial scales. This is based on information regarding:

(i) the current and past condition and dynamics of the reach;

(ii) current and past interventions (lateral and longitudinal artificiality indicators) within the reach;

(iii) the potential influence of interventions and processes operating at larger spatial scales identified in the space-time inventory (section 9.3).

Information sources to underpin (i) and (ii) are:

(i) current (and where possible historical) assessments of hydromorphological functionality, alteration/artificiality and adjustment of the channel and riparian functionality, alteration/artificiality along the reach (section 9.2), to assess the degree of change that appears to have occurred

(ii) assessment of additional indicators and historical information that summarise past dynamics to complement (i), including:

a. Planform change: lateral channel migration rate, changes in sinuosity index, changes in braiding index, changes in anabranching index (Table 8.1) and also a map of the corridor historically occupied by active river channel, all of which can be attained from overlaying the river margins extracted from historical maps and air photos (e.g. Figure 6.8).

b. Cross-sectional and long profile change: when available, information on changes in channel dimensions and bed levels can be reconstructed from historical topographic surveys (see sections 6.3.3.and 6.4.2), as well as being inferred from the indicators of contemporary adjustment that are already incorporated into (i).

Interpretations from the above include:

(i) A summary of:

a. the changes that have occurred within the reach, their type and magnitude including changes that appear to be attributable to (i.e. their timing corresponds to) interventions and so they are unlikely to be 'natural' channel adjustments

b. the apparent association of any of these channel adjustments with changes at larger spatial scales (both upstream and downstream) that may have influenced the longitudinal flow and sediment transport regimes to the reach and local reach gradient.

(ii) Block, cross section or planform diagrams illustrating the key changes and when / why they occurred

(iii) An assessment of the manner and the speed with which the adjustments have occurred in response to changes and specific interventions.

(iv) As a result, an assessment of the *sensitivity* of the river to imposed spatial and temporal changes / interventions. Such an assessment tends to be specific to rivers of particular types in particular catchment - landscape unit - segment contexts, but it is based on the understanding already gained of how particular reaches and river types have developed over time in response to changes that have occurred previously. The aim is to distinguish from the trajectory of changes that have been reconstructed, whether the river is absorbing changes, adjusting gradually or quickly to them, or showing abrupt changes (e.g. changes in river type) that illustrate that some threshold condition has been crossed. *Resilient* reaches absorb or adjust gradually, whereas *vulnerable* reaches show abrupt changes. It is important to identify reaches that are *very sensitive* to change, and to understand the circumstances under which they become *vulnerable* to abrupt changes. With such understanding, it may be possible to avoid reaching a condition of abrupt change or to identify ways in which the change may be reversed.

9.5 STAGE 4: Assess Scenario-Based Future Changes

9.5.1 Selecting and defining scenarios

Scenarios tend to be catchment-specific as are the potential responses to those scenarios. Therefore, it is probably most informative to look at some of the full Case Studies in Deliverable 2.1 Part 3 to consider how scenario-based future changes may be explored and their consequences predicted. Such predictions may be qualitative or may employ modelling to produce more precise, quantitative forecasts, but in either case, the knowledge accrued from applying the methodology described in this report will ensure that those forecasts are realistic.

Although the choice of scenarios is inevitably catchment-specific, two scenarios should be considered in all cases:

Scenario 1: No change in management (at all spatial scales) from that which is currently occurring. This scenario allows the spatial and temporal information built in the previous phases to be projected into the future, particulary considering past time lags between changes at different scales and the degree to which these may continue to feed through the catchment and affect reaches of the river network into the future.

Scenario 2: Climate change. Changes in climate not only affect (i) hydrological processes at the catchment scale, they also may induce (ii) changes in land cover and management that could affect runoff response and sediment delivery to the river network at the landscape unit scale; (iii) changes in the flow and sediment transport regimes, water temperature and the nature and vigour of riparian and aquatic vegetation at the segment scale; (iv) leading to complex changes in hydromorphology, ecology and their dynamics at the reach scale through the entire channel network. By considering responses / sensitivity to past changes through the cascade of spatial units, and coupling that with the consequences of likely shifts in hydrology, land cover and vegetation growth performance, it should be possible to provide reasonable insights into future trajectories of change and potential adjustments in reach character and morphodynamics within the river channel network over a few decades if no new interventions are introduced.

Other scenarios. The most obvious scenarios could involve a reduction or intensification of some existing human pressures, but in many cases a scenario involving a new type of planned intervention could be appropriate (e.g. the impact of dam construction).

9.5.2 Approaches to investigating river responses to future scenarios

River reaches adjust in many ways to different pressures. Because of the enormous variability of responses within and between rivers and their reaches, the impact of different future scenarios should be investigated in several complementary ways using: (i) knowledge on present and past characteristics of units at all spatial scales and the sensitivity and resilience of river reaches to changes induced by pressures on any of these units (gained from stages 1 to 3, sections 9.2, 9.3 and 9.4) with (ii) an assessment of how the scenario might affect transfers of water and sediment through the catchment to river reaches and (iii) an assessment of how reaches of different river type might respond to the changed water and sediment fluxes and any local interventions associated with the scenario.

(i) Knowledge of the sensitivity and resilience of river reaches to changes

Assembly of this type of knowledge is undertaken in Stages 1 to 3 (section 9.4). In particular, Stage 3 synthesises local knowledge on how the different types of reach that are present in a catchment have responded to pressures in the past. If the past pressures are relevant to the pressures within the scenario that is being considered, then this local knowledge is the by far the most reliable source of information for forecasting the likely future trajectories of changes within different types of reach.

(ii) Likely transfers of water and sediment to river reaches

Relevant local information on changes in river discharge and sediment regimes in response to pressures that have been imposed previously within the catchment have been assembled during many stages of the application of the hierarchical framework, and summarised in stage 2 (section 9.3). If those past pressures are relevant to the scenarios being considered then this local knowledge is the most useful for forecasting future changes in transfers of water and sediment and the future trajectories of hydromorphological response within reaches of different type. In this case, the types of reach being affected may be different from those affected in the past, but at least a reasonable assessment of the scale and nature of flow and sediment regime change can be assembled from local information.

(iii) Assessment of response at the reach scale

If future responses need to be assessed for pressures and reach types that have already been investigated through the application of the hierarchical framework (i.e. (i) above) then these responses provide the most effective starting point for constructing a likely trajectory of future change. This trajectory can then be checked using the following.

If responses need to be assessed within reach types that have not previously been affected by similar pressures, then other scientific knowledge and/or modelling approaches need to be applied using current reach properties and predicted changes in water and sediment transfer processes.

If no similar pressure has occurred within the catchment in the past, then assessments of future trajectories need to be entirely based on scientific knowledge and/or modelling to estimate likely changes in water and sediment transfer processes and their potential impact on reaches of different type.

Whatever the overlap between the proposed scenarios and past experience within the catchment, estimating likely trajectories of response of different river types to different pressures involves applying the hierarchical framework to past, present and possible future changes and then checking / modifying / extending / creating trajectories of change for particular (types of) reaches with:

1. The application of appropriate modelling tools to investigate scenarios in greater detail in relation to specific reaches, within the studied catchment.
2. Current scientific understanding of the possible, general responses of river segments and reaches to particular types of changes.

(iv) A brief background to the development of scientific understanding and modelling tools

Once again, it is important to stress that local knowledge derived from application of the hierarchical framework is by far the most reliable basis for assessing future changes in reaches of different type and thus different sensitivity and resilience. However, scientific understanding and modelling tools play a vital role when such information is absent or limited, and they also provide invaluable support for assessments and forecasts based on local knowledge.

Before considering the tools that could be used to check or develop trajectories of change in response to particular future scenarios, this section provides a brief historical background to those tools.

River reaches respond in different and often complex ways to changes in discharge of water (Q_w), and discharge of sediment (the sediment load - Q_s). Their responses vary widely according to many factors, of which reach slope (S) and bed material calibre (D) are of particular importance. Changes in reach slope and bed sediment calibre can, in turn, reflect changes in discharge and sediment regimes, locally-imposed reach modifications, or the upstream propagation of changes in downstream bed and water surface levels.

At a very early stage in hydromorphological research, these four factors were combined into a simple concept of a balance between form and process to achieve an 'equilibrium' condition within alluvial river reaches, that is encapsulated in Lanes (1955) 'balance':

$$Q_w S = f\,(Q_s, D)$$

Where f simply means 'a function of'. Although Lane's 'balance' is an enormous simplification, it provides a general starting point for thinking about how changes in Qw and Qs might lead to adjustments within river reaches. In very general terms, discharge primarily determines the size of the channel, slope determines the rate of energy expenditure, and sediment size and load determine the morphology of the channel. Thus changes in any of these properties lead to changes in the size, structure and, in extreme cases, the type of river channel that is present. Such changes may reflect climate change, direct or indirect human interventions, and how these and their consequences for the above variables, interact with inputs of water and sediment from channels / tributaries and subcatchments that may be unaffected by the interventions.

Schumm (1977) produced a simple conceptual extension to Lane's balance that considers how different channel dimensions might adjust to a change in Q_w or Q_s. Schumm proposed the following potential directions of adjustment to increases (+) or decreases (-) in Q_w and Q_s alone or in combination:

$$Qw^+ \approx b^+, d^+, \lambda^+, S^-$$

$$Qw^- \approx b^-, d^-, \lambda^-, S^+$$

$$Qs^+ \approx b^+, d^-, \lambda^+, S^+, P^-$$

$$Qs^- \approx b^-, d^+, \lambda^-, S^-, P^+$$

$$Qw^+ Qs^+ \approx b^+, d^{+/-}, \lambda^+, S^{+/-}, P^-, F^+$$

$$Qw^- Qs^- \approx b^-, d^{+/-}, \lambda^-, S^{+/-}, P^+, F^-$$

$$Qw^+ Qs^- \approx b^{+/-}, d^+, \lambda^{+/-}, S^-, P^+, F^-$$

$$Qw^- Qs^+ \approx b^{+/-}, d^-, \lambda^{+/-}, S^+, P^-, F^+$$

Where b is channel width, d is channel depth, F is channel width:depth ratio, λ is meander wavelength, P is sinuosity. These conceptual relations illustrate how the direction (but not the magnitude) of channel change due to an adjustment in either Qw or Qs can be predicted with reasonable confidence, but how simultaneous changes in both Qw and Qs can lead to extreme uncertainty in the direction and magnitude of change of many channel properties.

Over the last half century, a more precise and detailed understanding of likely outcomes has developed through a combination of physically based modelling and analysis of experimental and field observations (reflecting points 1. and 2. above). The nature of these two types of approach and their complementarity are explained in an accessible way by Church (2006) in relation to the theme of sediment transport (p331):

> "In a forward approach to the problem, we use known physics of sediment transport to deduce some conditions of fluvial sedimentation. In an inverse examination, we use observed properties of stream channels and fluvial sediments to make inferences about the sediment transport process. The forward approach can be applied relatively rigorously, but leads — in the present state of knowledge — only to rather general results. The inverse approach, which is attractive because river morphology and river sediments are much more easily observed than sediment transport, can yield quite detailed results on along-channel variations in transport, hence morphology, but is not yet so physically rigorous".

In addition, while Qw, S, Qs and D are fundamental controls on river morphodynamics, dead and living vegetation are important factors moderating channel responses that have been increasingly recognised over the last 20 years (Gurnell, 2014). Vegetation colonises newly-deposited or exposed sediments; its canopy can trap mobile sediment; its canopy and root systems can protect sediments from erosion; and its root systems can reinforce and stabilise sediments. Large pieces of wood (logs, root wads, entire uprooted trees) can have similar sediment retention and stabilising effects.

(v) Tools for supporting the development of future Trajectories of Change

Within REFORM we provide a range of tools to aid the identification of trajectories of responses of river reaches to changes induced by specific pressures within a catchment.

The Hierarchical Framework: We recommend that application of the hierarchical framework should be the primary tool in constructing potential trajectories of change to particular scenarios within a catchment. Different tools can be used within the framework to produce results of different accuracy and precision. More importantly, the scenarios and trajectories of response to different future pressures can be checked by one or more of these tools as appropriate. To help users implement the hierarchical framework, several full applications are presented in Deliverable 2.1 Part 3. These applications reflect different past pressures and future scenarios, including agricultural intensification and high fine sediment delivery (Case Study 1); high coarse sediment delivery (case study 5); dam construction and flow regulation in southern and northern European settings (Case Studies 2 and 3); and river bed gravel mining (Case Study 4). Although these are the primary pressures encapsulated in the five case studies, other historical and potential future pressures are also explored.

Modelling tools: Section 9.6 provides an overview of modelling tools employed within Deliverable 2.1. Deliverable 6.2 provides a more extensive and detailed description of modelling tools and their application. Particular modelling tools are also applied within the Case Study Catchments, and are presented in detail in Appendix I of Deliverable 2.1 part 2.

Scientific knowledge based on field observations and experiments: Building on the directional changes proposed by Schumm (1977) and explained in the preceding section (iv), Deliverable 1.2 section 4 attempted to resolve some of the uncertainities in the direction of changes by reviewing available scientific knowledge acquired from field observations. From an extensive literature review, a series of conceptual frameworks were proposed, describing how different pressures operating at different spatial and temporal scales in a catchment might modify processes and forms at the reach scale. The pressures considered were flow regulation (increased flow, flow regime modification, hydropeaking); river fragmentation; and morphological alterations (impoundment, large dams and reservoirs, channelization, alteration of riparian vegetation and instream habitat, embankments-levées-dykes, sediment addition, sand and gravel extraction, loss of vertical connectivity). For each pressure, the direction of response of river flows and alluvial water table levels; channel dimensions, stability and sediments; organic matter; and the size and function of the riparian corridor were suggested. For example, Figure 9.1 reproduces three diagrams from Deliverable 1.2 that suggest directions of adjustment in hydromorphological variables to large dams, fine sediment addition, and river channel enlargement.

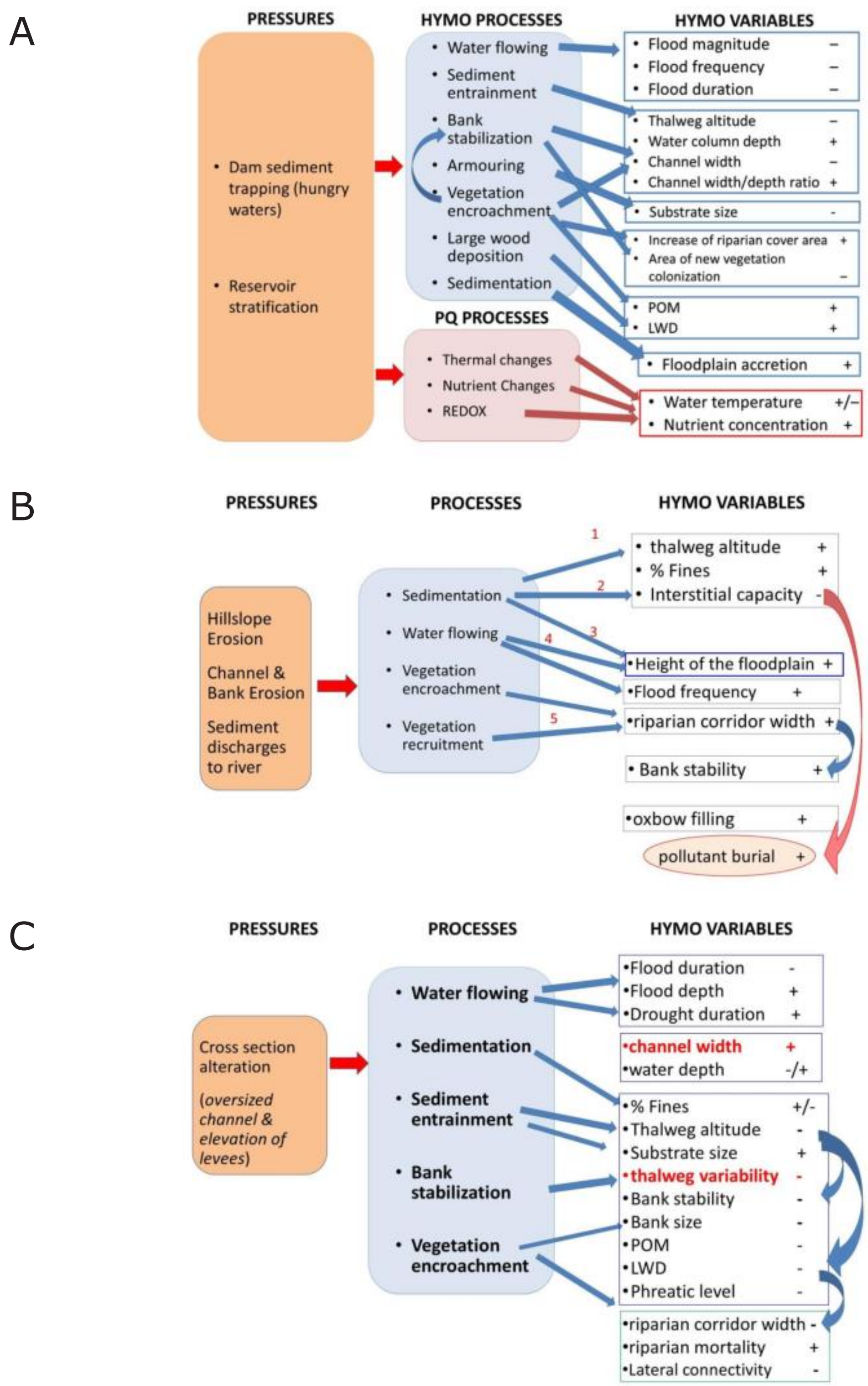

Figure 9.1 Conceptual frameworks representing effects on hydromorphological processes and variables form A. Large dams and reservoirs; B. Increased inputs of (fine) sediment; C. Channel cross section alteration.

Although such diagrams are an advance in identifying directions of change, they do not indicate magnitude of change nor do they encapsulate any complex responses that may occur. Furthermore, they represent major generalisations, and the directions of change indicated may not be transferable to particular catchment contexts. However, if the literature is explored in depth to identify relevant observations from environments that are analogous to the study site, then it may be possible to define a more reliable direction of change and an element of magnitude and greater complexity to the projected trajectories of change. Deliverable 1.2 provides a large literature resource that can be investigated. The recent publication of 'Treatise in Geomorphology' (Shroder, 2013) provides another starting point for assembling relevant literature. This resource includes up-to-date reviews of several relevant themes, including human impacts on river fluxes and morphology (Overeem et al., 2013); the impacts of land use and land cover change (James, 2013; James and Lecce, 2013; Royall, 2013); vegetation clearance (Harden, 2013); urban development (Chin et al., 2013); dam and reservoir development (Magilligan et al., 2013; Petts and Gurnell, 2013); and channelisation (Pierce and King, 2013).

Furthermore, some synthetic studies have attempted to define trajectories of potential changes in a more detailed and complex way. The following two examples illustrate how this may be achieved.

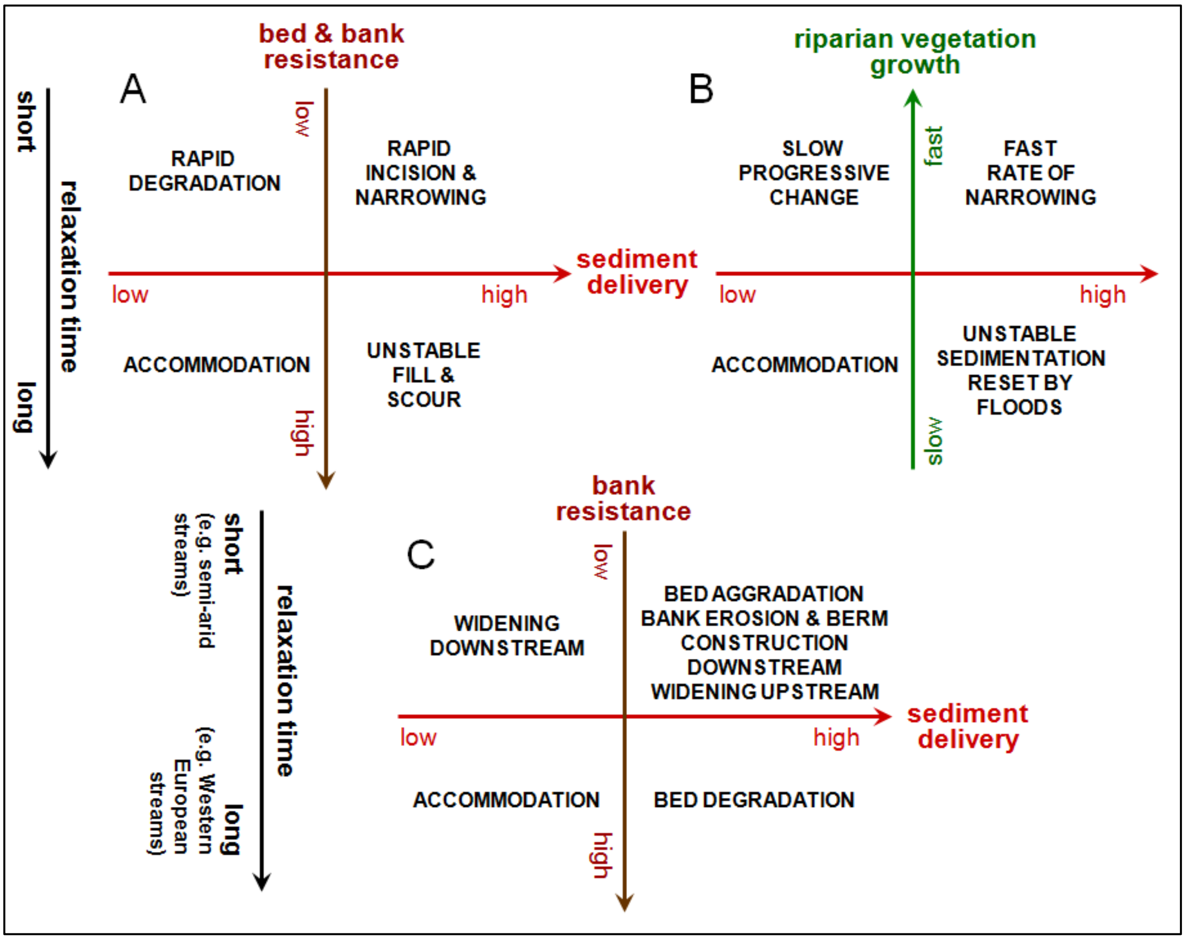

Figure 9.2 Channel responses to loss of sediment load and changed flow regime below dams (see text for explanation, after Petts and Gurnell, 2005).

Petts and Gurnell (2005, 2013) explored the complex responses of reaches downstream from dams, which reflect changes in the flow regime, whether or not any sediment passes through the dam, the distance from the dam and thus the input of flow and sediment from tributaries, the bed and bank materials, and the speed with which riparian vegetation colonises deposited sediments. Figure 9.2 summarises the possible responses of river channels downstream from the dam to the impact of a reduced sediment load and the time over which they occur (relaxation time). As indicated by Schumm, reductions in sediment load induce channel bed erosion / degradation but this effect is mediated (Figure 9.2 A) by the resistance of the channel bed and banks to erosion with rapid degradation occurring where resistance is low (top left quadrant) and accommodation (no observable channel change) occurring in reaches where the regulated flows are not large enough to be capable of eroding and transporting sediment (bottom left quadrant). In reaches receiving sediment, especially from tributary inputs, bed incision and channel narrowing, enhanced by riparian vegetation encroachment, may occur simultaneously (top right quadrant). Desynchronisation of sediment delivery from upstream reaches and tributaries can create highly unstable phases of channel scour and fill (bottom right quadrant). Channel narrowing following the removal of flood flows (Figure 9.2 B) can also occur in an unstable manner and at different rates according to the amount of sediment that is delivered (horizontal axis) but it is accelerated by riparian vegetation encroachment onto sediment deposits (vertical axis). However, where sediment sources are limited and thus sediment supply is low (left quadrants) or vegetation establishment and growth is slow (lower quadrants), flows are accommodated within the pre-existing channel form (bottom left quadrant). In the vicinity of unregulated tributary confluences (Figure 9.2 C), bed aggradation, lateral bench / berm construction, and channel migration can all occur if sediment delivery is high (right quadrants) and can progressively extend downstream, with vegetation encroachment again reinforcing the development of depositional landforms. In extreme cases of channel narrowing, the river type can change from, for example, a braided or wandering river channel to a single thread channel. If this is accompanied by a shift from an unreliable, flashy flow regime (as is common in many Mediterranean rivers) to a steady flow regime with decreased extreme flows (as is common when reservoirs regulate flows to support downstream abstractions), a change in river type from braided to single thread is also accompanied by a complete change in the biomass, growth rate and species composition of the riparian vegetation (see Case Study 2 in Deliverable 2.1 part 2).

Rinaldi (2003) developed a model of planform change associated with gravel extraction from river beds (Figure 9.3). Although developed from field obervations in Tuscany, Italy, it has been found to be quite widely applicable (Rinaldi et al., 2005) and so provides a useful indicative model of the possible responses to gravel removal from gravel-bed rivers of different planform type.

Refering to the directions of change indicated by Schumm (1977), bed incision is explained by an excess of stream power attributable to the unchanged discharge regime in comparison with the reduced quantity of sediment available for transport as a result of gravel removal. A reduction in sediment load often leads to channel narrowing in addition to bed incision (as illustrated by the responses to dam construction in Figure 9.2), because flow is concentrated into a deepening cross section and vegetation colonises and stabilises areas of the original bed that are left above the level of the incising bed. In the case of gravel extraction from river beds, these adjustments propagate upstream as well as downstream as bed levels adjust to those in the sediment starved reaches. Rinaldi (2003) illustrates how incision and narrowing yield different results in three different types of river (braided, meandering, sinuous with alternate bars) according to the amount of sediment removed, the relaxation time following extraction (Figure 9.3), and vegetation encroachment (Figure 9.4).

Complex models of trajectories of change for particular catchments, reach types, and scenarios similar to those shown in Figures 9.1 to 9.4 can be developed for particular reaches and catchments by applying the hierarchical framework and then coupling the resultant catchment understanding with scientific knowledge based on field observations and experiments. However, this level of detail can only be achieved with the involvement of a fluvial geomorphologist in the entire process.

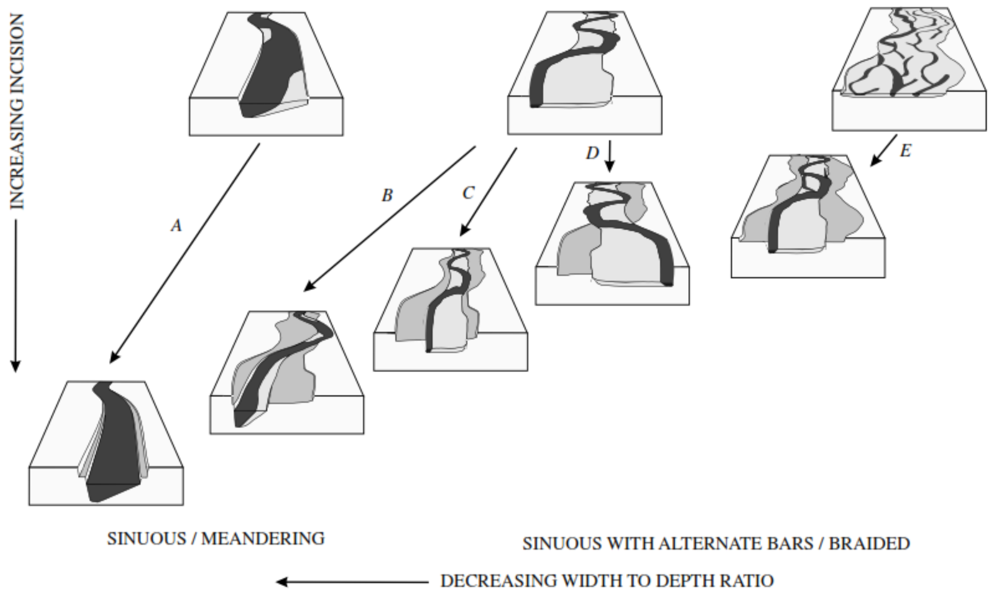

Figure 9.3 The main planform changes as a function of initial channel morphology and degree of incision (black – low water channel, light grey – active bars, dark grey – new floodplain from abandonment of previously active bars (from Rinaldi, 2003).

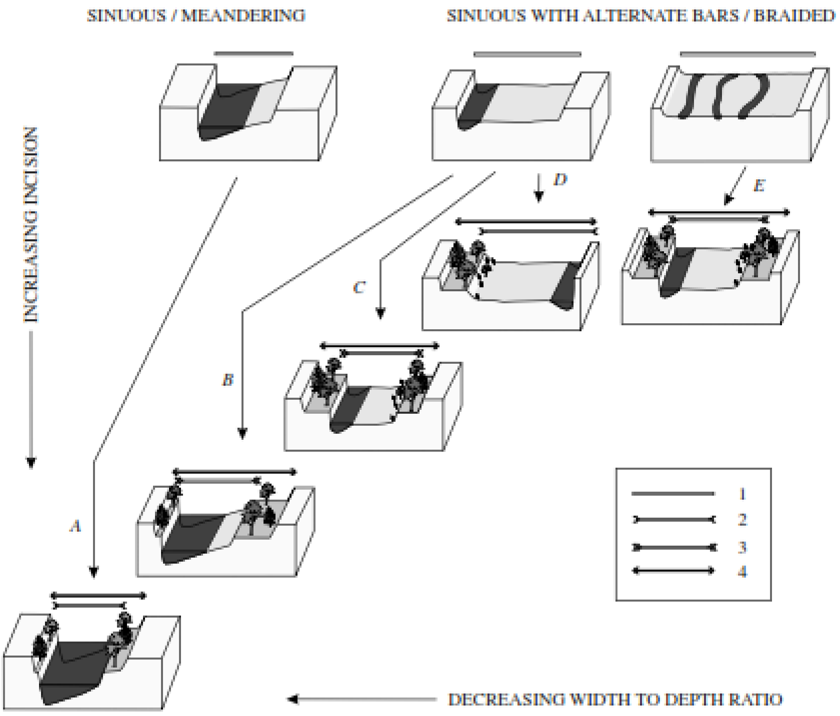

Figure 9.4 Adjustments in cross section and the development of vegetated surfaces as a function of incision and initial channel morphology. 1. Initial bankfull width, 2. Moderate bankfull narrowing, 3. Intense bankfull narrowing,4. Narrowing of the entire cross section (from Rinaldi, 2003).

9.6 Understanding the Past and Assessing Future Changes using Modelling

A broad array of approaches have been developed with the aim of modelling river systems. Depending on the temporal and spatial scales considered, different tools can be implemented to operate from catchment studies to particle movements and from geologic timescales to instantaneous measurements during experimental studies. In the following text, a brief overview of models developed within fluvial geomorphology with some example of their implementation is provided in section 9.5.1. Then, keeping in mind a management perspective, the modelling approaches implemented within REFORM are detailed (section 9.5.2) emphasising two scales: the catchment scale (in order to consider the sediment system in its entirety), and the reach scale (since planning restoration works necessitates concentration on specific fluxes and processes). These are followed by some discussion and recommendations (9.5.3). Four Annexes (F to I) provide additional information to support this section:

Annex F – Sediment Budget: Review of definition and principles

Annex G – Empirically defined Threshold Conditions

Annex H – Sediment Transport Formulae

Annex I – Models tested at Case Study Sites

9.6.1 Modelling approaches in fluvial geomorphology

Numerous approaches have been developed to model river systems. These were reviewed by Darby and Van de Wiel (2003), with recent updates (Van de Wiel et al., 2014), outlining the latest progress. Based on these reviews, different models are briefly described below, using a similar structure. Thus, approaches are grouped as conceptual, statistical/empirical, analytical/numerical models, ending with physical modelling.

(i) Conceptual models

Conceptual models provide qualitative descriptions and predictions of landform and landscape evolution. Numerous conceptual models have been proposed. This section provides a brief overview, highlighting some of the models that have been most influential.

The cycle of erosion (Davis, 1899) was one of the first conceptual models in geomorphology. Modern quantitative fluvial geomorphology is often said to have started with the work of Horton (1945) on stream order (Chorley, 1995). Later, Wolman and Miller (1960) related magnitude and frequency of forces in geomorphic processes, highlighting the influence on land forms of events of moderate magnitude occurring frequently rather than rare events of unusual magnitude. Schumm (1973) defined geomorphic thresholds and complex response of rivers and drainage basins and Wolman and Gerson (1978) described disturbance and response in geomorphic systems. These works provided a conceptual basis for considering processes that were not quantified or observed easily (Doyle and Julian, 2005).

More recently, Montgomery et al., (1996) predicted bed material accumulation at a point by conceptually representing the balance between sediment supply and transport. They represented sediment supply as an empirical function of catchment area and sediment transport capacity as a function of catchment area and slope. This led to a threshold channel slope being defined below which sediment supply exceeds transport capacity and, therefore, where bed material accumulation is predicted to occur. This approach assumes spatially uniform patterns of sediment supply and runoff generation across the area.

A related conceptual framework, the sediment budget, accounts for sources, sinks and processes of mass exchange between water and sediment at a range of temporal and spatial scales. A review, which defines and explores the principles of sediment budgets, is provided in Annex F. However, some notable contributions include that of Dietrich and Dunne (1978). In developing a quantitative sediment budget for a small coastal watershed in Oregon, they provided a conceptual framework and suggested a range of approaches for estimating fluxes of sediment by various processes through the landscape. Furthermore, conceptual representation of bed material supply and transport processes can be approached using GIS techniques, as suggested by Prosser et al. (2001). Wilkinson et al. (2006) implemented this GIS-based approach to formulate a spatially distributed sediment budget model to predict the locations of bed material accumulation in the Murrumbidgee river catchment (Australia).

The channel evolution model (CEM), originally developed by Schumm (1981) and modified for channelized streams (Simon and Hupp, 1987, Simon 1989) allows the understanding of the dynamics of stream disturbance and recovery processes. More details on this conceptual model can be found in NRCS (2007, 2009).

Cellular modelling has also contributed significantly to geomorphological advances, This type of modelling uses relaxed interpretations of equations to determine fluid flow, based upon simplified approaches which relate more to conceptual models. However, there is a fine line between cellular modelling and numerical modelling. In geomorphology, the basic principles of cellular modelling are that landforms are represented by a lattice of cells and that the interactions between cells (the routing of water and sediment) are treated using simple rules based on abstractions of the governing physics (Nicholas, 2005). Murray and Paola (1994) proposed one of the first cellular models to explore braided river dynamics in a spatially distributed way. The main advantages of cellular models are that the whole river basin evolution over geological timescales can be considered (Coulthard, 2001; Willgoose, 2005; Codilean et al., 2006). One of the limitations lies in the fact that flow is represented as steady state and does neither conserve mass of water nor momentum. More details and discussion on the advantages and limitations of cellular models are provided by Coulthard et al. (2007). Recently, the landscape evolution model Caesar has been combined with a 2D hydrodynamic flow model (Lisflood-FP, Bates et al., 2010; http://www.coulthard.org.uk/CAESAR.html).

(ii) Statistical and empirical models

There is a long history of statistical and empirical modelling within fluvial geomorphology and related disciplines. These simple models are useful in exploring concepts and attempting to understand system responses.

An example of early work of this type was that of Leopold and Maddock (1953), who related empirically and graphically the measured geometry and hydraulics of the river channel to the flow and drainage area and built a statistical description of how the geometry changes with the flow.

More recent research includes Lamouroux (1998), who linked statistical hydraulic models with multivariate habitat models; illustrating how the hydraulic geometry of stream reaches is a key physical description for predicting the ecological impact of physical constraints at a range of spatial scales (Lamouroux, 1998). Legleitier (2012) implemented a geostatistical framework for quantifying the variability and spatial organization of river morphology. Geostatistics is much more than a method for interpolating data for visualization; it is a suite of tools for detailed structural spatial analysis. At its simplest, geostatistics is based on the derivation of a spatial model of the variation in sampled data (variogram). Parameterizing the experimental variogram and evaluating its change over time has provided considerable information on processes and their controlling factors (Chappell et al., 2003). Thanks to recent advances in high resolution datasets available through remote sensing techniques (mainly LIDAR), these approaches help to overcomes the limits imposed by conceptual and numerical models. This discipline appears very powerful for quantifying spatial patterns in rivers and enhancing our system understanding (Marcus and Fonstad, 2010; Legleiter, 2014).

A particularly useful line of research has been to define different threshold conditions that can help to predict the occurrence of certain bed forms or the separation of rivers of different planform, such as braiding and meandering channels. These empirical relationships can be applied by river managers to gain a broad assessment of how close river segments and reaches may be to changing key characteristics. A summary of some widely-used, empirically-defined threshold conditions is given in Annex G.

(iii) Analytical and numerical models

Analytical and numerical models use mathematical equations to describe physical processes that are occurring. The main difference lies in the fact that analytical models have exact solutions whereas numerical models use numerical schemes that require some approximations.

It should be noted that this section does not intend to provide a complete list of the hydrodynamic and morphodynamic models that are available as this information has already been compiled within WP6 with details on the model dimension, scale, outputs and literature references provided at:

http://wiki.reformrivers.eu/index.php/Category:Tools.

The construction, calibration and validation of a numerical model requires data on channel geometry, hydrology, grain size.

For example, as a minimum, the construction of a 1D numerical model requires:

- river cross sections or bathymetry for the main channel and floodplain;
- estimated or measured discharge at the upstream end of the modelled reach (hydrograph, hydrological characteristics);

- water levels recorded during low flow and flood events along the reach for calibration and validation of the model;
- stage-discharge relationship at the downstream end of the modelled reach (if available);
- estimated grain size in the main channel (d_{50} and if possible d_{16} and d_{84});

The river bed evolution can also be modelled if two sets of cross sectional data are available for validation (and the discharge during the period considered). The grain size sorting coefficient (and eventually subsurface data) is also necessary.

2D and 3D models require twice or three times more data, respectively, than 1D models, since bathymetry needs to be completely described and measured 2D/3D current fields are necessary for a proper validation. Depending on the complexity of the studied system and on the objectives of the study, 2D or 3D models may be useful but become costly due to the data acquisition requirements.

(iv) Physical models

Physical modelling complements other approaches and may be used to simulate complex processes and feedbacks in many geomorphic phenomena. Physical models have been used successfully to investigate many issues in fluvial geomorphology over a range of scales, including (Peakall et al., 1996):

- confluence morphology (Mosley, 1976; Ashmore and Parker, 1983, Ashmore, 1993);
- fluvial sediment transport (Ashmore and Church, 1988, Hoey and Sutherland, 1991);
- bar deposition and migration (Ashmore, 1982; Ashworth, 1996, El Kadi Abderrezzak et al., 2013).
- channel change (Davies and Lee, 1988);
- channel pattern development (Leopold and Wolman, 1957; Schumm and Khan, 1972);
- river response to changing extrinsic variables such as tectonics (Jin and Schumm, 1987), aggradation (Ashworth and Best, 1994) and base level (Koss et al., 1994).

Physical models are expensive and up/downscaling is not straightforward, especially for non-uniform sediments (El Kadi Abderrezzak et al., 2013). They are generally implemented when economic pressures exists (structure or confluence).

9.6.2 Approaches Implemented within REFORM

Different modelling approaches have been tested within the various Case Study Catchments investigated by the project partners involved in WP2. The objectives were not to benchmark the different methods but rather to offer a range of tools, examples of the results that may be obtained, and how these can contribute to the assessment and understanding of hydromorphology within the multi-scale framework described in this report.

The approaches implemented in the context of different Case Study Catchments are listed in Table 9.5. A general description of the modelling approaches is provided in the following paragraphs; and further details of the outputs specific to each case study are detailed in Annex I.

Table 9.5: Models tested within the WP2 Case Study Catchments.

Model	Site	Spatial scale	Objectives	Time scale	Refer to Annex
Sediment budget (1D-HECRAS + SIAM)	Frome (UK)	Network scale (414 km²)	Estimation of sediment budget	Flow duration curve	I.1
1D hydro-dynamic (Rubar3) with simplified inputs	Loire (FR)	Landscape unit scale (450 km)	Spatial pattern of hydraulic parameters	Flow duration curve	I.2
1D Hydro-dynamic (HEC-RAS)	Magra (IT)	Segment scale (~ 30 km)	Spatial pattern of hydraulic parameters	Specific discharge + Flow data	I.3
CAESAR	Tagliamento (IT)	Segment scale (33 km)	Prediction of future channel morphology; estimate of bedload transport	Flow data	I.4
1D hydro-dynamic (Rubar3) + empirical estimation of sediment transport + morphodynamic model (rubarBE)	Loire (FR)	Segment to reach scale (~ 30 km)	complementary hydraulic parameters + sediment transport and budget	Specific discharge + Flow data	I.5
1D hydro-dynamic (Rubar3) + empirical estimation of sediment transport	Frome (UK)	Reach scale (~ 10 km)	complementary hydraulic parameters + estimation of sediment transport	Specific discharge + Recent flow data	I.6
1D Hydro-dynamic (HEC-RAS) + 2D Hydro-dynamic (River 2D) + habitat model (MEM)	Lech (AT)	Reach scale - Geomorphic unit (~ 2 km)	complementary hydraulic parameters + habitat evaluation	Specific discharge	I.7
2D hydrodynamic (CCHE 2D)	Drau (AT)	Reach scale - Geomorphic unit (~ 2 km)	complementary hydraulic parameters for regulated and restored condition	Specific discharge	I.8
2D Hydro-dynamis (IBER 2D)	Curueño (ES)	Reach scale - Geomorphic unit (~ 1 km)	Locate and quantify hydromorphologic al processes + fluvial habitats	Specific discharge + Flow data	I.9

(i)- Estimation of sediment budget at network and landscape scales

(i.1) Sediment Impact Analysis Method

The Sediment Impact Analysis Method (SIAM) is embedded within the Hec-Ras software. SIAM can distinguish between wash load and bed material load based on a user-defined threshold grain diameter. The local bed material balance is computed as the difference between bed material supply and sediment transport capacity. A full description of the software is available at http://www.usbr.gov/pmts/sediment/model/srhsiam/ (accessed in July 2013).

(i.2) 1D hydro-dynamic model with simplified inputs

A classic 1D hydro-dynamic model, solving the Barré-de-St-Venant equations also can be used for a sediment budget approach. The objective of using a simplified geometry is to reduce calculation time while keeping pertinent representation of river geometry. Once the model is calibrated and validated on known events a simplified geometry is derived. Based on the reach definition, and calculated width, depth and water profile (calculated for a range of discharges ranging from low flow to flood discharges), a simplified geometry defined by $2 \times n$ points is derived (where n is the number of discharges considered). The simplified geometry is optimised on the energy slope to reduce differences between the water profile calculated in the simplified geometry and the water profile calculated in the initial geometry. A sediment budget is then routed through the simplified geometry to obtain the volume deposited/eroded on each reach.

(ii) - Reach scale modelling

(ii.1) 1D hydrodynamic model

1D models that include evolution of the bed may be of interest for reach scale modelling. Once calibrated and validated, complementary hydraulic parameters are derived for a range of flow conditions that are relevant when studying channel forming discharge. For example, the following discharges could be considered:

- baseflow (Q_{base})
- approximately 50% of bank full ($Q_{0.5bf}$)
- approximately bankfull (Q_{bf})
- an overbank event (Q_T)

As the definition of the selected discharges can lead to misinterpretation, a method based on return period equivalent to the above definitions of flow is suggested. The baseflow corresponds to the flow with the highest occurrence on the flow duration curve. The bankfull discharge should be taken as the $Q_{1.5}$ to Q_2 or Q_{median}. The overbank event could be defined as Q_5 or Q_{10}. For example, Q_{10} has been proposed in the flow regime analysis described in section 5.4.1 because this has been recognised in the geomorphology literature as a useful flow for channel form as well as floodplain inundation in rivers with highly variable flows (e.g. those with a strong dry season or more arid condition). Nevertheless, there is a need to check whether Q_{10} is really an overbanking flow, otherwise a higher return period should be considered.

For each discharge, the velocity, width over depth ratio, wetted area and wetted perimeter can be extracted (section averaged values). The average bed shear stress τ_b total stream power Ω, and specific stream power ω (Bagnold, 1980) can be determined and compared to the results obtained during the reaches characterisation phase.

$$\tau_b = \rho_w \, g \, R_h \, J$$

$$\Omega = \rho_w \, g \, Q \, J \qquad \text{and} \qquad \omega = \Omega / W$$

where ρ is the density of water, g is the acceleration due to gravity, R_h is the hydraulic radius, J is the energy slope, Q is the flow discharge and W is the channel width. It is often assumed that the energy slope is equivalent to the bed slope although such an assumption assumes steady uniform flow at discharge Q.

Shear stress and stream power modelling can be used to assess sediment conveyance continuity, locations of reduced shear stress indicating reaches where aggradation is most likely. Critical values of bed shear stress and stream power are thus determined using the formulas presented in Annex H. The models used in the WP2 Catchment Case Study applications (Table 9.5) are briefly described below, with reference to the literature where a complete description can be found.

RubarBE

RubarBE is a one dimensional model developed by Irstea, which solves the Barré-de-St-Venant equations by an explicit second order Godunov type numerical scheme. A full description of the model is available in the software manual (Paquier, 2013). It is used on the case study of the Loire.

HEC-RAS

The one dimensional model HEC-RAS (Version 4.1) was developed by the US Army Corps of Engineers (http://www.hec.usace.army.mil/software/hec-ras/). The hydrodynamic numerical model is based on the solution of the one-dimensional energy equation by the implicit Preissmann scheme. Energy losses are evaluated by friction (Manning´s equation) and contraction/expansion. For further information see USACE (2010). The model is used in the case studies of the Frome, Lech and Magra.

(ii.2) Empirical estimation of sediment transport

The application of a bed material transport formula is a common means of estimating sediment fluxes in streams. The main advantage of using bedload and suspended load (or total load) sediment transport capacity equations is that the approach can be applied on any stream for which information on flow, channel geometry and bed sediment characteristics is available. The application of these formulas is generally straightforward and can provide a relatively rapid means of estimating sediment flux across a range of flow scenarios. Amongst the numerous empirical and semi-empirical formulae that are available, the most common ones are detailed in Annex H.

Based on a sediment transport formula, a sediment rating approach can be used to calculate sediment transport rates over a range of floods. A simplified sediment balance can thus be approximated by:

1. dividing the hydrograph of duration *T* into appropriate time steps Δt
2. calculating for each flow discharge *Q* a sediment discharge $Q_s(Q)$
3. summing each volume $Q_s\Delta t$ over the whole period T to determine the transported volume V

$$V = \sum Qs\left[Q(t)\right]\Delta t$$

(ii.3) 1D morphodynamic model

Morpho-dynamic models are used to predict the bed profile by explicitly representing hydraulics and sediment transport processes. Customary models remain based on empirical transport relations and a volumetric sediment balance or Exner equation.

RubarBE

The 1D rubarBE model is built upon the Saint-Venant equations for shallow water waves, the Exner equation of sediment mass conservation and a spatial lag equation for non-equilibrium sediment transport. The model has been successfully tested on laboratory and field data (El Kadi et al., 2008). It is used in the case study on the Loire.

(ii.4) 2D hydrodynamic model

2D models are based on the depth averaged Reynolds equations and include the following assumptions: i) vertical scales (e.g. flow depth) are much smaller than horizontal scales (e.g. extent of discretized region); ii) averaging flow velocity over the depth is permitted; and iii) the distribution of pressure is hydrostatic. The outputs of a 2D model are depth averaged, so the effects of restoration can be locally examined (to compare connectivity of secondary channel for instance).

River2D (Version 0.95a)

River2D is a two dimensional hydrodynamic model that has been developed at University of Alberta, Canada (http://www.river2d.ualberta.ca/). It is based on Finite Elements and on a conservative Petrov-Galerkin upwinding formulation, and was customized for fish habitat evaluation studies by performing PHABSIM type fish habitat analysis. A full description of the model is available in the software manual. The model is used in the Lech case study.

CCHE2D

The two dimensional hydrodynamic numerical model CCHE2D was developed at the National Center for Computational Hydroscience and Engineering in Mississippi, USA (http://www.ncche.olemiss.edu/cche2d). The model is based on an Efficient Element Method and three different turbulence closures are implemented in the model: a depth-integrated parabolic eddy viscosity model; a depth-integrated Mixing Length model; and a depth-integrated k-ε-model respectively. For further details see Zhang (2005). The model is used in the case study of the Drau.

(ii.5) Habitat evaluation model

Habitat evaluation models are used to interpret abiotic conditions (e.g. flow velocity, water depth, bottom shear stress, grain size distribution etc.) in terms of characteristic living environments for specific life stages and target species in order to determine the suitability for different species. With these models, changing habitats due to changing flow conditions (e.g. impact of hydro-peaking or climate change), or based on altered topography (e.g. effects of river restorations) can be investigated. Habitat evaluation models rely on the (abiotic) results of one, two and/or three dimensional hydrodynamic models and can be applied at various spatial scales (e.g. macro-, meso- and micro habitat modelling)

MEM

The Mesohabitat Evaluation Model (MEM) was developed at the University of Natural Resources and Life Sciences, Austria. It evaluates the availability of suitable habitats for fish and macro invertebrates, based on flow velocity, water depth, bed shear stress and the stability of bed substrate. For further details see Hauer (2007). The model is used in the Lech case study.

Further approaches that can provide recommendations for the maintenance or restoration of physical habitats are the holistic methodologies used for the environmental flow assessment ("Eflows"). These methods are distinguished from the previous single purpose modelling tools because they aim to assess the flow requirements of the many interacting components of aquatic systems (Arthington, 1998; King et al., 2008; Navarro and Schmidt, 2012).

Further details can be found in the section 2.7.2 of the REFORM project Deliverable 1.1.

9.6.3 Discussion and Recommendations

The list of tools and approaches presented in this section is not exhaustive. The choice of a relevant method should be made based on the modelling objectives (especially temporal and spatial scales), data available, time and cost constraints and knowledge of the advantages and limitations of different modelling approaches. Furthermore, whichever method or methods are selected, they are most effectively used in combination with other approaches to help construct an integrated space-time picture against which management can be developed. Table 9.5 presents some typical models tested within the WP2 Case Study Catchments.

For example, the sediment budget approach is very attractive in the context of evaluations to support catchment management, but the concept needs careful consideration in relation to the spatial and temporal scales considered and the scope of the research. Whereas small headwater catchments may react strongly and immediately to single hydrological events or human deforestation, the response time of large river systems is in the order of millennia (Phillips, 2003).

Problems with the application of existing empirical, numerical models of sediment transport lie in the need to calibrate them to local conditions and the availability/expense of data and suitably skilled modellers. Even when calibrated and performed by specialists the output from sediment transport models is usually indicative rather than absolute. Modelling river sediment transport and morphological changes is a complicated task as few data are available for verification and validation (Cao and Carling, 2002).

Empirical estimation of sediment transport is common despite the fact that numerous authors have highlighted the inaccuracy of these approaches. Undeniably, results provide a rough estimation of sediment transport, which should be considered only as indicative. Gomez and Church (1989) evaluated bed load formulae and noted that there were more bed load formulae in existence than there were reliable data to test them. Habersack and Laronne (2002) made an extensive evaluation of classic bed load formulae in comparison with field measurements on the Drau River using both section averaged and local hydraulic parameters and illustrated how the application of local hydraulic parameters improves the results compared to section-averaged. Similarly, Camenen et al. (2011) measured bed load sediment transport through a section of the Danube River and emphasized the need to distribute the bed shear stress throughout the section when using 1D modelling and to calculate bed load locally in order to improve bed load transport computation, specifically in wide rivers. Recking et al. (2010) and Claude et al. (2012) provide further comparisons of measured data with the results of the application of empirical formulas.

As a summary, Table 9.5 provides the models used in REFORM WP2 for different temporal and spatial scales and objectives. Table 9.6 gives some recommendations on the type of model to be used depending on the spatial and temporal scales and objective of the study. Again, one can also refer to the compilation within WP6 with details on the model dimension, scale, outputs and literature references provided at:

http://wiki.reformrivers.eu/index.php/Category:Tools.

Table 9.6: Suggested recommendations on the type of model to be used depending on the objective of the study.

Spatial scale	Temporal scale	Objective	Type of model
Catchment scale	10^2-10^3 years	Qualitative descriptions and predictions of landform and landscape evolution	Conceptual model, channel evolution model
		Sediment budget	GIS based models
Segment to landscape unit scale	10-10^2 years	Sediment budget	Empirical estimations based on flow duration curve and simplified 1D modelling
		Sediment transport, budget (and bed evolution)	1D models (with bed evolution)
Reach scale	0.1-10 years	Qualitative descriptions and predictions of landform and landscape evolution	Statistical model using Lidar data, Cellular model
		Morphodynamics for complex situation	Physical models
		Sediment transport and bed evolution	1D and 2D models with bed evolution
		Habitat	Statistical hydraulic models (+ habitat model) 2D and 3D hydraulic models (+ habitat model)
	event	Sediment transport and bed evolution	2D and 3D models with bed evolution

10. References

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