5. CHARACTERISATION OF SCALE-DEPENDENT FEATURES: JUSTIFICATIONS, DEFINITIONS AND DESCRIPTIONS

Having defined the boundaries of the spatial units (section 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 (section 7). 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 degradation. Therefore, reference will be made to human-induced properties that must be characterised.

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 data sets (e.g. Table 4.2, Section 4 - Characterisation). 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 text.

Section 5 considers each spatial scale in the hierarchy from region to reach, describing the aims of the characterisation, the groups of characteristics that are of interest at each scale, and the specific characteristics that can 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.

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[1])
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. SRTM, ASTER GDEM) CCM2 River and Catchment Database (v2.1) One Geology Europe European soils data base CORINE land cover JRC Forest Cover Map
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.	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 and /or riparian (and aquatic) vegetation.	Digital Elevation Models (e.g. SRTM, ASTER GDEM) CCM2 River and Catchment Database (v2.1) One Geology Europe European soils portal (soil maps, USLE K erodibility factor, PESERA soil erosion estimates) CORINE land cover CORINE biotope Nature 2000 JRC Forest Cover Map JRC Riparian Woodland Map Google Earth / other satellite imagery / Orthophotos

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, geomorphic units, 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. 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 Digital Elevation Models (e.g. SRTM, ASTER GDEM) LIDAR data Pan-European and National vegetation databases National surveys including: Physical habitat surveys Riparian habitat surveys Morphological surveys (Field reconnaissance can provide useful confirmation / additional data)

[1] Detailed information on datasets and their availability is provided in Table 4.2, Section 4 – Delineation of Spatial Units.

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 and morphology 5.2.2 Geology-soils 5.2.3 Land cover	(1) Catchment area; (2) WFD size category; (2) max., average, min. elevation; (3) relative relief; (4) WFD elevation zones proportion with (1) exposed aquifers; (2) rock type classes; (3) soil permeability classes (1) proportion under land cover classes
5.3 Landscape unit	5.3.1 Water delivery potential	(i) Rainfall (ii) Relief / topography (iii) Surface:Groundwater (iv) Land cover	(1) summary characteristics of rainfall amount and regime (1) drainage density; (2) hypsometric curve; (3) surface slope - elevation proportion with (1) exposed aquifers; (2) soil/rock permeability classes (1) proportion under land cover classes
	5.3.2 Sediment delivery potential	(i) Potential fine sediment availability (ii) Potential coarse sediment availability	(1) soil erosion map layer; (2) average soil erosion rate (1) potential sources map layer (2) Sources-slope gradient map layer
	5.3.3 Vegetation	(i) Natural vegetation	(potential) plant associations / dominant species within different elevation zones along the river network
5.4 Segment	5.4.1 Flow regime	(i) Morphologically representative discharge (ii) Extreme flows (iii) Annual pattern of monthly flows (iv) Abrupt anthropogenic flow fluctuations	(1) Qpmedian (2) Qp2; (3) Qp10 characteristics of 'natural' and 'current' flows (Table 5.3) characteristics of 'natural' and 'current' flows (Table 5.3) (1) number (ii) size (3) duration characteristics (Table 5.3)
	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 (2) other sediment properties including dynamics can be added as listed in 5.5.3

	5.4.4 Riparian vegetation	(i) Presence of a riparian corridor (i) Structure of the riparian corridor (iii) Wood delivery potential	(1) average width; (2) area; (3) proportion of valley bottom; (4) continuity (1) proportion trees, shrubs, short, bare (1) proportion bank top under mature trees
	5.4.5 Physical Pressures	(i) Longitudinal continuity	(1) channel blocking structures; (2) channel spanning / 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 (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 (ii) Lateral sediment delivery (iii) Sediment budget	(1) Bedrock exposure; (2) Composition (>64mm); (3) Composition (<64mm); (1) local fine sediment delivery; (2) local hillslope coarse sediment delivery (3) local coarse sediment delivery from bank erosion (1) Reach (or segment) gaining, losing or in-balance with respect to sediment.
	5.5.4 Riparian and aquatic vegetation	(i) Riparian vegetation (ii) Large wood (ii) Emergent aquatic vegetation	(1) Age structure; (2) Lateral structure; (3) Patchiness; (4) Species (1) Large wood presence and abundance (1) Extent; (2) Patchiness; (3) Species presence and abundance
	5.5.5 Physical Pressures	(i) River bed condition (ii) River bank condition and lateral continuity	(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 (1) hard bank reinforcement; (2) bank edge levées/embankments; (3) set-back levées/embankments; (4) bank top infrastructure; (5) immobilised river margin;

		(iii) Riparian corridor connectivity and condition	(6) actively eroding river margin (7) width of erodible corridor; (8) number of channel-spanning structures; (1) riparian corridor accessible by flood water; (2) riparian corridor affected by intense woodland management activities; (3) abundance of alien, invasive plant species (4) 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 . See Table 5.6
	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 changei

5.1 REGION

At the regional scale, macro-features of biogeography and hydroclimate are considered. These provide broad boundary conditions for the characteristics of the study catchment at all spatial scales. Two properties are suggested:

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 or Ecoregion 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

At the catchment scale, the aim is to give an overview of the topographic, geological and land cover controls on hydrological responsiveness and sediment delivery to the river network. Information on such properties can be gathered under three themes, some of which are needed for classifying river types within the Water Framework Directive (WFD: Annex II) and so need to be characterised at this scale:

5.2.1 Size and Morphology

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

- catchment area (km^2).
- 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 miminum 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).

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 a particularly useful for characterizing the water absorbing properties of a catchment. 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 as a ready-prepared map layer. At a minimum, the proportion of the catchment under the following land cover types should be estimated from a land cover map layer.

- permanent snow and ice
- open water (major lakes and reservoirs)
- bare rock / sediment (including mining areas)
- forest
- grassland
- arable agriculture
- urban-industrial (including major transport infrastructure)

Most of the required land cover classes are recorded at level 2 of CORINE and the resolution of CORINE (25 hectares) is sufficient for catchment and landscape unit scale characterisation. The major omissions (permanent snow and ice, and open water) can be extracted from satellite imagery if no alternative data source is available. ‘Permanent’ ice and snow cover (i.e. the cover that persists through the summer) can be assessed by classifying late summer satellite imagery. Satellite imagery can also be analysed to prepare purpose-specific land cover maps for any specified time period over the last 30 years, if major changes in land cover have been experienced.

5.3 LANDSCAPE UNITS

Landscape units are areas of the catchment with similar morphological characteristics. They are the building blocks from which water and sediment are delivered to the river network. They are characterised in a similar way to the entire catchment but to a greater level of detail.

5.3.1 Water Delivery Potential

(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 modeling 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.

(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

Proportions of the same broad land cover classes as were used at the catchment scale enable further characterisation of runoff potential of the landscape unit:

- permanent snow and ice
- open water (major lakes and reservoirs)
- bare rock / sediment (including mining areas
- forest
- grassland
- arable agriculture
- urban-industrial (including major transport infrastructure)

5.3.2 Sediment Delivery Potential

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 a 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 Availability

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 1km 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). However, 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, we recommend that this approach should only be considered if major changes in land use have occurred. For a recent GIS-based application of the USLE, see Erdogan et al. (2007).

(ii) Potential Coarse Sediment Availability

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).

These can be recognised on aerial imagery as torrents 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. This is jointly analysed with DEM data to produce the following indicators:

- The proportion of the landscape unit that comprises potential sources of coarse sediment
- A map layer that allocates each coarse sediment source polygon to one of four average hillslope gradient classes (very steep, > 40^o; steep, 15^o - 40^o; moderate, 3^o - 15^o; gentle < 3^o)

5.3.3 Vegetation

Riparian vegetation and, in low energy river systems, aquatic vegetation have an enormous influence on the hydromorphological characteristics of fluvial systems, since certain plant species often act as river ecosystem engineers (Gurnell et al., 2012, Gurnell 2013). Therefore, it is crucial to characterise vegetation beyond the level incorporated into the land cover map layer. The predominant 'natural' plant associations or, as a minimum, the dominant species close to the river network within each landscape unit need to be characterised, since these constitute the potential vegetation along the river margins that can interact with fluvial processes and so constrains likely outcomes of manipulation / naturalization of river margins. Where aquatic plants have the potential to have significant cover, information on their species composition should also be assembled. If environmental conditions vary greatly close to the river network within the landscape unit (e.g. where there are large variations in the elevation of the rivers), then several characterisations of floodplain, riparian and aquatic vegetation may be needed for contrasting environmental conditions. Pan European potential information sources are the EU Habitats of Nature 2000 and the map layer of forest cover of riparian zones can be obtained from JRC (Clerici et al., 2011). Information on riparian vegetation will be developed specifically for REFORM and included in an appendix in the final report. It will list:

- Potential plant associations / dominant species within different elevation ranges along the river network (e.g. above the tree line, and within altitudinal ranges below the tree line where the dominant species differ.

NOTE: Where insufficient information is available, it will be necessary to undertake field surveys within any pockets of naturally-functioning (i.e. unconstrained, dynamic) river channel and riparian zone where plant colonisation is unrestricted.

5.4 RIVER SEGMENTS

Within each landscape unit, different conditions of flow regime or channel dynamics may occur along the channel network as a consequence of major tributaries confluences, geological changes and changes in valley confinement. River segments reflect these changes and are defined as segments of the river network within a single landscape unit that are affected by relatively small variation in catchment area (to the extent that there are no major tributaries within the segment) or valley confinement. They are characterised according to the following groups of properties:

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 landscape unit, 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 5 years is required, with a minimum temporal resolution of one day. 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.

Once the recorded flow time series is aggregated to a particular time unit, there are numerous characteristics that can be extracted 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 UPM and CEDEX; IARI, developed in Italy by ISPRA). These methods will be summarised in an appendix in the final report.

Table 5.3 suggests a range of flow regime characteristics that are relevant to hydromorphological assessment (including vegetation). The characteristics are grouped to indicate their hydromorphological relevance:

- Morphologically representative discharge (for further discussion see Leopold et al. 1964; Simon and Castro, 2003).
- Magnitude, duration, timing of extreme flow conditions
- Annual pattern of monthly flows
- 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.

Table 5.3 Suggested flow regime characteristics for a hydromorphological assessment: (i) channel-forming discharges; (ii) extreme flows; (iii) annual pattern of monthly flows; (iv) abrupt anthropogenic flow fluctuations

Group and Rational	**Characteristics**
(i) 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)
(ii) 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
(iii) 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, LQ, and UQ flows for each month.
(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 degree of valley confinement: confined, partly-confined, unconfined (from section 4.4)
- The degree of river confinement: the typical river bankfull width (an average of reach estimates - see 5.5.1) divided by the typical valley width (Rinaldi et al., 2012, 2013; Polvi et al., 2011).

5.4.3 Sediment.

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.

NOTE: It is also possible at this scale to develop a range of additional characteristics relating to sediment inputs, dynamics and the segment sediment budget. However, this type of detailed work is usually undertaken at the reach scale and so the methods are described in section 5.5.3, below.

5.4.4 Riparian Corridor Features.

Qualitative information concerning the main riparian corridor features within a segment is extracted from air photographs and satellite imagery.

(i) Presence of a Riparian Corridor

Characterisation commences by defining the outer limit of any corridor of naturally-functioning riparian vegetation cover. The size and continuity of this natural corridor indicates the area that is currently available for accommodating flood water, river channel dynamics and interactions between fluvial processes and vegetation. It is defined by the outer limit of naturally-functioning riparian vegetation cover within any restricting embankments. The following characteristics are quantified:

- Average width (m)
- Area (km^2)
- Proportion of the connected valley bottom / floodplain under riparian vegetation cover: average width of riparian corridor / (typical valley width minus typical river bankfull width).
- Continuity: proportion of the length of the bankfull channel margin abutting the natural riparian corridor

(ii) Structure 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 riparian corridor 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.

(iii) Wood Delivery Potential

- Proportion of the active 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 of hydromorphological processes and forms (lateral continuity is assessed at the reach scale) can be recognized. Many of these can be enumerated using aerial imagery if other information sources are not available. The longitudinal (upstream to downstream) continuity of water, sediment, and large organic material (e.g. large wood), and in some cases the base level of the river profile, is interrupted by blocking (dam / check dam / weir / pier-deflector) structures; and spanning structures (bridges).

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

- Count of high, medium and low impact spanning and partial blocking structures:
    - 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.

The removal of sediment or large organic material (dead wood, vegetation) from the channel also affects longitudinal continuity but data are difficult to obtain, so this is best estimated at the reach level (see 5.5.6):

5.5 REACH

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 5.4). 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.

Table 5.4. 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 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	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 4.2)	√	√
Baseflow sinuosity	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 4.2).		√
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 4.2)		√

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 anastomosing channels or the midline of the braid plain for multi-thread braided and wandering channels.

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. In particular, 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 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 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 of 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.

5.5.2 River Energy.

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

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 5.3) 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.
- 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 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 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. 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. Ann appendix in the final report will describe and recommend optimum methodologies for such surveys to yield high quality data with a minimum of field and laboratory effort. The following are useful summary characteristics:

- Bedrock exposure: % bed or bank surface comprised of exposed bedrock
- Sediment composition (>64mm fraction): % bed or bank surface covered by boulders
- Sediment composition (<64mm fraction): % gravel (cobble), %gravel (pebble+granule), %sand, %silt plus clay (Table 5.5)

In addition, the following can be extracted if a complete particle size distribution is available (see Appendix 5C):

- Median
- 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 5.5 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

(ii) Lateral sediment delivery

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 > 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 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 research. 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 and / or reaches, since these will aid understanding of the hydromorphological characteristics of those segments or 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 reach (or segment) scale. Separate indicators of fine and coarse sediment delivery are based on creating buffer zones around the channel network within a GIS and then assuming that the available fine sediment within the buffer zone is likely to reach the channel network in any year and that the potential delivery of available coarse sediment depends upon the land surface slope. The very simple approach used to estimate the following characteristics reflects the fact that they only attempt to give a relative rather than an absolute indication.

1. A minimum 500m wide buffer zone is estimated on either side of the bankfull river channel.
2. Fine sediment delivery is estimated by overlaying the buffer zone onto the soil erosion map layer for the relevant landscape unit and then calculating the total sediment mobilised within a year inside the buffer zone.
3. Coarse sediment delivery is indicated by overlaying the buffer zone onto the land surface instability layer for the relevant landscape unit and then calculating the area of the buffer affected by unstable land surfaces in each of the four slope classes (see section 5.3.2).
4. The above information can be greatly expanded with field data collected at the geomorphic unit scale within reaches (see section 5.6.2)

From the above the following sediment delivery characteristics are estimated:

- Local fine sediment delivery from hillslopes – the total soil erosion per year estimated within the buffer zone divided by the length of bankfull channel margin (fine sediment delivery in $t.yr^{-1}.km^{-1}$ river edge)
- Local coarse sediment delivery from hillslopes – the total unstable area within each slope class divided by the length of the bankfull channel margin (4 indicators of coarse sediment source area per 1km bankfull river edge reflecting each of the four slope classes (see section 5.3.2)).

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

Note: 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 within the reach (or segment). 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. However, this requires a temporal analysis, notably using information from historical aerial imagery. Therefore, quantification of bank dynamics will be presented in section 8 of the final report.

(iii) Sediment 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 and those developed in section 8, coupled with supporting information from field surveys and modelling can provide very useful information on reach (and segment) sediment budgets.

A variety of 1D models are available that provide a means of investigating sediment budgets. For example, the SIAM (Sediment Impact Analysis Methods) 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 develop a map of potential sediment budget imbalances in the channel network. Because (i) the model integrates channel morphological, hydrologic, and hydraulic information that are collected at different spatial scales and are applied to a network of river reaches (or segments) and (ii) it is an important tool for linking spatial scales and exploring trajectories of change, it will be discussed in section 8 of the final report. The output of the model is:

- Identification of whether reaches or segments are generally gaining or losing sediment or are approximately in-balance.

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 disturbed 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 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 vegetation 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 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.

Another set of important characteristics is:
- The dominant species present (particularly trees and shrubs, but also shorter vegetation) and / 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 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) Emergent 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:
- Extent: (i) occasional patches; (ii) abundant stands along baseflow channel margins; (iii) abundant across > 50% baseflow channel area
- Patchiness: (i) strongly patchy; (ii) shows some patchiness; or (iii) large, extensive stands.

- A list of the main aquatic plant species present (may require field survey) and their relative abundance or coverage (most consistent results recorded at the height of the growing season)

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

5.5.5 Physical Pressures

Characteristics are subdivided into three groups:

(i) River bed condition

In gravel-bed rivers, the structure of the gravel bed can be indicative of sediment supply-transport pressures, but this can only be assessed if surface and subsurface sediments are investigated which necessitates field sampling unless information is already available. 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, medium and low impact channel blocking structures within the reach (a subset of the segment scale data)
    - high – substantial 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 spanning (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 the potentially erodible channel margin immobilised by bank reinforcement; artifical levées, infrastructure
- Proportion of actively eroding channel margin
- Width of erodible corridor (i.e. riparian corridor under naturally-functioning riparian vegetation (as defined in 5.4.4) with unreinforced banks: narrow (< 0.25 bankfull width); moderate (0.25-1 channel width); wide (> 1 channel width).
- A count of high, medium and low impact spanning 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 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 affected by intense woodland management activities such as clear-felling, thinning, coppicing / sever 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

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 5.6 provides descriptions of geomorphic units that can often be identified from aerial imagery. In particular, 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 cannot be identified from aerial image are included in the Table using an italic font. Other sources such as habitat surveys, morphological and fluvial audit surveys provide additional information concerning features that are either not identifiable from aerial imagery because they are predominantly vertical structures or that may not be seen from above because of over-hanging trees or other structures.

5.6.2 Information from field surveys

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

- Confirm that those units identified from remote sources are present
- Check for the presence of other geomorphic units included in Table 5.6 but not recognized from remote 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)
- Assess the abundance of each type of geomorphic unit using a simple scale such as: single, occasional, frequent, numerous

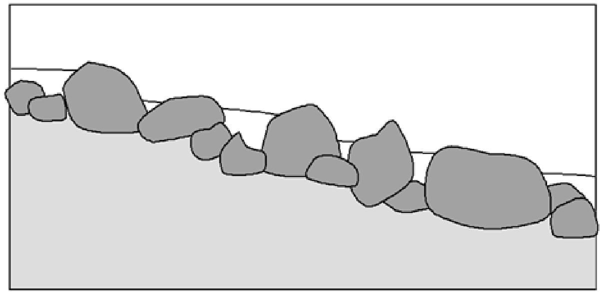
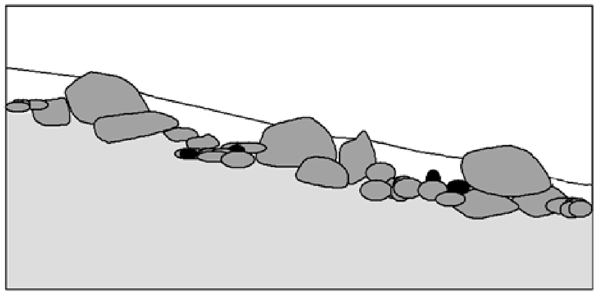
When a field survey is undertaken, features that are indicative of a trajectory of channel adjustment should be recorded, such as.

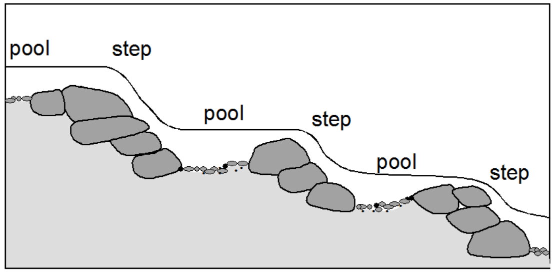
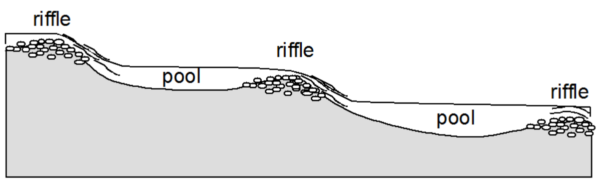
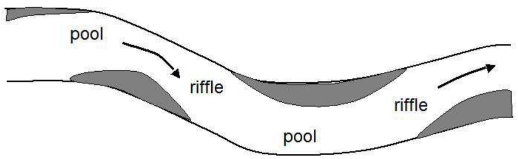
- Evidence of channel widening (e.g. bank erosion and / or undercutting occurring on both banks
- Evidence of channel narrowing (e.g. stabilizing, vegetated bars or benches on both banks or frequent presence of wide benches)
- Evidence of bed incision
    - Narrow and deep channel cross profile
    - 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 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

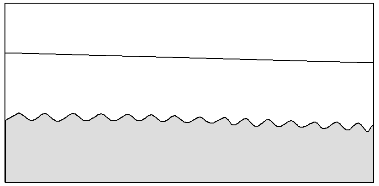
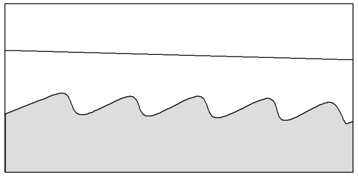
Table 5.6 Geomorphic units: A. features within the bankfull channel; B. marginal and bank features; C. floodplain features.

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

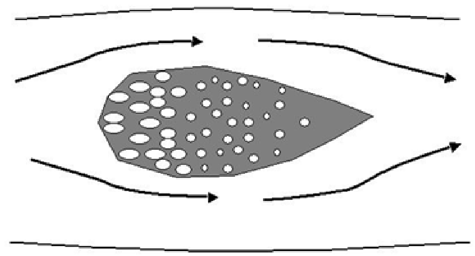
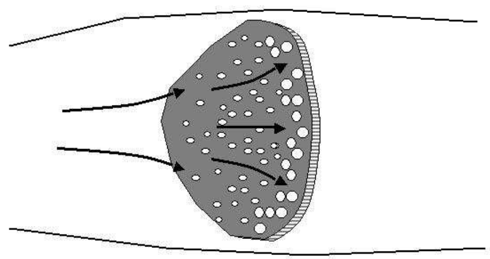
A1. Geomorphic Units within the Bankfull Channel: The River Bed:

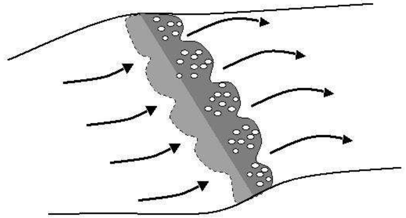
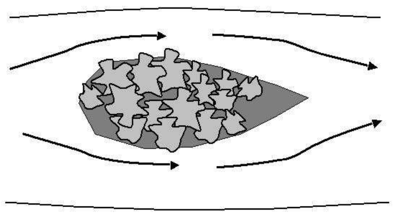
Geomorphic Unit	Sub-type	Description	Diagram	Reference
Cascade / Rapid		Two types of steep channel unit that are difficult to distinguish on aerial images. They are composed of mainly disorganised boulders exposed through the water surface and surrounded by mainly supercritical flow with some small pool areas that rarely span the channel width. Rapids show a lower extent of supercritical flow and may include ribs or stone lines oriented approximately perpendicular to the channel.	cascade (profile)  rapid (profile) 	Grant et al.,1990; Halwas and Church, 2002.

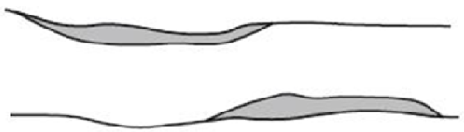
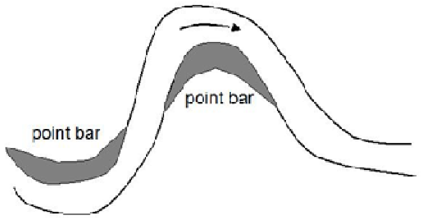
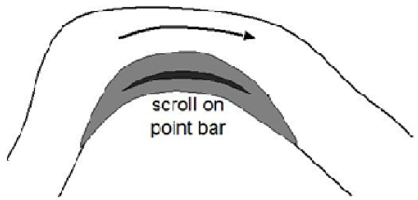
Step (-pool)		A steep accumulation of boulders and cobbles transverse to and spanning the channel, generally with a pool downstream that is scoured by the plunging (waterfall) flow over the step. Steps and pools are common bed forms in boulder-cobble bed mountain stream channels where gradients exceed 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)  	Bridge, 2003; Church, 1992; Grant et al., 1990; Wood-Smith & Buffington, 1996.
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; Wood-Smith & Buffington, 1996.

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 (plan). 	*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 alignment to ripples; upstream slope may be rippled*	Dunes (plan). 	*Bridge, 2003; Knighton, 1998; Simons and Richardson, 1966.*

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

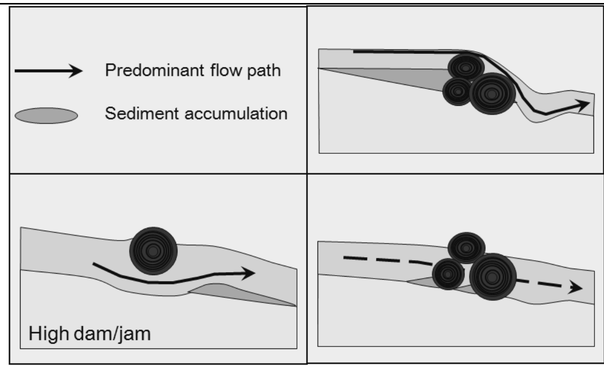
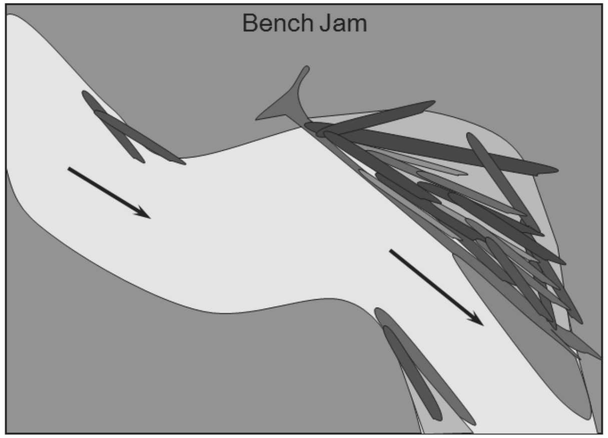
Mid Channel Bar		Depositional bed feature located in the central part of the river channel, whose surface is exposed for most of the time but is submerged at bankfull flow.		
	Longitudinal bar	Mid-channel, elongate, lozenge-shaped or lobate bar found in gravel and mixed bed channels; bar sediments typically fine downstream away from coarser bar head; common in active meandering and braided rivers.	Longitudinal bar (plan) 	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.

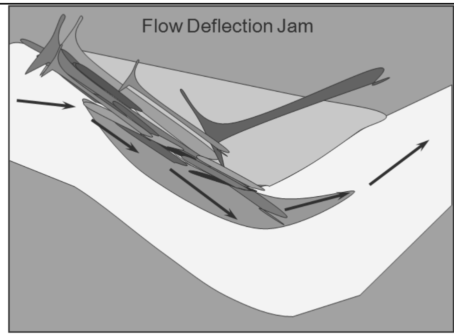
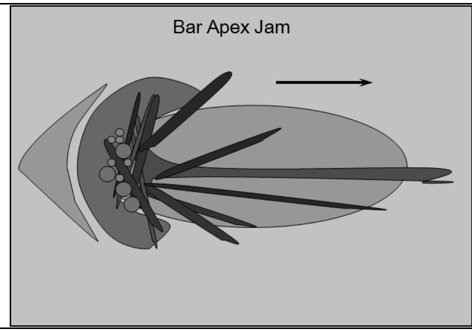
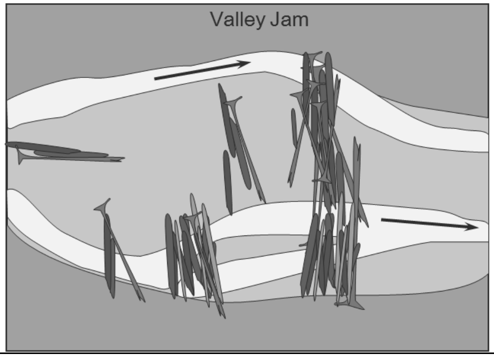
	Diagonal bar	Mid channel bar that is attached to the banks and runs obliquely across gravel and mixed bed channels. Diagonal bars are often associated with riffles, with a series of diamond shaped units exposed above the water surface..	Diagonal bar (plan) 	Brierley and Fryirs, 2005; Church and Jones, 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.

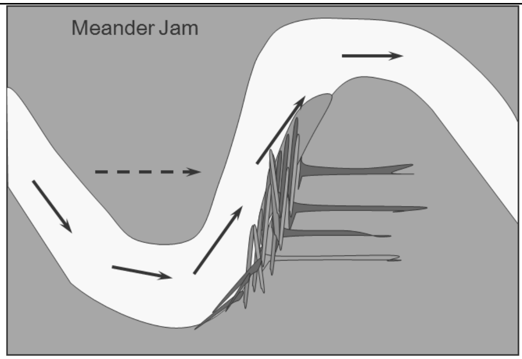
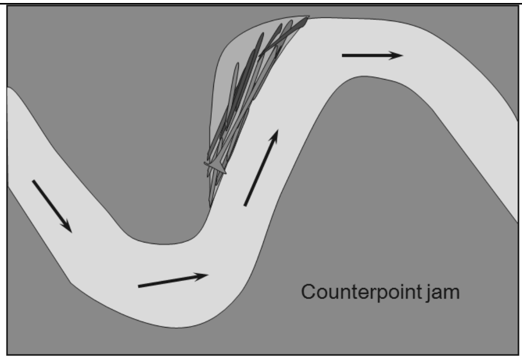
Marginal Bar		Depositional bed feature attached to the margins of the river channel, whose surface is exposed for most of the time but is submerged at bankfull flow.		
	Lateral bar	Bank attached bar, often distributed periodically along one and then the other side of channel to form alternate bars. Bar 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

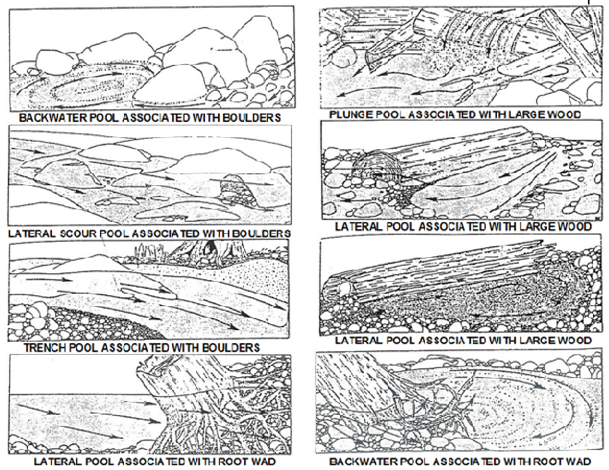
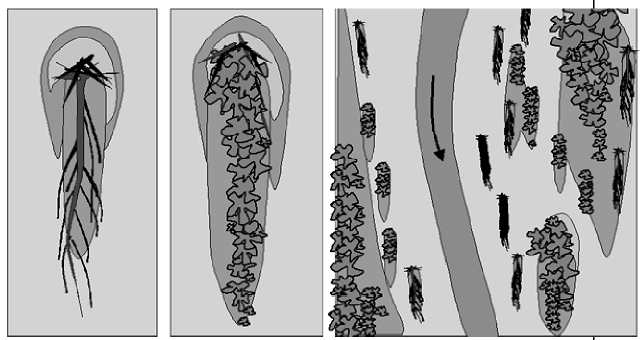
A3 Geomorphic Units within the Bankfull Channel: Large Wood and Vegetation Features

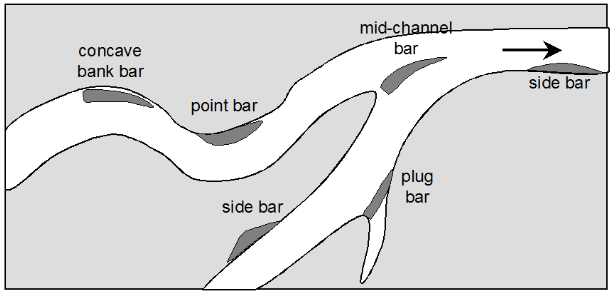
Geomorphic features formed in association with deposition of large wood or vegetation colonisation in various locations within and around the river channel. Many of these features are similar to bed and marginal features created by sediment deposition, but large wood and vegetation act to protect and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

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 spanning 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

	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
	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

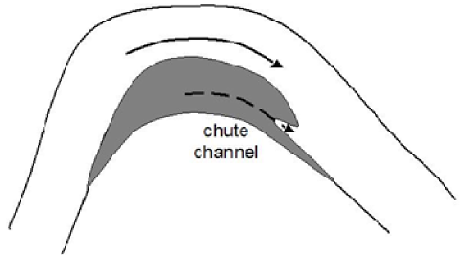
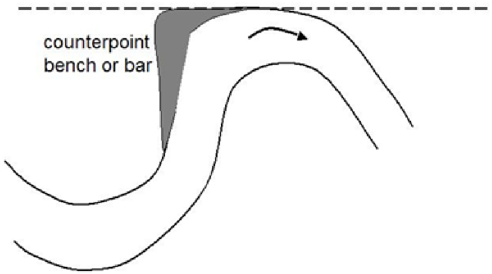
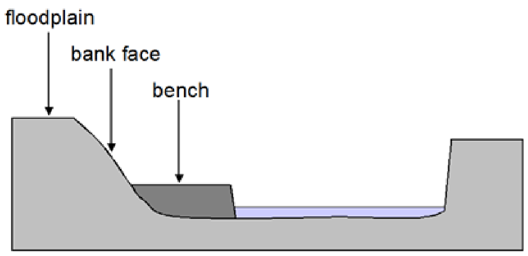
	Meander jam	Found on the outer margins of bends of large meandering channels where whole trees and large wood pieces transported from upstream jam against the downstream bank of river bends, protecting the bank from erosion and so affecting channel curvature		Abbe and Montgomery, 2003
	Counterpoint jam	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

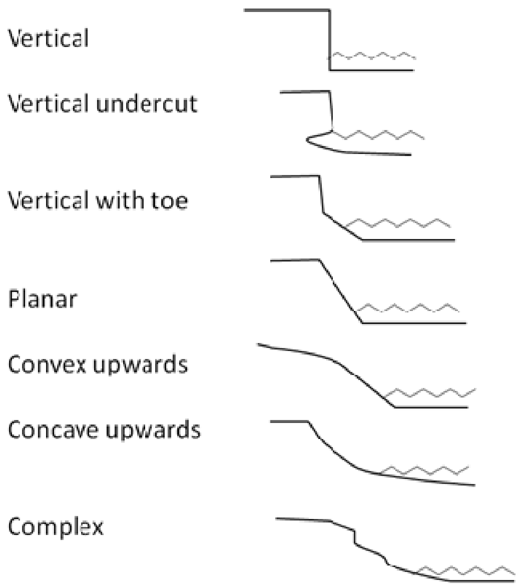
Forced pools, bars, riffles		A common feature of relatively small rivers and streams, where growing or fallen trees, large wood and other roughness elements (e.g. boulders, bed rock outcrops) can induce significant ponding of water, bed or bank scour, and erosion and deposition of sediment, and as a 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

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:

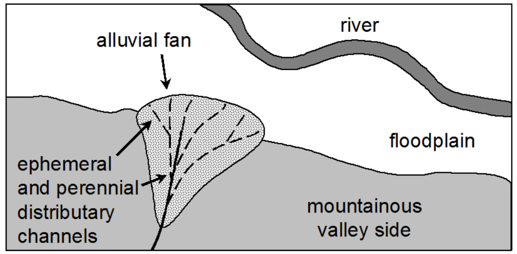
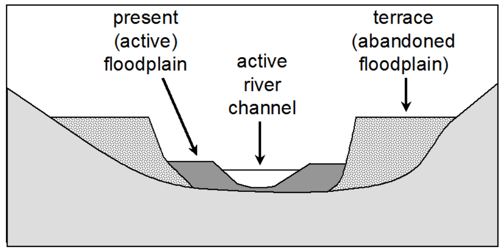
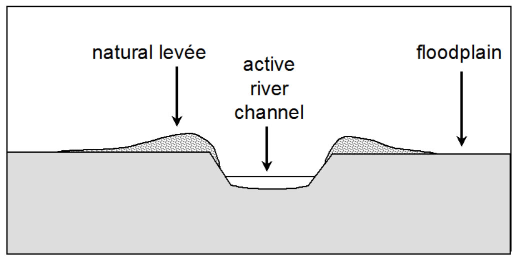
Geomorphic features formed at the interface between the bankfull channel and the floodplain

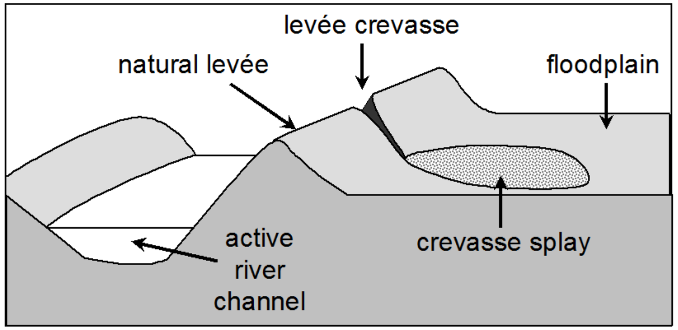
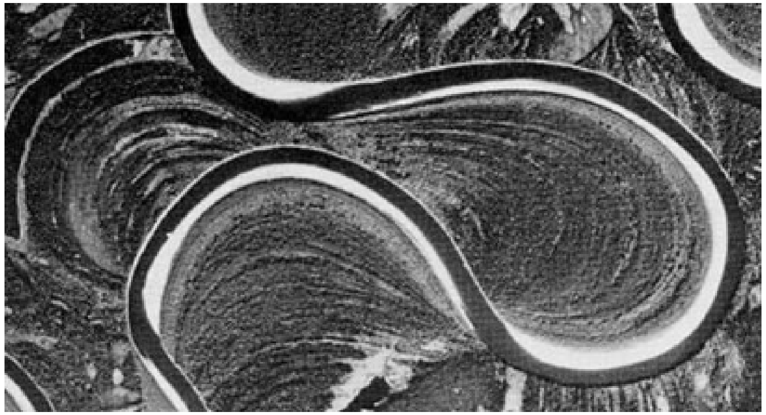
	Chute channel	Chute channels are formed where flow across a bar or floodplain surface leads to scour and incision of a channel. In the diagram, a chute channel is illustrated on a point bar but they also form across large medial bars, across the floodplain at the neck of meander bends, andelsewhere on floodplains where flood waters become concentrated as they drain back into the main channel.		Bridge, 2003; Grenfell et al., 2012
	Counterpoint 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 a 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 that they often adjoin.		Hickin, 1984; Lewin, 1983; Page & Nanson, 1982; Thorne & Lewin, 1979
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		Brierley and Fryirs, 2005; Gurnell et al., 2012; Shi Changxing et al., 1999.

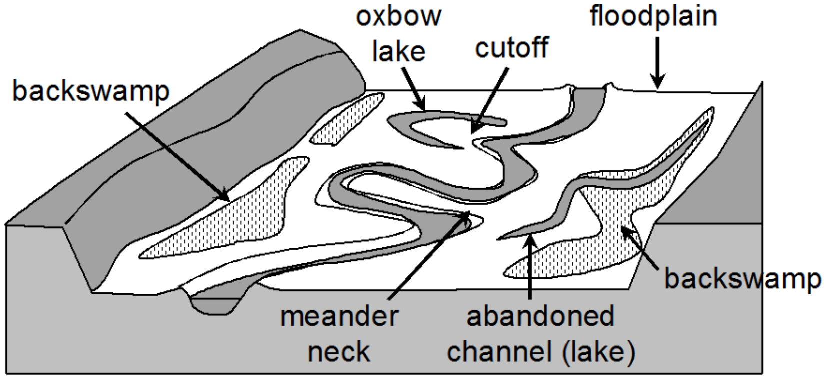
Bank	*Bank profile types vary widely but can be divided into subtypes according to their steepness and the degree to which they display one or more profile elements (see diagram)*	*Large, vertical feature at the junction between river channel and floodplain. The morphology of a river bank varies as a 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.*		
	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.

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.		Brierley and Fryirs, 2005;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.		Brierley and Fryirs, 2005; 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.		

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 floodplain and whether they have developed from point or counterpoint scroll bars or benches		Brierley and Fryirs, 2005; Nanson and Croke, 1992.

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.
Backswamp		These major wetland features occur on floodplains towards the valley margins, away from the main channel, and in the lowest areas of 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 forming where tributary streams drain directly onto the floodplain.		Nanson and Croke, 1992

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