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# Classification of river morphology and hydrology to support management and restoration

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## ABSTRACT

As part of an hierarchical, multi-scale, hydromorphological framework for European rivers that has been developed within the REFORM project, a procedure for classifying rivers has been devised. The procedure includes components that categorise river channel morphology, floodplain morphology, flow regime, and groundwater – surface water interactions, and is designed for operational use in the context of river management. Channel morphology is classified at a first level by a basic river typology interpreted using remotely-sensed images, and at a second level by an extended river typology that integrates information from field observations. Floodplains are classified by adopting the Nanson and Croke typology with specific reference to the types of floodplain that are most likely to be encountered widely across Europe. Nine flow regime types are identified using a series of hydrological indicators. Finally, where groundwater has a significant influence on river flows, a range of potential groundwater – surface water interactions are identified reflecting the morphological river type and its geological and climatic setting.
Within the REFORM project, the river typology has been tested using case studies representative of a wide variety of European catchment conditions. Four case studies are used to illustrate the classification procedure and to discuss its main strengths and limitations.

*Keywords*: river classification, channel morphology, floodplain, flow regime, groundwater

## 1. Introduction

Classification and characterization of river morphology and hydrology are increasingly recognised as fundamental integrating components for interdisciplinary studies that seek to develop understanding of river behaviour to support river management applications (e.g., Sear et al., 1995; Gilvear, 1999; Kondolf et al., 2003; Downs and Gregory, 2004; Brierley and Fryirs, 2005, 2008; Meitzen et al., 2013; Tadaki et al., 2014).

In European countries, the introduction of the Water Framework Directive (WFD; European Commission, 2000) has highlighted the importance of both hydrological processes and the morphodynamics of river channels and their floodplains (abbreviated to 'hydromorphology') in the classification of water bodies, development of understanding of their functioning, and identification of appropriate management actions (Newson and Large, 2006; Vaughan et al., 2009). This has led to a considerable research effort in this area, of which the EU FP7 project REFORM (REstoring rivers FOR effective catchment Management) is an example. Within the context of REFORM, hydrological and morphological delineation and characterization of rivers represent a fundamental initial stage for developing knowledge and understanding of current river corridor forms and processes (Gurnell et al., 2014, 2015).

Numerous river classification schemes have already been developed for a range of applications, from interpreting landscape evolution to developing river restoration design (e.g., Kellerhals et al., 1976; Schumm, 1977; Brice, 1964, 1984; Church, 1992; Rosgen, 1994; Montgomery and Buffington, 1997). Such schemes have been elaborated in several recent comprehensive reviews (e.g., Kondolf et al., 2003; Fuller et al., 2013; Tadaki et al., 2014). Furthermore, many flow regime classification schemes have been devised (Poff and Ward, 1989; Poff, 1996; Poff et al., 1997), and a classifications of floodplains by Nanson and Croke (1992) is well established.

Despite the availability of many pre-existing classification schemes, there are two major limitations that preclude their direct application within the REFORM hierarchical, hydromorphological framework: (1) many of the existing classifications are not easily applied by river managers because they have been designed to improve scientific understanding rather than as a management tool; (2) few provide an integrated characterization of the various components of river and floodplain morphology and hydrology, but tend to consider only one component of the river environment. In this sense, the integration of hydrology, hydrogeology, and geomorphology has been recognised to be essential for understanding habitat dynamics in fluvial ecosystems (Poole, 2010).

As a result of these limitations of previous classifications in relation to our requirements, we have developed a combined classification approach that addresses several complementary aspects of the river corridor system to promote integrated understanding of river processes for management purposes. To achieve this aim, the various typologies that are to be integrated need to be relatively simple and to be able to cope with the fact that most European rivers reflect some degree of human modification. Inclusion of flow regime analysis allows morphology and hydrology to be compared, and hydrological change to be analysed. Inclusion of a groundwater pathway typology helps to further understand the importance of hydrology, particularly in cases where the flow regime type indicates an important groundwater contribution. The link between hydrology, groundwater, and vegetation, and the potential morphological feedbacks associated with riparian and aquatic vegetation are also important aspects that need to be addressed. Finally, the temporal variability of the river system needs to be accounted for in a classification scheme. Therefore, the classifications that have been developed can be used to characterise current and past river conditions, particularly identifying changes in channel morphology and in flow regime, but also considering related potential changes in groundwater and surface water interactions and floodplain characteristics.

Experiences at the science-management interface indicate that collaboration with practitioners in the development of theoretical or empirical frameworks and scientific tools is crucial for their successful application (e.g., Rogers, 2006; Tadaki et al., 2014). The classification approach presented in this paper is part of a wider framework (Gurnell et al., 2014, 2015) that was developed in collaboration with river managers, promoting the implementation of a common 'language' and understanding of river systems.

The specific aims of this paper are to: (i) provide an overall description of the classification procedure that has been developed within the context of the REFORM hydromorphological framework; (ii) briefly highlight and discuss the main characteristics, strengths, and limitations of the procedure.

## 2. The REFORM classification approach

The classification scheme described in this paper is part of a wider hydromorphological framework (Gurnell et al., 2014, 2015). The framework incorporates information on morphological features of the river channel and its corridor into a larger spatial and temporal assessment of the controls on reach dynamics, and a process-based interpretation of the current status of river reaches, their historical dynamics and their likely future trajectories of change. The approach that underpins the framework makes maximum use of available data, is sufficiently flexible to be suitable for application across the varied environments encountered within Europe, and is also sufficiently simple to be used as an operational tool.

During the first phase of delineation of river reaches for assessment (summarised in section 2.1), a Basic River Typology (BRT) is used (section 2.2). An Extended River Typology (ERT) is then used for characterizing river reaches, summarising the information on reach properties and indicators (section 2.3). The characterization is completed by a description of different types of floodplain that may be associated with different river types (section 2.4), a classification of the river hydrological regime (section 2.5), and the nature of groundwater-surface water interactions (GSI, section 2.6) that may accompany the river types in the extended typology. Finally, the importance of the temporal dimension of the classification and characterization is highlighted (section 2.7).

These different classification components combine to give managers a baseline categorisation of contemporary river reach morphology and hydrology against which they can investigate past and present processes and changes to guide management actions.

### *2.1 Delineation of spatial units*

The first part of the REFORM framework delineates spatial units (see Gurnell et al., 2015 for details). The catchment is divided into landscape units, mainly based on geological setting and topography. The boundaries of landscape units form the first delineation of segments of the river valley network. However, subdivision of large segments may be necessary based on additional factors such as major changes in valley gradient, catchment area, confluences of major tributaries, and lateral confinement). Based on Brierley and Fryirs (2005) and Rinaldi et al. (2012, 2013), three valley settings are differentiated: (i) confined (i.e., more than 90% of the river banks are directly in contact with hillslopes or ancient terraces); (ii) partly confined (i.e., river banks are in contact with the alluvial plain for between 10 and 90% of their total length); and (iii) laterally unconfined channels (i.e., less than 10% of the river bank length is in contact with hillslopes or ancient terraces).

The basic spatial unit is the reach, i.e. a section of river and floodplain along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions. The boundaries of river segments form the first delineation of river reaches, but subdivision of segments may be necessary to define reaches of similar channel and floodplain morphology that may reflect local changes in bed slope too small to demarcate a segment, and also local changes in sediment particle size, discharge (e.g., from minor tributaries) and sediment supply. At the reach scale, the controlling factors are mainly reflected in the planform characteristics of the river channel and floodplain, including the geomorphic units that are present. Therefore, at this stage, a morphological classification is the foundation for the delineation of reaches. This provides a first indication of the spatial distribution and connectivity of the morphological patterns that are present, which subsequently aids interpretation of catchment to reach scale processes and their morphological impacts across space and time (see section 2.7).

### *2.2 Basic River Typology (BRT)*

The first simple level of morphological classification of river reaches, derived from Rinaldi et al. (2013), is based on river channel planform character (number of threads and planform pattern) in the context of valley setting (confinement).

This Basic River Typology (BRT) defines seven river types (plus a type 0 for highly altered reaches) using readily-available information, mainly remotely-sensed imagery (Figure 1, Supplementary Data, Table S1). Different types are associated with two broad categories of valley confinement (i) confined reaches, and (ii) unconfined and partly-confined reaches.

Confined reaches are divided into three morphological types based on the number of threads, i.e. single-thread; transitional (wandering); multi-thread.

For single-thread, confined reaches (type 1), sinuosity is not meaningful as it is determined by the valley rather than the channel planform. Therefore, these channels are not further classified at this stage, because accurate distinctions based on other characteristics, particularly the bed configuration, cannot be made from remotely-sensed images.

Transitional and multi-thread confined reaches are identified using the same criteria as for unconfined and partly-confined transitional and multi-thread channels (see below).

Six broad types of unconfined and partly confined reaches are distinguished (2. Single-thread: Straight; 3. Single-thread: Sinuous; 4. Single-thread: Meandering; 5. Transitional: Wandering; 6. Multi-thread: Braided; 7. Multi-thread: Anabranching) using a planform assessment of sinuosity, braiding, and anabranching indices. The sinuosity index (*Si*) is the ratio of reach length measured along the (main) channel and measured following the direction of the overall planimetric course (or ‘meander belt axis’ for single thread rivers) (Brice, 1964; Malavoi and Bravard, 2010; Alber and Piégay, 2011).

The braiding index (*Bi*) is the number of active channels separated by bars at baseflow, and is estimated as the average count of wetted channels in each of at least 10 cross sections spaced no more than one braid plain width apart (Egozi and Ashmore, 2008).

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

Finally, it is important to identify highly modified reaches (e.g. urban and other highly channelised / reinforced reaches) as a separate category (type 0), since their lateral stability and geomorphic units cannot reflect any 'natural' boundary conditions. In this case, the previous indices are not used as discriminating criteria.

### *2.3 Extended River Typology (ERT)*

Following the initial delineation of river reaches, the multi-scale hierarchical framework includes a characterization phase, during which additional information on reach properties and indicators is collected. Based on this additional knowledge, an Extended River Typology (ERT) has been developed.

Although the ERT is informed by previous geomorphological research (e.g. Schumm, 1985; Rosgen, 1994; Knighton and Nanson, 1993; Nanson and Knighton, 1996; Montgomery and Buffington, 1997; Church, 2006; Fuller et al., 2013; Nanson, 2013), it is designed for practical application by stakeholders and river managers, and it builds explicitly on the simple BRT classification described in the previous section.

Twenty-two extended morphological types are discriminated (Table 1, Figures 2 and 3) according to their confinement (confined, partly confined, unconfined), dominant bed material size (bedrock, boulder, cobble, gravel, sand, silt), and planform (straight-sinuous, meandering, pseudo-meandering, wandering, braided, island-braided, anabranching). The following points should be noted:

(i) the extended types are intended as 'naturally-functioning' morphologies to the degree that they have some ability to adjust their plan- and bed-form. Therefore type 0 (highly altered reaches) is retained in the extended typology for any reach with a predominantly artificial bed and/or heavily engineered, stabilised banks.

(ii) Straight and sinuous types are combined in the ERT (Table 1), because both types are related to similar morphological units when they possess similar bed material and level of confinement. However, to avoid inconsistency between the classifications, the combination of, for example, a 'straight' channel (simple classification) with a 'straight-sinuous with alternate bars' (extended classification) should lead to a 'straight with alternate bars' extended type.

(iii) A new transitional type, 'pseudo-meandering' is incorporated to describe straight or sinuous channels that display large, alternate bars at low flow (Bartholdy and Billi, 2002; Rinaldi, 2003; Visconti et al., 2010). While the bankfull channel conforms to a straight or sinuous channel, the low flow channel is so heavily affected by the exposure of alternate bars that it would be defined as meandering if its *Si* index were to be calculated.

The river types are arranged in Figures 2 and 3 to provide indirect information on the typical spatial distribution of channel morphologies in a fluvial system, as they are linked to confinement, sediment particle size (decreasing from top to bottom of the Figures), and to sediment quantity and river energy (from left to right along each line in the Figures). Figure 2 illustrates typical confined channel morphologies located in the upper portion of a catchment, whereas in Figure 3 the typical downstream distribution of channel morphologies tends to move from top left to bottom right. However, deviations from this principle are possible depending on the specific conditions of the catchment (e.g., due to the alternation of lower energy, alluvial reaches and higher energy, confined reaches, or to other factors).

The 22 extended types are not an exhaustive list of possible combinations of planform, valley setting, sediment size, and geomorphic units, but rather an indicative, general framework for identifying catchment- or region-specific ranges of morphologies. This is because river characteristics cannot be neatly divided into classes, they vary continuously and thus transitional types are likely to be encountered quite frequently (Kondolf et al., 2003). Furthermore, the set of distinguishing morphological attributes may vary between biogeographical regions and may be degraded or reduced by human interventions, but a check-list of the units that may be present within the channel and its floodplain is provided in Table S2 (Supplementary Data) as a starting point.

### *2.4 Floodplain Typology (FT)*

The extended classification of river types is designed to provide a simple means for managers to allocate a river reach to a type. In many cases the observed planform may be an artifact of human modifications to the reach or of conditions within larger spatial units that influence the reach. However, the presence of geomorphic units, bed sediment particle size and apparent channel stability that are appropriate to the river type provide evidence concerning whether or not a particular reach is functioning in accordance with its type. Since alluvial rivers provide the sediments to build their floodplains, the characteristics of the floodplain provide further evidence that the river is functioning in an appropriate way for its type (e.g. Brierley and Fryirs, 2005). In addition, for rivers that have been subject to significant human-modification, floodplain features and the floodplain type indicate the river type that may have existed prior to human modification. Furthermore, where there has been an historical change in the river type, the floodplain type provides an indication of the past character and trajectory of change experienced by the river.

Nanson and Croke (1992) proposed a genetic classification of floodplains based on river energy (bankfull unit stream power) and floodplain sediments (non-cohesive or cohesive), that is a relatively simple tool suited to the present management-oriented applications. Therefore, this classification has been adapted to recognise broad categories of floodplain and link them to the extended river types that may have constructed them. Table 2 summarises 10 broad types of floodplain that are likely to be encountered widely across Europe, and a further three types (described by Nanson and Croke for semi-arid environments), which may have some relevance to the driest parts of Europe.

In relation to Table 2, the following points should be noted:

(i) the term ‘floodplain’ is used quite loosely, since confined or partly-confined rivers may only show patchy marginal sediment accumulations or disconnected pieces of floodplain. Furthermore, no specific information is provided on the degree of activity of this surface: ‘floodplain’ can be used to classify a modern floodplain or a recent terrace, i.e. a previously active floodplain that has become a terrace due to channel bed incision over recent decades to centuries.

(ii) The river types listed in the first column of Table 2 are indicative types: in some cases other (adjacent) types (Table 1) may be associated with similar floodplain features.

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

(iv) The floodplain sediment size classes (gravel, sand, etc.) listed in Table S3 (Supplementary Data) are generally finer than the bed material size listed for the river types in Table 1, reflecting the nature of the floodplain rather than river bed sediments.

(vi) The geomorphic units listed in the Table S3 are floodplain units, whereas those in Table S2 are mainly channel and channel margin units. Analysis of geomorphic units provides insights into the balance of erosional and depositional processes and process-form linkages along a given stretch of river.

### *2.5 Flow Regime Type (FRT)*

A classification of Flow Regime Types (FRT) applicable to European rivers (Bussettini et al., 2014) is summarised in this section. Starting from the flow regime classification scheme proposed by Poff & Ward (1989) and Poff (1996) for streams in the United States, several schemes have been devised, with some adaptations, for European application (e.g., Oueslati et al., 2010). The classification scheme adopted for the present application incorporates the following characteristics: (i) intermittency; (ii) groundwater – surface water interaction (Boni et al., 1993); (iii) prevailing type of flow source (Poff and Ward, 1989; Poff, 1996).

The classification is based on threshold values (Figure 4) of the hydrological indicators summarised in Table S4 (Supplementary Data). Compared to the scheme of Poff & Ward (1989) and Poff (1996), where a temporary flow regime is based on the extent of intermittency, with the threshold for perennial flow fixed at ten days of zero flow conditions (zero discharge) within a year, the classification developed here (Table 3) assumes a more restrictive threshold, defining "permanent" regime rivers as those having surface channel flow throughout the entire year. The threshold 'ZERODAY'≥1 separates 'intermittent' from 'perennial' regimes. Subdivision of 'intermittent' regimes adopts different values of 'ZERODAY' from those suggested by Poff & Ward (1989) and Poff (1996), which have been previously identified and calibrated on the rivers of the Mediterranean areas of Europe by Oueslati et al. (2010). The subdivision of 'perennial' flow regimes employs threshold values of several indicators (FLDPRED, FLDTIME, BFI, DAYCV, Figure 4). A long-term series of daily flow data (average daily flow) is required for application of this method; at least 20-years of records are needed for a robust analysis (Huh et al. 2005). The classification model assigns a hydrological type to each gauged stream or to any whose discharge time series has been estimated. Within the hierarchical framework, the flow regime type (FRT) is estimated at the segment scale, since variability of flow regime typically occurs at a larger spatial scale than the reach, mainly related to the confluence of major tributaries. Therefore, reaches are allocated to the FRT of the segment within which they are located.

### *2.6 Groundwater – Surface water Interactions (GSI)*

A critical hydrological aspect of the 22 extended river types that strongly affects their flow regime, water quality, morphology, as well as their ecology is the nature and extent of any groundwater-surface water interactions (GSI) (Klijn and Witte, 1999; Blum et al., 2009; Van der Velde et al. 2009; Rozemeijer et al., 2010; Price, 2011; Hendriks et al., 2013; Hendriks et al., 2014a). Therefore, GSI have been incorporated into the categorisation of river types.

Figure 5 summarizes the GSI processes and their feedbacks with morphology and ecology in the river, the riparian zone and the catchment. One important aspect of the ecology, which feeds back into river morphology and the flow regime, is the type, vigour and biomass of the riparian and aquatic vegetation that is present. This is heavily dependent upon water availability (access to soil moisture and near-surface groundwater), flow regime, and water quality (Gurnell, 2014).

Relevant GSI act at various scales: the (sub-)catchment or landscape unit scale, the reach scale, and the local scale. Dahl et al. (2007) described these GSI scales, respectively, as the hydrogeological setting of the catchment and regional geomorphology (catchment scale), the hydrogeological setting adjacent to the riparian area (reach scale), and the dominant flow path through the riparian area (local scale). The GSI at the catchment scale mainly affects the water availability, flow regime, and general water quality of the river. For instance, rivers or river segments in (sub-) catchments or landscape units with a hydrogeology consisting of solid bedrock or thin, shallow aquifers depend largely on precipitation for their runoff and will run dry during periods of drought. The water quality of such rivers is mainly determined by the composition of the rain water or snow melt and shallow soil processes. On the other hand, rivers or river segments in (sub-) catchments or landscape units with thick and well-connected sandy aquifers with high permeability show high base flow and are much more resilient to drought, because the aquifers provide substantial inflow of (deep) groundwater to the streams in the catchment (seepage). The water quality in such rivers is strongly affected by geochemical processes within the aquifers underlying the catchment.

At the reach scale, the GSI is determined by a combination of the hydrogeological setting adjacent to the riparian area and whether the river is predominantly confined (small riparian area) or unconfined (large riparian area). At this scale, GSI can affect both the (ground) water level, the water quality and water temperature in the river and the riparian zone. Confined river reaches with a hydrogeological setting of bedrock will undergo very little or no effects of GSI at the reach scale, while unconfined reaches with a thick phreatic aquifer are subjected to extensive GSI through the river bed and in the riparian zone. In circumstances where the phreatic aquifer at the reach scale is well connected with deeper, regional aquifers, water availability and water quality at the reach scale is also affected by the groundwater conditions in a larger part of the catchment.

At the local scale, the GSI flow path can be dominated by diffuse flow, overland flow, or drainage (artificial or induced by roots or animals) through the riparian zone, or by direct GSI through the river bed (Dahl et al., 2007). These flow paths affect the local water quality and water temperature, as well as the local (ground) water level and soil moisture conditions (Rozemeijer et al., 2010). For present purposes, the scale of these local GSI processes may appear too small. However, if a certain type of local GSI is dominant in larger parts of the catchment, this can have a significant effect on the flow dynamics and water quality of larger parts of the river. For instance, catchments with large areas of (artificial) drainage are often characterised by more frequent and higher peak flows. Also, the effect of soil composition and processes on water quality is different in areas where drainage is dominant over diffuse flow or overland flow. Hence, for a complete characterisation of GSI it is sensible to determine the dominant local GSI process at the reach scale.

For the present purpose, a simplified GSI characterization has been developed to cover the most important aspects of GSI for each of the 22 extended river types. . A brief description of the general GSI characteristics of these types at the (sub-)catchment or landscape unit scale, the reach scale, and the local scale is given in Table 4, although it should be kept in mind that, depending on the specific regional and local hydrogeological and morphological circumstances, large differences in GSI may occur.

### *2.7 Temporal changes*

The use of the classification framework is not limited to the characterization of channel and floodplain in their current condition, since this would provide a static view, lacking consideration of river processes and temporal adjustments, which is one of the main limitations of many geomorphic classifications (Kondolf et al., 2003).
A temporal analysis recognises that fluvial systems are dynamic and may follow a complex trajectory through time in response to different driving variables acting at various spatial and temporal scales (e.g., Brierley et al., 2008; Dufour and Piégay, 2009). Therefore, the present morphological and hydrological classifications are intended to be initially applied to the contemporary channel and floodplain, but then to be used in an historical analysis that contributes to an understanding of change in river conditions and controlling factors. Having reached an understanding of how the river has changed over time in response to different influencing factors, based on application of the full REFORM hydromorphological framework (Gurnell et al., 2015), prediction of future channel and floodplain evolution can be also attempted.
A minimum level of historical analysis is required to assess historical channel changes, consisting of a characterization of channel (and floodplain) morphology, and, depending upon data availability, a complementary hydrological analysis (Grabowski et al., 2014). Ideally such an analysis could extend back over a time frame of 100 years or more. For example, historical topographic maps spanning the late XIX century or aerial photographs from the 1930s – 1960s generally provide very valuable information on past channel and floodplain morphology and conditions. Furthermore, analysis of a complete set of available aerial images can provide deep insights into the evolutionary trajectory of river changes including phases of evolution and possible cause-effect relationships, which can be complemented by data sets relating to other spatial units within the REFORM hydromorphological framework (Gurnell et al., 2015).

## 3 Testing and applications

The river typology has been tested within the context of the REFORM project for a range of case studies which are representative of a wide variety of catchment conditions at the European level (Gurnell et al., 2014).
In this section, we provide some examples of applications from four rivers: Frome (catchment area: 459 km$^2$), southern England; Porma (catchment area: 1145 km$^2$) and Curueño (catchment area: 293 km$^2$), north-western Spain; and Magra (catchment area: 1700 km$^2$), central-northern Italy. These examples are used to briefly illustrate some components of the classification and characterization (further details on these case studies are reported in Grabowski and Gurnell, 2015; González Del Tánago et al., 2015; and Belletti et al., 2015, respectively). The classifications of the river types and the other main components of the fluvial systems are summarised in Table 5.
Channel morphologies within the four catchments show a wide range of types, depending on different physical conditions and controlling factors. The Porma, Curueño, and Magra catchments exhibit a relatively similar range of river types (e.g. Figure 6). The upper portions of the catchments are characterised by confined, straight or sinuous morphologies with bedrock or coarse bed sediment (types 1, 2, 6, 7). The alluvial segments of the middle reaches are dominated by partly confined or unconfined, predominantly gravel, wandering, braided, or pseudomeandering channels (types 9, 11, 12), as a result of their relatively high energy, and abundant bedload. The most downstream reaches are unconfined pseudomeandering (type 12, Porma catchment), and unconfined sinuous (type 13, Magra catchment). In contrast, the Frome river reaches are characterised by an unconfined, very low gradient and

low energy setting, with sinuous (type 17), meandering (type 18), and low-energy anabranching (type 19) river types and predominantly sand-gravel bed sediment.

In relation to the types of floodplain present, those of the entire Frome river network have been heavily modified for agriculture over several centuries, including the widespread construction of ditch networks for water-spreading and drainage, and ploughing of cultivated areas. As a result, many floodplain geomorphic units are no longer identifiable. However, the presence of sinuous side channels, wetlands, and ponds (often oxbows) and occasional scroll-like features, indicate the occurrence of degraded anabranching floodplains (type J) associated with reaches with type 19 channels, and lateral migration to stable (type G/I) floodplains associated with river types 17 and 18.

Floodplain types along most of the middle alluvial segments of the Magra river can be classified as type C (braided) or D (wandering). Within the Porma and Curueño catchments, floodplain types range from type B (confined, vertical accretion) along upper segments, to type D (wandering, gravel bed) in the downstream portion of the Curueño and the middle Porma, to type E (lateral migration, non-scrolled) along the most downstream reaches of the Porma. As for the Frome, a common characteristic of these rivers is that their floodplains, especially in downstream reaches, have suffered a significant loss of geomorphic features and functionality, as a result of human activities (agriculture, urbanization).

The different climatic, topographic and geological conditions of the example rivers are reflected in contrasting flow regime types. The River Frome has a perennial stable or super-stable flow regime, reflecting very strong GSI with the alluvial aquifer and underlying Chalk (limestone) bedrock. In contrast, the flow regimes of the upper and middle reaches of the Magra are classified as perennial flashy and perennial runoff, respectively. In the case of the Porma and Curueño rivers, their natural flow regimes mostly correspond to perennial flashy, although nowadays the middle and lower reaches of the Porma river are regulated by a large dam and exhibit a perennial stable and perennial flashy flow regime, respectively. The partly confined or unconfined alluvial segments of the Magra, Porma, and Curueño, are also characterised by extensive GSI with the phreatic groundwater body at the reach scale. However, the higher energy and perennial flashy or perennial runoff regimes along the Magra, Curueño and unregulated segment of the Porma, reflect a less stable and seasonally variable phreatic level compared to the Frome.

A detailed characterization of temporal changes of morphological types of the four case studies has also been conducted (Gurnell et al., 2014). Despite agricultural intensification, the River Frome has experienced very limited morphological changes over the last 100 years that have not affected the river types that are present. Overlays of the channel position extracted from the earliest and most recent Ordnance Survey maps (Figure 7), illustrate a reach showing some of the largest lateral movements (Figure 7A) and a more typical level of lateral movement (Figure 7B), with the largest changes attributable to human cut-offs of river bends. The main channel changes that have been observed along the Frome are channel narrowing and accumulation of fine sediment within and on the river bed with no change in river type in this low-energy, groundwater-dominated system. However, application of the REFORM framework has revealed within-channel changes connected to catchment-wide changes in fine sediment delivery, transfer and storage that present significant management issues (Grabowski and Gurnell, 2015).

Significant changes in river type have occurred in the Porma and Magra catchments, in response to a series of human modifications of some of the controlling factors that are revealed by application of the REFORM framework (Gonzalez del Tánago, 2015; Belletti et al., 2015). Channel morphologies of some reaches of the Magra and Porma, observed on aerial photos from 1954 and 1956 (Figure 8) can be compared with the contemporary morphology of the same reaches (Figure 6).

Changes in river type for some reaches of the middle-lower Magra River, denote an overall decrease in the quantity of sediment in the river system as a result of a combination of human factors (e.g., afforestation, dams, gravel mining, groynes). When a detailed multitemporal analysis of changes is performed on a complete set of historical maps and aerial photos, more specific information on channel evolution and its association with human factors is obtained (Belletti et al., 2015), including a first phase of minor narrowing and bed incision from about the end of the 19th century to the 1950s, and a second phase of major narrowing and incision after the 1950s (Rinaldi et al., 2009) leading to different possible trajectories of changes (Figure 8). The upper case (Figure 9, case A) represents reaches along which the original braided morphology was maintained despite channel narrowing. In other reaches, island-braided (type 9) reaches changed to wandering (type 11) reaches (Figure 9, case B), and in other reaches wandering (type 11) reaches proceeded to change to pseudomeandering (type 12) reaches (Figure 9, case C).

## 4. Discussion and final remarks

Limitations and strengths of the procedure presented in this paper can be best appreciated if the overall context and aim of the methodology within the REFORM framework (Gurnell et al., 2015) is taken into consideration. Nevertheless, previous river classifications have tended to refer to a single aspect of the river environment (e.g. the channel morphology), but we have presented a combined approach that classifies both morphology and hydrology to provide a broader characterization of the river and floodplain system. Furthermore,  the approach was developed and shared among a large multidisciplinary group within the REFORM project, including stakeholders experienced in river management and restoration. Such collaboration among research scientists and stakeholders from different disciplinary backgrounds is fundamental to creating a common ground of knowledge and promoting successful application of such an approach to management.

A common problem of all ‘special’ classification schemes is the use of classes or categories defined by specific boundaries or limits imposed on natural continua. Because of the variety found in the natural environment, these classes and their boundaries need to be applied flexibly, employing expert judgement based on practical knowledge and experience (Kondolf, 1995; Kondolf et al., 2003). We recognise that this is a limitation of our methodology, but we emphasise that the system is not intended to provide a series of rigid classes or types (channel, floodplain, flow regime, GSI), but rather to support an open ended approach that uses the typologies flexibly and in a way that is appropriate to local circumstances. Furthermore, the set of distinguishing morphological attributes may vary between biogeographical regions, so the morphological criteria we have provided should be taken as a starting point from which a more informed set of criteria can be developed to suit local circumstances. Therefore, although concerns can be raised in relation to operator variance in applying not just a generic set of procedures but also in adopting a relatively open-ended approach (Brierley et al., 2013), we believe that these concerns can be overcome and our approach can deliver numerous benefits as member states of the European Union devise applications to fit local circumstances and requirements.

A second key aspect is that many existing classification schemes have been designed to improve scientific understanding rather than to provide a management tool. As a consequence, application of many existing river classifications requires a high level of scientific knowledge, which often discourages their application by river managers and practitioners. However, our procedure was deliberately designed to be relatively simple and to contribute to guiding understanding for river management.
Conversely, some concerns could also be raised regarding the time and data demands of our approach in comparison with current approaches being used by public agencies. However, recent developments in automated spatial disaggregation and discretization of fluvial features (e.g., Alber and Piégay, 2011; Roux et al., 2015) in addition to more established GIS technologies could support rapid delineation and characterisation of river types and features, further facilitating the application of our typologies by river managers and practitioners.
In addition, these issues regarding apparent complexity are mainly related to the particular background of the operator. With a suitable background knowledge of the underlying principles in fluvial geomorphology, difficulties in the application of the classification and characterization should be minimised, and the small additional effort would be rewarded by an enormous advance in the insights gained.

Another common problem, when used by river management agencies and especially by non-geomorphologists, is that river classification may be seen as the final (and often the only) output of a characterization process, , with the implicit assumption that the channel is completely described once it has been classified (Kondolf et al., 2003). However, in our approach classification of the different components of the river system is the starting point of a characterization process that recognises that rivers are dynamic and that changes of type can occur through time in response to variations in controlling factors. The classification of the river provides a basic framework for linking channel morphology, driving variables, and boundary conditions and for then elaborating upon these links, as has been illustrated in our example applications. A full understanding of forms and processes under current conditions is essential to set the river and its floodplain in an evolutionary context.
Concerning the applicability of the classification procedure, the methodology has been applied to a sufficiently wide range of conditions across Europe to demonstrate its appropriateness for the European context. However, we believe that it has the potential to be adopted in other non-European countries because it is based on physical processes, indicators, and criteria that have a general application and because the approach is open ended, so that other types of river channel, floodplain, flow regime and GSI found in a specific physical context could be added.
The broad understanding of river types and their response to changes in controlling factors (i.e. flow regime, sediment supply, gradient slope, vegetation) generated by changes within catchment to reach scale spatial units, is fundamental to the development of sustainable river management strategies. The REFORM framework (Gurnell et al., 2015) and its approach to typing rivers aims to support managers in this endeavour. In particular, variability of river types is determined by those factors which also exert some control on river behaviour, sensitivity, and instability. Therefore, the ERT can be used as the basis for a preliminary assessment of the river's capacity for adjustment or sensitivity, which is determined by the range of processes that are feasible for the setting characterising each river type. For example, confined single-thread channels (e.g., bedrock, colluvial, alluvial cascade and step pool) are associated with the lowest capacity for adjustment, as confinement prevents

lateral mobility, and vertical change is impeded by bedrock or coarse alluvial material. Unconfined single-thread, low energy rivers also generally show low sensitivity, whereas unconfined, high energy, braided or wandering rivers have a much higher capacity for adjustment. Although the river type provides rather basic information, the assessment of temporal changes in type allows a more detailed, reach-scale evaluation of the actual capacity for channel adjustments in relation to the extent and rates of changes or the proximity of the river reach to some threshold condition.

Finally, the classification approach proposed here may have important benefits for the application of the European WFD, which seeks to assess hydromorphological as well as ecological functioning and whose main objective is the achievement of water bodies of good ecological status, based on type-specific reference conditions (corresponding to unaltered hydromorphological and physical-chemical conditions in the related river type site). Because the approach incorporates only the physical controls over hydromorphological processes and forms, and thus is independent of any responses of aquatic species or communities, the river types are not affected by any inherently biotic pre-conceptions, which could lead to a circularity in the overall ecological assessment of hydromorphological condition and function (i.e. a site is judged to be in reference condition for its hydromorphological quality and the separate assessment of ecological status then shows it to be in reference condition for that quality element, see Hildrew et al, 2009). In our opinion, this makes the developed river typologies more consistent with the rationale behind the WFD.

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Table 1 – Main characteristics of the 7 Basic River Types and the 22 morphological types of the Extended River Typology. ERT: Extended River Type; BRT: corresponding Basic River Type; C: Confined; PC: Partly confined; U: Unconfined. In bold: dominant bed material type/size.

| ERT (BRT) | Confinement class | Bed material size | Planform | Typical slope (m m$^{-1}$) |
|---|---|---|---|---|
| *Heavily Artificial* | | | | |
| 0 (0) | C, PC, U | Artificial | Any | Any |
| *Bedrock and Colluvial Channels* | | | | |
| 1 (1) | C | **Bedrock** | Straight-Sinuous | Usually steep |
| 2 (1) | C | **Coarse mixed** | Straight-Sinuous | Steep |
| 3 (1) | C | **Mixed** | Straight-Sinuous | Lower than ERTs 1 and 2 |
| *Alluvial Channels* | | | | |
| 4 (1) | C | **Boulder** | Straight-Sinuous | >>0.04 |
| 5 (1) | C | **Boulder**, Cobble | Straight-Sinuous | >0.04 |
| 6 (1) | C | Boulder, **Cobble**, Gravel | Straight-Sinuous | >0.02 |
| 7 (1) | C | Cobble, **Gravel** | Straight-Sinuous | >0.01 |
| 8 (6) | C, PC, U | **Gravel**, Sand | Braided | <0.04 |
| 9 (6) | C, PC, U | **Gravel**, Sand | Island-Braided | <0.04 |
| 10 (7) | C, PC, U | **Gravel**, Sand | Anabranching (high energy) | <0.01 |
| 11 (5) | C, PC, U | **Gravel**, Sand | Wandering | <0.04 |
| 12 (3) | C, PC, U | **Gravel**, Sand | Pseudo-meandering | <0.04 |
| 13 (2/3) | PC, U | **Gravel**, Sand | Straight-Sinuous | <0.02 |
| 14 (4) | PC, U | **Gravel**, Sand | Meandering | <0.02 |
| 15 (6) | C, PC, U | Fine Gravel, **Sand** | Braided | <0.02 |
| 16 (3) | C, PC, U | Fine Gravel, **Sand** | Pseudo-meandering | <0.02 |
| 17 (1/2) | PC, U | Fine Gravel, **Sand** | Straight-Sinuous | <0.02 |
| 18 (4) | PC, U | Fine gravel, **Sand** | Meandering | <0.02 |
| 19 (7) | C, PC, U | Fine Gravel, **Sand** | Anabranching | <0.005 |
| 20 (2/3) | PC, U | Fine Sand, **Silt**, Clay | Straight-Sinuous | <0.005 |
| 21 (4) | C, PC, U | Fine Sand, **Silt**, Clay | Meandering | <0.005 |
| 22 (7) | C, PC, U | Fine Sand, **Silt**, Clay | Anabranching | <0.005 |

Table 2 – Classification of floodplains.

| ERT | Floodplain Class | Floodplain Type | Bankfull unit stream power (W $m^{-2}$) |
|---|---|---|---|
| (1), 2, 4, 5 | High energy, non-cohesive floodplains | A. Confined, coarse textured | > 1000 |
| 3, 6, 7 | | B. Confined, vertical accretion | 300 – 1000 |
| 8, 9, 15 | Medium energy, non-cohesive floodplains | C. Braided | 50 – 300 |
| 10, 11 | | D. Wandering, gravel-bed | 30 – 200 |
| 12, 13 | | E. (Sinuous / meandering) lateral migration, non-scrolled | 10 – 60 |
| 13, 14 | | F. (Sinuous / meandering) lateral migration, scrolled | 10 – 60 |
| 16, 17, 18 | | G. (Sinuous / meandering) lateral migration, backswamp | 10 – 60 |
| 17, 18 | | H. (Partly-confined, sinuous / meandering) lateral migration, counterpoint | 10 – 60 |
| 20, 21 | Low energy, cohesive floodplains | I. Laterally stable | < 10 |
| 19, 22 | | J. Anabranching (low energy), organic rich | < 10 |
| Floodplain types defined by Nanson and Croke (1992) that are unlikely to be encountered in Europe | | | |
| 20 (semi-arid) | High energy, non-cohesive floodplains | K. Unconfined, vertical accretion, sandy | 300 – 600 |
| 16 (semi-arid) | | L. Cut and fill | ~ 300 |
| 19, 22 (semi-arid) | Low energy, cohesive floodplains | M. Anabranching (low energy), inorganic | < 10 |

Table 3 – Classification of Flow Regime Type

| Class | Definition |
|---|---|
| *I. Temporary streams* | |
| 1. Harsh Intermittent (HI) | Streams without flow for almost the whole year. Flow is activated during intense rainfall (e.g., streams of the Southern Europe and Mediterranean areas). |
| 2. Intermittent Flashy (IF) | Streams with runoff in the river bed for less than 8 months/year; runoff is present occasionally, because of rainfall, snowmelt or seasonal fluctuations of the aquifer level. |
| 3. Intermittent Runoff (IR) | Stream with runoff in the river bed for more than 8 months/year. |
| *II. Perennial rivers fed predominantly by snowmelt* | |
| 4. Perennial Snowmelt (SN) | Streams prevailingly fed by snow and glacier melt. |
| 5. Perennial Snow-rain (SR) | Streams fed by a mix of surface runoff and snow melt. |
| *III. Perennial rivers fed predominantly by groundwater* | |
| 6. Perennial Super-stable (SS) | Rivers with very low variability of the flow regime; in the case of unregulated rivers (natural regime), these are predominantly groundwater fed (baseflow). |
| 7. Perennial Stable (SG) | Rivers having a stable flow regime, due to the regulation effect of groundwater; in the case of unregulated rivers, flow is predominantly fed from groundwater (baseflow). |
| *IV. Perennial rivers fed predominantly by surface runoff* | |
| 8. Perennial Flashy (PF) | Rivers fed predominantly by surface runoff (quick flow), with high flashiness of floods. Flow regime is highly influenced by intense flood events and seasonal droughts. |
| 9. Perennial Runoff (PR) | Rivers fed predominantly by surface runoff (quick flow) and groundwater (baseflow). Flow regime is characterized by low seasonal variability. |

Table 4 – Typical Groundwater – Surface water Interactions (GSI). In bold: dominant bed material type / size.

| ERT | Bed material size | Typical GSI |
|---|---|---|
| *A. Confined bedrock and colluvial channels* | | |
| 1 | **Bedrock** | No GSI or limited GSI with the phreatic aquifer formed by the colluvial material. Additionally, if permeable faults or fracture zones are present, local GSI occur in these zones. Local flow paths are likely to be dominated by direct exchange through the river bed material and overland flow over bedrock river banks. |
| 2 | **Coarse mixed** | |
| 3 | **Mixed** | |
| *B. Confined alluvial channels on coarse substrates* | | |
| 4 | **Boulder** | Local GSI with the phreatic groundwater body via the river bed. Where the phreatic aquifer is connected to deeper groundwater bodies, GSI at the (sub-)catchment scale with deep semi-confined aquifers occurs. Local flow paths are likely to be dominated by overland flow on the river banks and direct exchange through the river bed. |
| 5 | **Boulder**, Cobble, | |
| 6 | Boulder, **Cobble**, Gravel | |
| 7 | Cobble, **Gravel** | |
| *C. Partly confined, unconfined (or confined multi-thread) alluvial channels on intermediate (gravel-sand) substrates* | | |
| 8-11 | **Gravel**, sand | Extensive GSI with the phreatic groundwater body at the reach scale in the riparian zone (only unconfined reaches) and via the river bed. Where the phreatic aquifer is connected to deeper groundwater bodies, GSI occurs at the (sub-)catchment scale with deep semi-confined aquifers. Local flow paths in the riparian zone are likely to be dominated by diffuse flow or direct exchange through the river bed. |
| 12-13 | | |
| 14 | Fine gravel, **sand** | |
| 15 | | |
| 16-18 | | |
| 19 | | |
| *D. Partly confined, unconfined (or confined multi-thread) alluvial channels on fine (silt-clay) substrates* | | |
| 20-21 | Fine sand, **silt**, clay | Limited and/or localized GSI with the phreatic groundwater body at the reach scale in the riparian zone (only unconfined reaches) and via the river bed. Where the phreatic aquifer is connected to deeper groundwater bodies, GSI occurs at the (sub-)catchment scale with deep semi-confined aquifers. The fine sediment fraction of the substrates prevents large GSI fluxes, and may cause local GSI in zones with higher permeability. Otherwise, local flow paths in the riparian zone are likely to be dominated by overland flow or drainage. |
| 22 | | |

Table 5 – Examples of classification of river, floodplain and flow regime typology, and groundwater-surface water interactions in four catchments (Frome, Magra, Porma, and Curueño). ERT: Extended River Typology (see Table 1), FT: Floodplain Typology (see Table 2), FRT: Flow Regime Type (see Table 3), GSI: Groundwater–Surface water Interactions (see Table 4).

| **River** | **Segment** | **Confinement** | **ERT** | **FT** | **FRT** | **GSI** |
|---|---|---|---|---|---|---|
| Frome | 1 | U | 17 | G | SS | C |
| | 2 | U | 17/18 | G | - | C |
| | 3 | U | 17/19 | G / J | - | C |
| | 4 | U | 17/19 | G / J | - | C |
| | 5 | U | 19 | G / J | SG | C |
| | 6 | U | 18/19 | G / J | SS | C |
| Magra | 1 | C | 1/2 | - | - | A |
| | 2 | C / PC | 6/13 | - | PF | B |
| | 3 | PC / U | 13/12/9/11 | C / D | - | C |
| | 4 | PC | 12 | D / E | PR | C |
| | 5 | U | 11 | C / D | - | C |
| | 6 | U | 11/13 | n.a. | - | C / D |
| Porma | 1 | PC | 7 | B / C | PF | C |
| | 2 | PC | 7 | B / C | S | B / C |
| | 3 | PC | 13 | D | - | C |
| | 4 | PC / U | 12 | D / E | - | C |
| Curueño | 1 | PC | 7 | B | PF | C |
| | 2 | C | 2 | - | PF | A |
| | 3 | PC | 11 | C / D | - | C |

Table S1 - Basic River Typology based on Confinement and Planform

| Type | Valley Confinement | Threads | Planform | *Si* | *Bi* | *Ai* |
|---|---|---|---|---|---|---|
| 0 | Heavily artificial | Any | Any | Any | Any | Any |
| 1 | Confined | Single | Straight-Sinuous | n/a | approx. 1 | approx. 1 |
| 2 | Partly confined / Unconfined | Single | Straight | < 1.05 | approx. 1 | approx. 1 |
| 3 | Partly confined / Unconfined | Single | Sinuous | 1.05 < *Si* < 1.5 | approx. 1 | approx. 1 |
| 4 | Partly confined / Unconfined | Single | Meandering | >1.5 | approx. 1 | approx. 1 |
| 5 | Confined / Partly Confined / Unconfined | Transitional | Wandering |  | 1 < *Bi* < 1.5 | *Ai* < 1.5 |
| 6 | Confined / Partly Confined / Unconfined | Multi-thread | Braided |  | *Bi* > 1.5 | *Ai* < 1.5 |
| 7 | Confined / Partly Confined / Unconfined | Multi-thread | Anabranching |  | *Bi* < 1.5 or *Bi* > 1.5 | *Ai* > 1.5 |

Table S2 – Description of the 22 morphological types of the ERT. Geomorphic units: AB: Alternate bar; AC: Abandoned channel; B: Bar; Be: Bench; BL: Boulder levées; Bs: Backswamp; C: Cascade; CC: Crevasse channel; Ch: Chutes; Co: Cut-off channel; CS: Crevasse splay; F: Forced; G: Glide; I: Island; L: Levées; LB: Lateral bar; MB: Marginal bar; MCB: Mid-channel bar; P: Pool; PB: Point bar; PBe: Point bench; Po: Pond; R: Riffle; Ra: Rapids; RD: Ripples (and Dunes); RS: Rock step; RSw: Ridge and Swale; SB: Scroll bar; Sc: Scroll; SP: Step-Pool; SS: Sand splay; VI: Vegetation induced.

| ERT | Geomorphic Units | Stability | Description |
|---|---|---|---|
| 0 | Possible occasional B | Very Stable | Highly modified reaches |
| 1 | RS, C, Ra | Usually strongly confined and highly stable | Sediment supply-limited channels with no continuous alluvial bed |
| 2 | BL, C, SS, AC | Can be highly unstable | Small, steep channels at the extremities of the stream network |
| 3 | Poorly defined, featureless channels. | Very stable, shallow (often ephemeral) channels | Small, relatively low gradient channels at the extremities of the stream network |
| 4 | C, P | Stable for long periods but occasional catastrophic destabilisation | Very steep with coarse bed material consisting mainly of boulders and local exposures of bedrock |
| 5 | SP | Stable for long periods but occasional catastrophic destabilisation | Sequence of channel spanning accumulations of boulders and cobbles (steps) separated by pools |
| 6 | G, Ra, FB, FP | Relatively stable for long periods, but floods can induce lateral instability and avulsions | Predominantly single thread but secondary channels are sometimes present |
| 7 | R, P, G, LB | Subject to frequent shifting of bars | Coarse cobble-gravel sediments sorted to reflect the flow pattern and bed morphology |
| 8 | MCB, R, P | Usually highly unstable both laterally and vertically | Multiple channels separated by active bars (bar-braided) |
| 9 | I, MCB, R, P | Usually unstable both laterally and vertically | Distinguished from type 11 by > 20% channel area covered by islands of established vegetation |
| 10 | I, R, P | Lateral instability usually present | Islands covered by mature vegetation extend between channels |
| 11 | I, MCB, MB, R, P | Usually highly unstable both laterally and vertically | Exhibit switching from single to multi-thread |
| 12 | Large, continuous AB, R, P | Usually unstable both laterally and vertically | Differs from type 11 in its lower sinuosity and very pronounced alternating lateral bar development |
| 13 | Large alternate (continuous) PB, R, P | Subject to frequent shifting of bars | Sinuous pattern with discontinuous bars of coarse sediment |
| 14 | R, P, PB, Ch, Co, SB, Pbe | Laterally unstable channels subject to lateral migration | Meandering pattern with frequent point bars of coarse sediment |
| 15 | B, RD | Unstable both laterally and vertically | Same morphology of 8 but with predominant sand material |
| 16 | Continuous, large AB, P, RD | Vertically unstable due to bar movement and sometimes migrate laterally | Highly sinuous baseflow and alternating bars within a straight to sinuous channel |
| 17 | R, P, PB, RD, occasional Be, SB, L, Bs | Laterally unstable channels subject to lateral migration | Same morphology of 13 but with predominant sand material |
| 18 | P, PB, RD, S, L, RSw, Bs, AC | Unstable channels subject to meander loop progression and extension with cut-offs | Same morphology of 14 but with predominant sand material |
| 19 | I, RD, L, VIB, VIBe, RD, AC | Stable | Vegetation stabilising bars between channel threads, forming islands that develop by vertical accretion of fine sediment |
| 20 | L, Bs | Very stable | Silt to silt-clay banks often with high organic |

| | | | |
|---|---|---|---|
| | | | content are highly cohesive |
| 21 | L, Bs, Pbe | Very stable | Similar to 20 but with higher sinuosity |
| 22 | I, L, CC, CS, Po, VIB, VIBe, AC, Bs | Very stable | Silt to silt-clay banks often with high organic content are highly cohesive; extensive islands covered by wetland vegetation |

Table S3 – Floodplain sediments and geomorphic units.

| Floodplain Type | Sediment | Geomorphic Units |
|---|---|---|
| A. Confined, coarse textured | Poorly sorted boulders and gravel with some sand and buried soils | Boulder levées, sand / gravel splays; back / abandoned channels, scour holes, usually thin overbank deposit of fine alluvium |
| B. Confined, vertical accretion | Basal gravels with an overburden of abundant sand with silt | Large levées, deep back channels, scour holes |
| C. Braided | Gravels with sand and occasional silt usually showing a fining-upwards sequence | Undulating floodplain comprised of the aggrading surfaces of abandoned channels, bars, and islands |
| D. Wandering, gravel-bed | Gravels, sands, silts and organic sediments | Complex undulating floodplains comprised of the aggrading surfaces of features associated with both braided and single thread river floodplains including abandoned channels; point, lateral and medial bars; and islands |
| E. Lateral migration, non-scrolled | Sands with some gravels | Gently undulating, smooth floodplain surface, sometimes with abandoned channels |
| F. Lateral migration, scrolled | Sands with some gravels | Undulating floodplain surface incorporating distinct parallel scrolls or ridges with intervening swales and occasional backswamps in lower lying areas |
| G. Lateral migration, backswamp | Sands, silts and organic sediments | Flat to undulating floodplain surface featuring ridge and swale topography with extensive smooth areas of vertically accreted fine sediments often associated with extensive backswamps and ponding on distal areas of the floodplain |
| H. Lateral migration, counterpoint | Sands, abundant silts and organic sediments | Parallel ridges and parallel to tightly curving meander bends, low areas between the ridges often poorly drained and so may contain linear wetland areas |
| I. Laterally stable | Silts, clays and organic material | Flat floodplains with low levées, sand splays and sometimes backswamps indicative of poor drainage |
| J. Anabranching (low energy), organic rich | Abundant silts and clays with some sands and gravels and abundant organic / lacustrine deposits | Flat floodplains with extensive islands, often bordered by levées; crevasse-channels and splays, lakes and peat swamps. |
| Floodplain types defined by Nanson and Croke (1992) that are unlikely to be encountered in Europe | | |
| K. Unconfined, vertical accretion, sandy | Predominantly sands with interbedded muds | Flat floodplain surface lacking major levées around channels. Channels alternate between wide relatively straight and narrow sinuous states |
| L. Cut and fill | Sands, silts and organic sediments | Flat floodplain surface with little surface relief around channels that oscillate between shallow sinuous channels and deeply incised flat-bedded gullies. |
| M. Anabranching (low energy), inorganic | Abundant silts and clays with some sands and gravels and little organic matter | Flat floodplains with extensive levees, islands and flood basins, crevasse-channels and splays; relatively sparse vegetation; floodplain braid-channels free of trees, very broad and shallow and may initiate at, terminate at or cross over the anabranching channels |

Table S4 – Hydrological indicators used for the classification of Flow Regime Types.

| Acronym | Extended name | Definition |
|---|---|---|
| DAYCV | Daily discharge coefficient of variation (%) | Average (across all years) of the standard deviation of daily discharge divided by the annual mean discharge (× 100) |
| FLDFREQ | Flood frequency (1/yr) | Average number of floods per year with dis- charge higher than the mean annual maximum daily discharge (flood threshold) |
| FLDPRED | Seasonal flood predictability | Maximum proportion of all peaks over the discharge threshold (POT) that falls in one of the twelve "60-day seasonal windows" (Jan-Feb,..., Dec-Jan), divided by the total number of POTs. |
| FLDTIME | Timing of floods (day) | First day of the 60-day seasonal windows when FLDPRED is highest. The first 60-day period is January-February and the last one is December-January |
| BFI | Base Flow index (%) | Proportion between the "minimum of monthly discharge" and "mean monthly discharge', multiplied by 100 |
| ZERODAY | Extent of intermittency (number of days) | Average annual number of days having zero discharge |

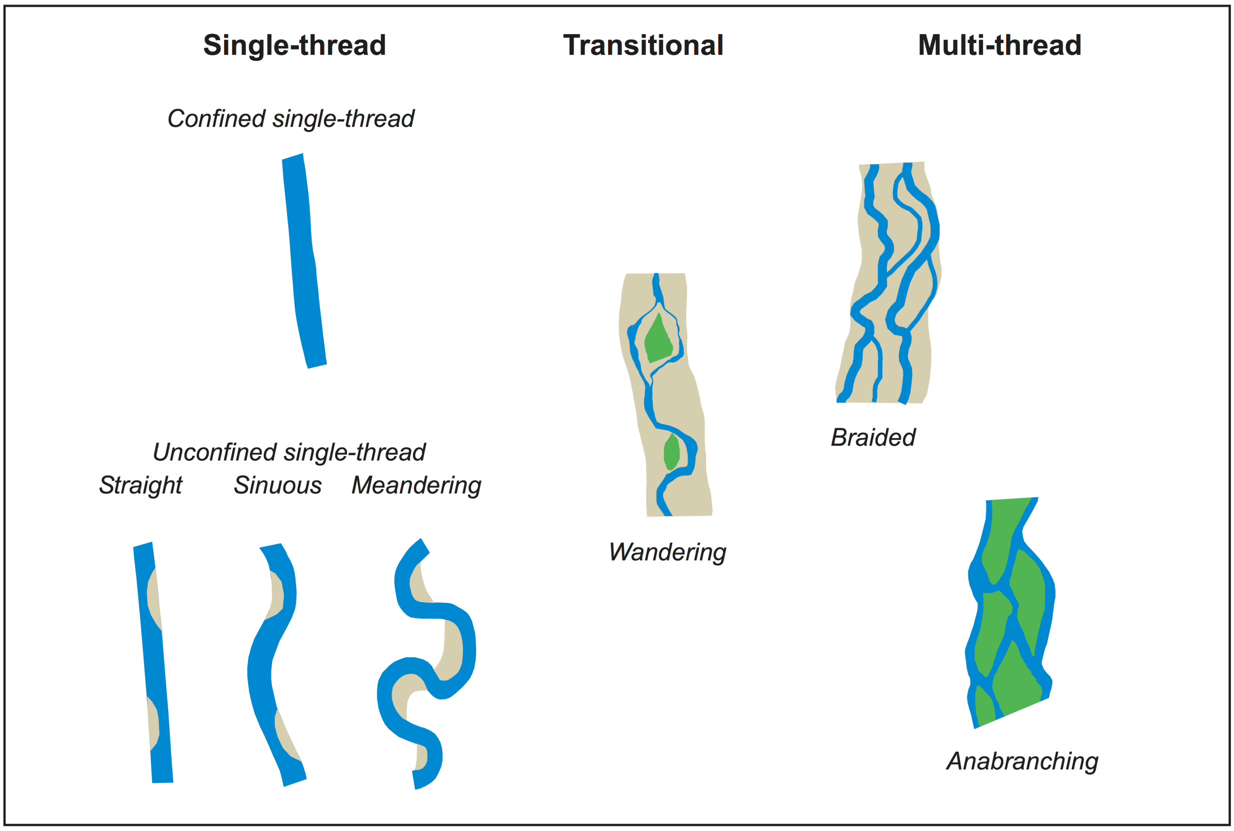

Figure 1 - The seven river types of the Basic River Typology.

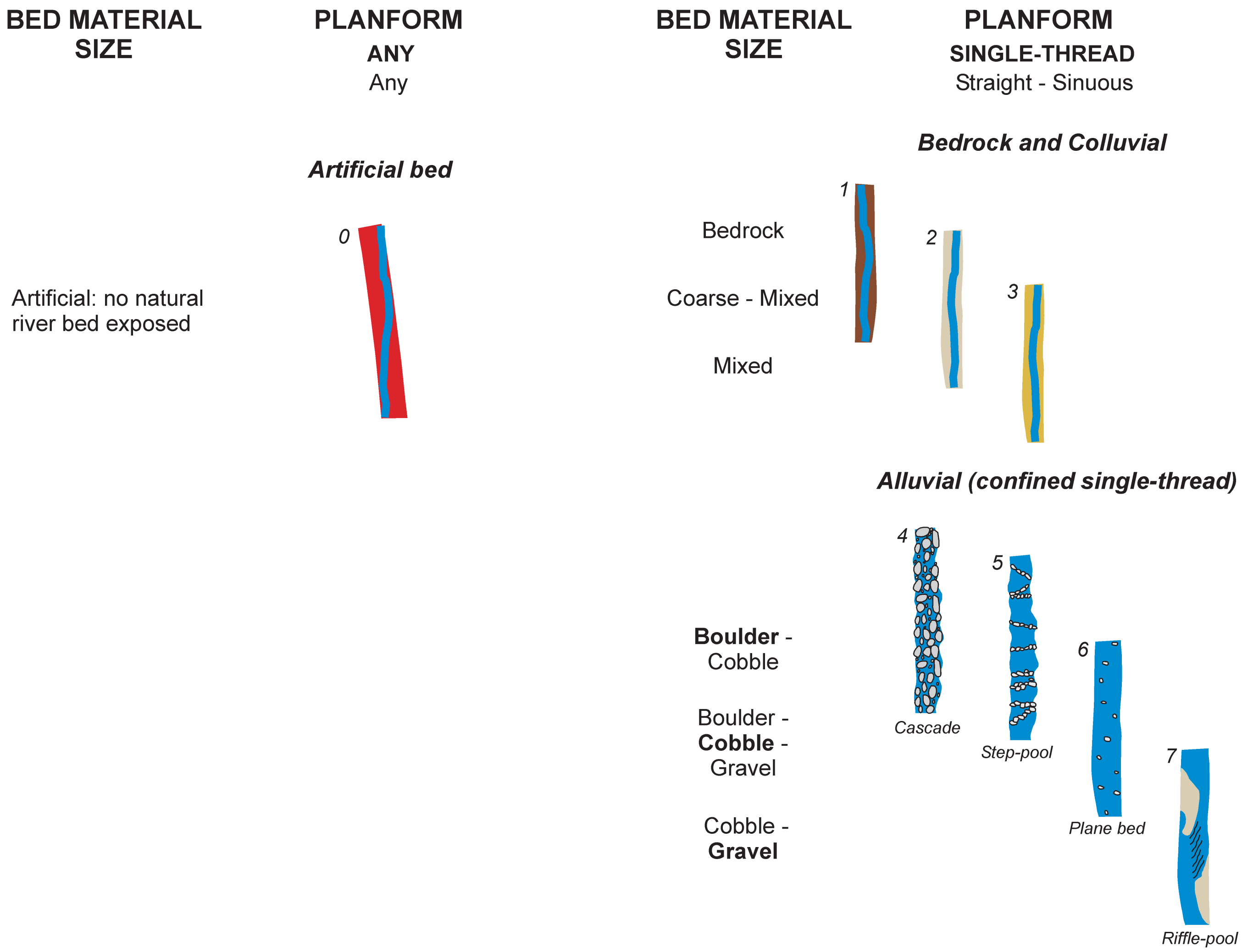

Figure 2 - River types 0 to 6 of the Extended River Typology.

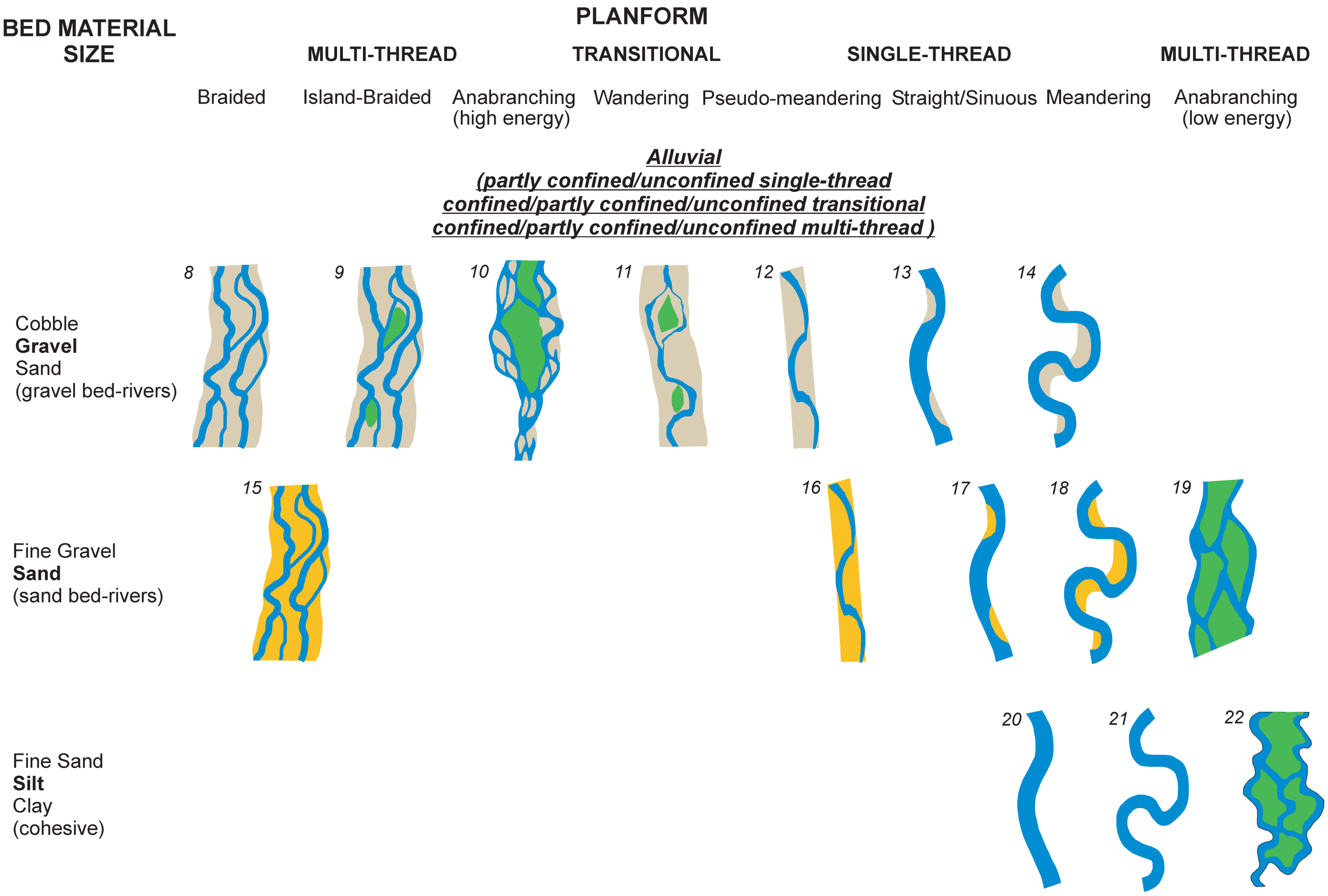

Figure 3 - River types 7 to 22 of the Extended River Typology.

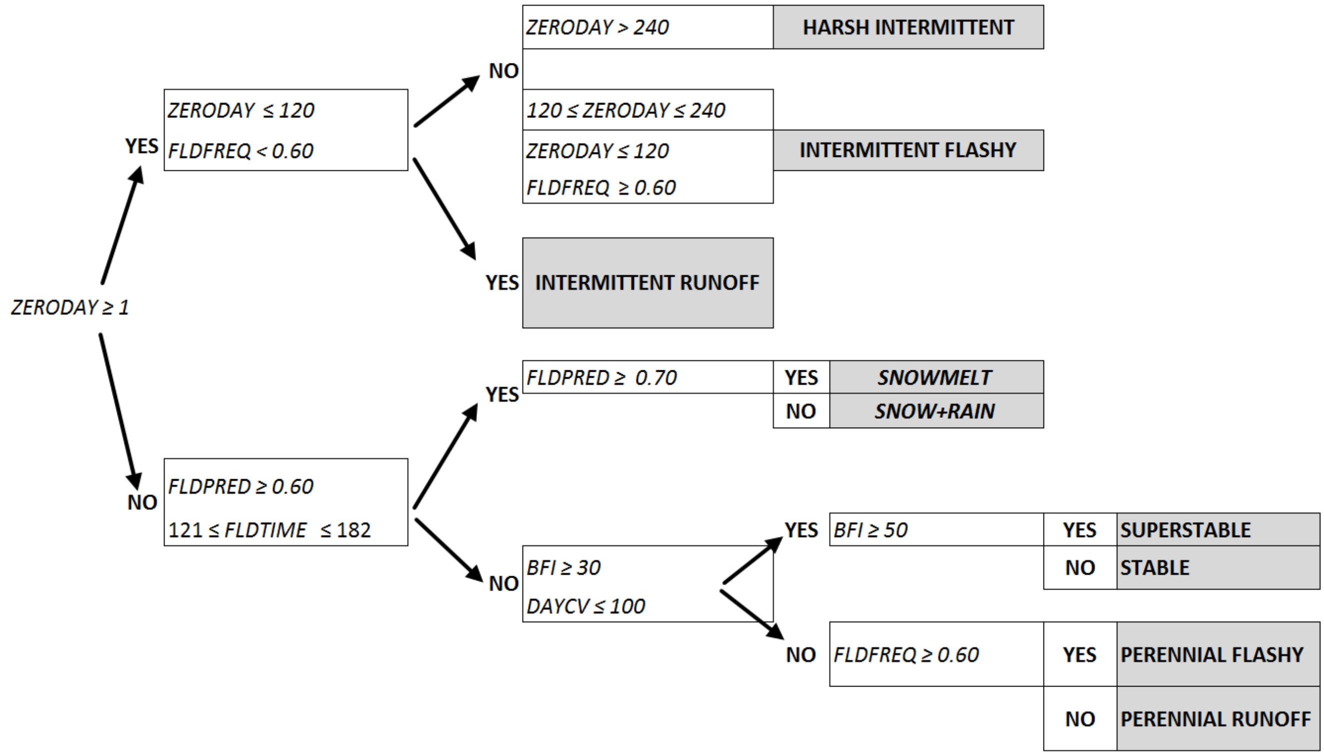

Figure 4 – Flow diagram illustrating the Flow Regime Classification (from Bussettini et al., 2014).

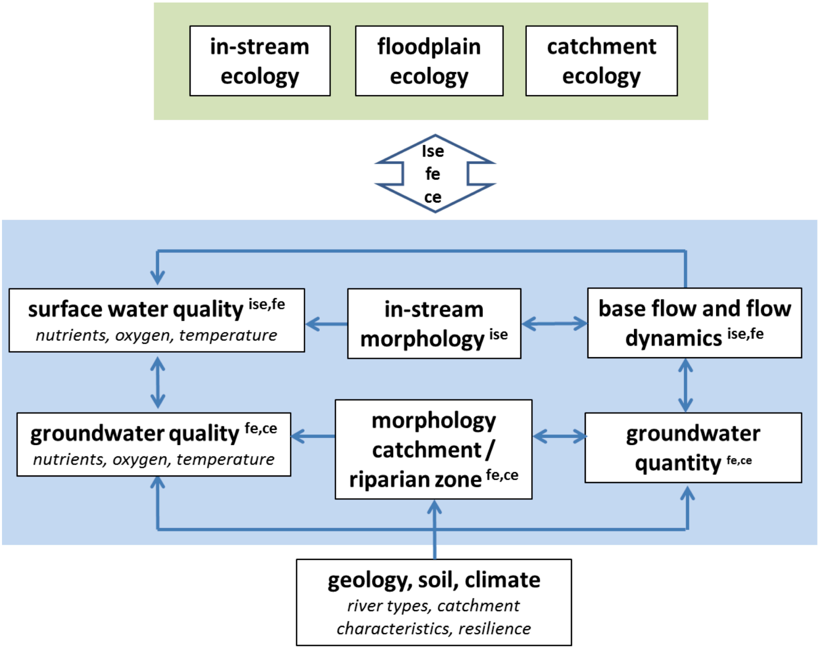

Figure 5 – Schematic diagram of groundwater - surface water interaction and its feedbacks with morphology and ecology. In the blue box, the abiotic aspects and their interactions are shown. The superscripts indicate feedbacks with the in-stream ecology (ise), floodplain ecology (fe), and ecology in the rest of the catchment (ce) (based on Hendriks et al., 2014b).

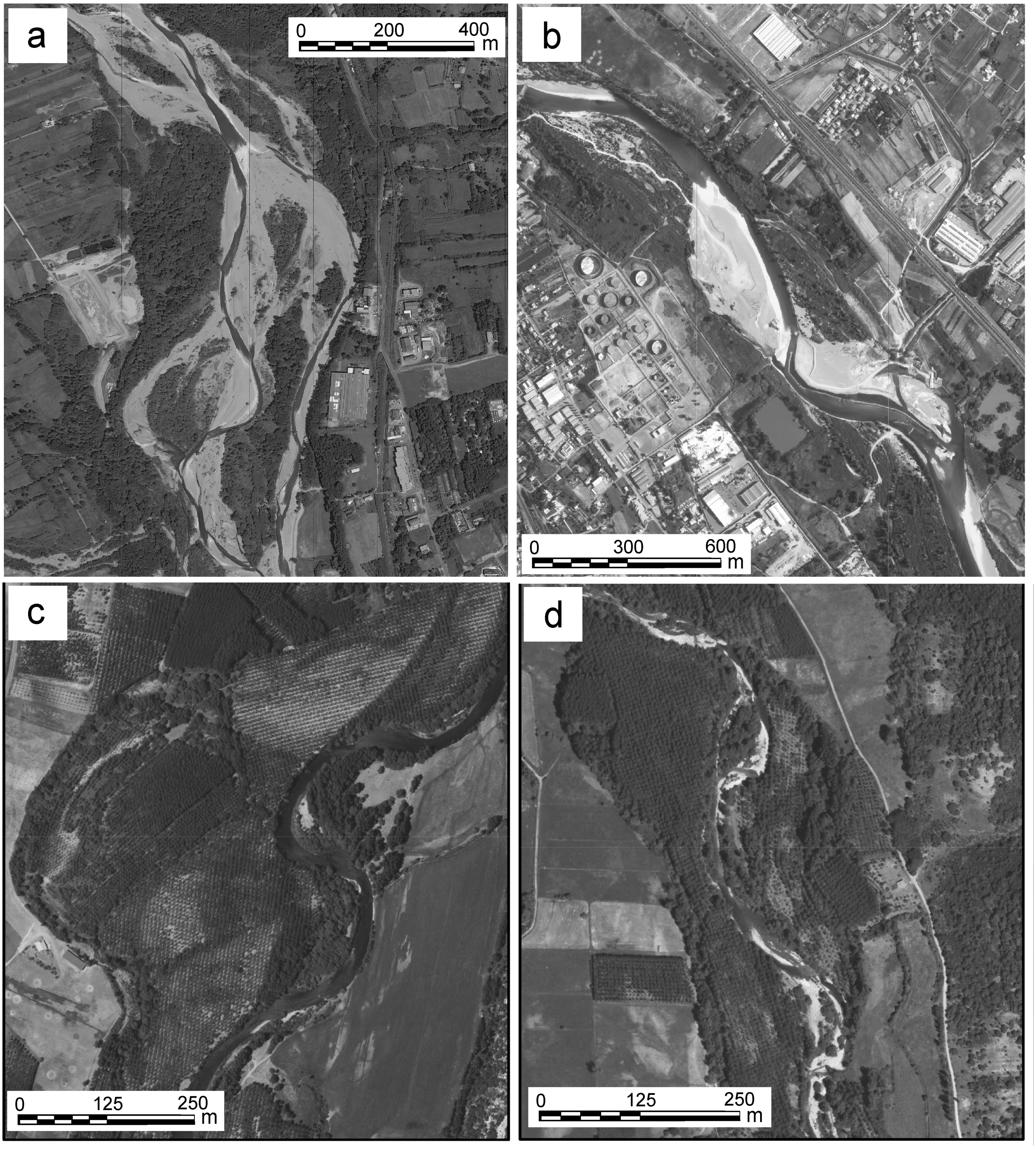

Figure 6 – Examples of river types observed in the catchments of the Magra (central-northern Italy), Porma and Curueño (north-western Spain). A: Island-braided reach (type 9, Magra River); B: wandering reach (type 11, Magra River); C: Pseudo-meandering reach (type 12, Porma River); D: wandering reach (type 11, Curueño River).

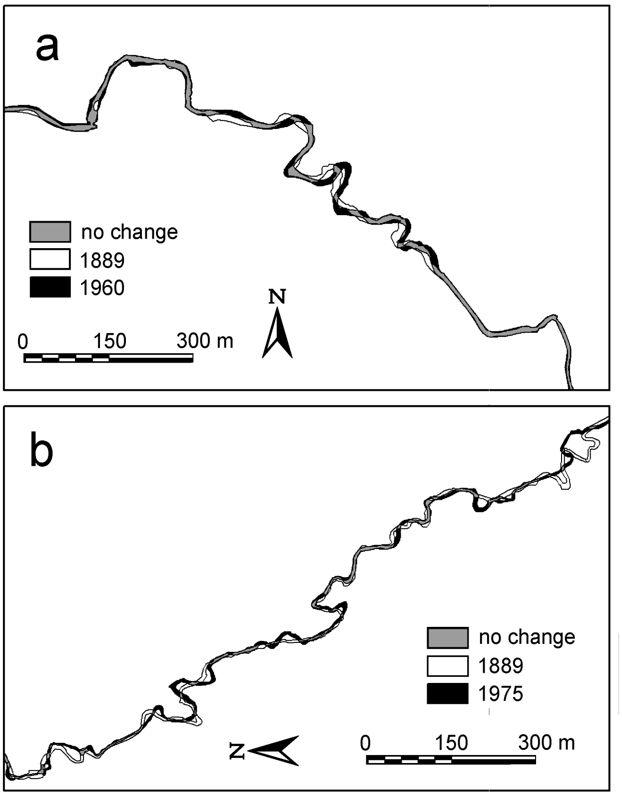

Figure 7 – Examples of temporal changes in river channel position along two reaches of the River Frome. A: Natural changes in channel edge position, 1889-1960, in one of the most laterally active reaches of the River Frome; B: Changes in channel edge position, 1889-1975, typical of many reaches of the River Frome, some of the largest changes in this reach represent human-imposed cut-offs of bends or recovery from such cutoffs (channel edge positions based on Ordnance Survey mapping, horizontal accuracy ca. 2.5 m).

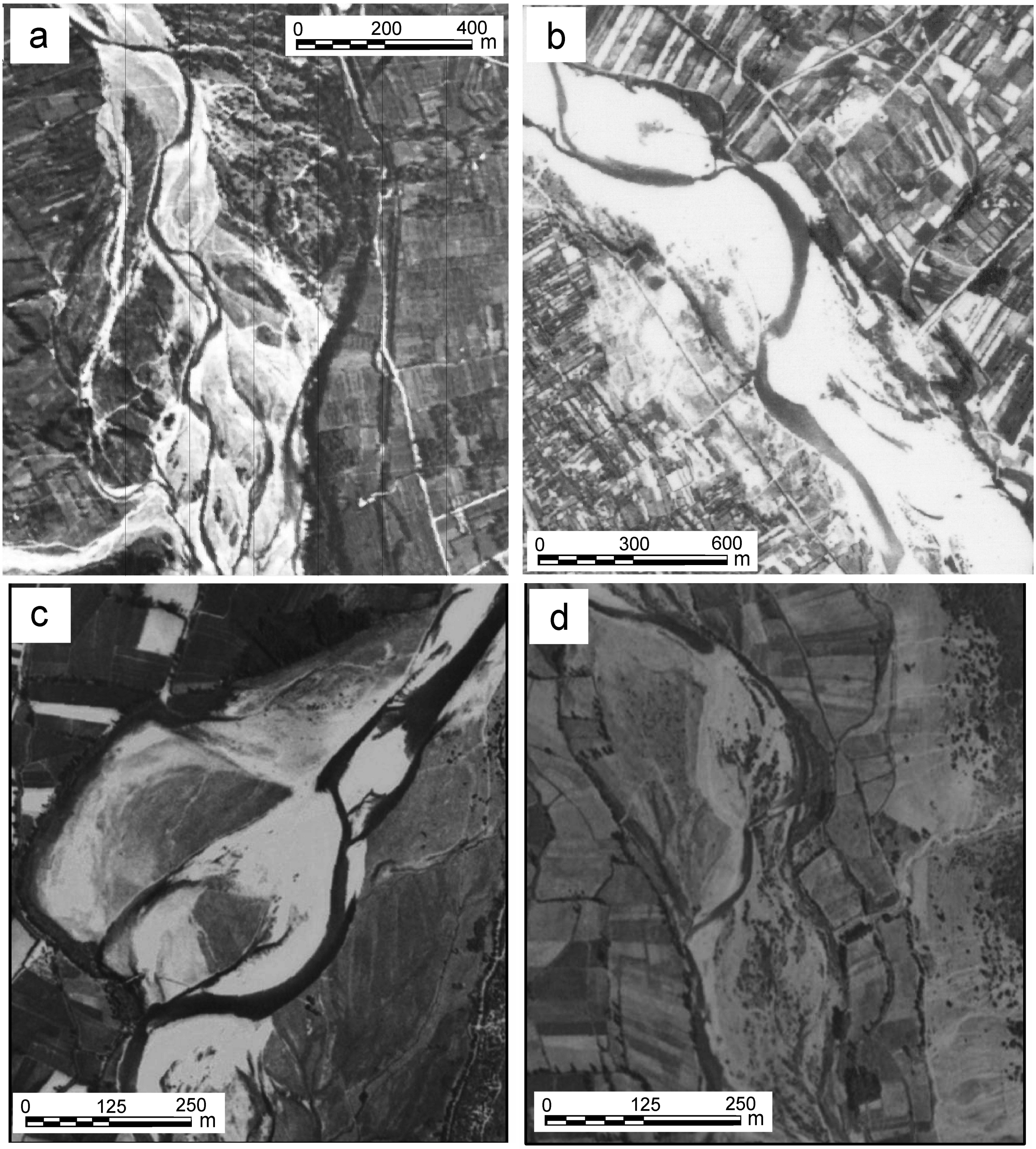

Figure 8 – Examples of river types from aerial photos of 1950s, for the reaches shown in Figure 6, illustrating that the current morphologies are derived from temporal changes of different river types.

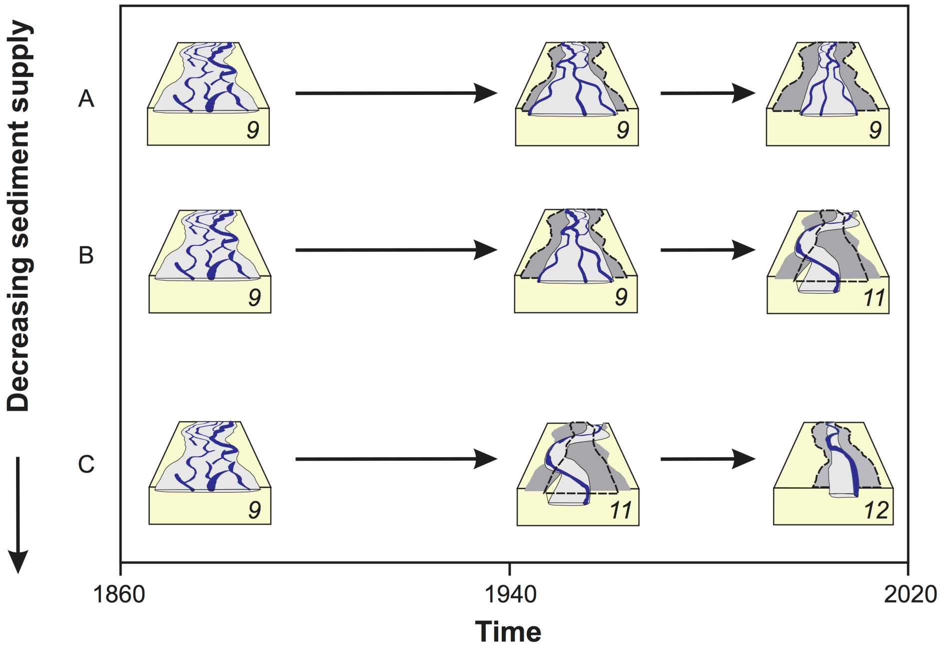

Figure 9 – Summary of the categories of temporal changes in channel morphology observed in the middle to lower Magra River. A: channel narrowing but no change in river type; B: progressive narrowing and change from braided to wandering; C: progressive narrowing and change from braided to wandering, and from wandering to pseudo-meandering.