INDICATORS OF RIVER SYSTEM HYDROMORPHOLOGICAL CHARACTER AND DYNAMICS: UNDERSTANDING CURRENT CONDITIONS AND GUIDING SUSTAINABLE RIVER MANAGEMENT

M. González del Tánago[a*], A.M. Gurnell[b] , B. Belletti[c] and D. García de Jalón[a]

[a] *E.T.S. Ingeniería de Montes, Forestal y del Medio Natural, Universidad Politécnica de Madrid, Ciudad Universitaria, 28040 Madrid, Spain*

[b] *School of Geography, Queen Mary University of London, Mile End Road, London, E1 4NS UK*

[c] *Department of Earth Sciences, University of Florence, Via S. Marta 3, 50139 Firence, Italy*

**Corresponding author: Tel: ++34 91 3366794; Fax: ++34 915439557; E-mail: marta.gtanago@upm.es*

ABSTRACT

A set of multi-scale, process-based hydromorphological indicators of river character and dynamics has been developed to support river management and restoration activities. Indicators are selected to represent key hydromorphological processes at each spatial scale, i.e., catchment, landscape unit, river segment, river reach. Their evaluation allows identification of the cascade of these processes through the spatial units and the historical changes in their propagation as a consequence of natural or human induced hydromorphological changes. The approach is deliberately open-ended so that it can be adapted to local environmental conditions and management, and it can make the most effective use of available data sets. The indicators support assessments of the current condition of the river and its catchment; past changes within the catchment and their impacts on river reaches. Therefore, they represent a sound foundation for assessing the way the catchment to reach scale units and the geomorphic units within reaches may respond to future natural changes or human interventions. The procedure is illustrated using the example of the river Frome (UK).

KEY WORDS

Indicators; hydromorphology; fluvial processes; river assessment; river management; scale

1. INTRODUCTION

Developing integrative, scientific tools to facilitate the understanding of interactions between hydrological and geomorphological processes of rivers and to guide river management applications represents a significant research challenge in applied River Science (Fryirs et al., 2008; Brierley et al., 2010; Rinaldi et al., 2015a). Collectively, hydrological and geomorphological (hereafter hydromorphological) considerations provide a fundamental physical template for the spatially and temporally varied heterogeneity of river habitats and biophysical processes of river networks (Ward et al., 2002; Brierley and Fryirs, 2005; Thorp et al., 2006). The new field of hydromorphology deals with the structure, evolution, and dynamic morphology of hydrologic systems over time (Vogel, 2010), and it emerges from the enormous societal challenges and pervasive human impacts on fluvial systems. It is increasingly recognized that hydromorphological processes govern riverine ecosystems (e.g. Vaughan et al., 2009; Poole, 2010; Rinaldi et al., 2013; Elosegui and Sabater, 2013) and that their enhancement is essential for successful river restoration and biological conservation (Fausch et al., 2002; Beechie et al., 2010; González del Tánago et al., 2012; Hughes et al., 2012; Meitzen et al., 2013).

Hydromorphological degradation is one of the major causes of poor ecological status within European rivers (Fehér et al., 2012) and the recovery of fluvial processes and channel dynamics in many cases represents the main concern of the programme of measures to improve the ecological status of rivers within the context of the European Water Framework Directive (WFD, EC 2000). This European Directive includes requirements for hydromorphological assessments of water bodies, and their implementation within European member states has fostered considerable research on hydromorphology.

Rivers are dynamic, complex systems and progress in understanding their dynamics, and particularly their responses to changes in controlling factors, is not simple. Multi-dimensional geomorphic processes, multiple modes of adjustments at reach to network scales, the existence of geomorphic thresholds and the potential for self-organization represent common sources of nonlinearity and complexity that hinder predicting responses of river systems (Phillips, 2002; Church, 2002; Dean and Schmidt, 2011; Horn et al., 2012). Nevertheless, there have been many attempts to conceptualize and quantify hydromorphological forms and processes in a simple way (see Barquín and Martínez-Capel, 2011). The interest of progressing towards building practical tools to assess and monitor key hydromorphological processes and to understand their role in supporting target biotic communities is maintained, and it has been underpinned by many authors (Brierley et al., 2010; Brierley et al., 2013; Rinaldi et al., 2015a).

Rivers are multidimensional systems, including longitudinal (upstream-downstream), lateral (hillslope-channel), vertical (hyporheic-channel bed) and temporal components (Ward, 1989; Poole, 2002). Besides multidimensionality, rivers are organized hierarchically, with fine-scale elements (e.g. geomorphic units such as gravel bars) embedded within reaches, which in turn are embedded in coarser-scale elements such as river segments, river networks, catchments and bioregions (Frissell et al., 1986; Montgomery and Buffington, 1998; McCluney et al., 2014). Any attempt to characterize hydromorphologial character and behaviour of rivers has to encompass this complexity, emphasising processes such as flows of matter (i.e. water, sediment, wood, nutrients) and energy through a catchment and the controlling and responding properties and features of river corridors, including river adjustments and resulting forms at different spatial and temporal scales. Therefore, indicators that capture river forms and processes and their changes across scales are valuable contributors to assessing current hydromorphological character and dynamism and to understanding historical river trajectories and predicting future trends.

The use of indicators is increasingly recognised to be a valuable tool in environmental management, potentially providing early warning signals of changes and a valuable means of communication (Dale and Beyeler, 2001; EEA, 2003). By conceptualizing processes and assessing trends, indicators help to simplify, quantify, analyse and communicate complex information (Singh et al., 2009) offering great potential to river management by contributing to understanding of river responses to human disturbances, monitoring the consequences of stream restoration works and assessing stream restoration success (Pander and Geist, 2013). Many indicators have been developed for application to river environments including indicators of human impacts (Gergel et al., 2002), water quantity (James et al., 2012), water quality (e.g. Liu et al 2012) and biological integrity (e.g. Karr, 1981; Chessman, 1995). In relation to hydromorphology, indicators of flow regime and hydrologic alteration (e.g. Richter et al., 1996; Olden and Poff, 2003), geomorphic condition (Ollero et al.2011; Rinaldi et al., 2013) and riparian environmental quality (González del Tánago and García de Jalón, 2011) have been proposed, as well as numerous surveying methods and associated indices for river physical habitat assessment (e.g., Thomson et al., 2001; see reviews by Fernández et al., 2011 and Belletti et al. 2015a). Most of this research has addressed a single component of river hydromorphology (e.g., flow regime, riparian zone), revealing magnitude, form or structure and changes over time, but not considering interactions with other components of the river system. Furthermore, the majority of the existing hydromorphological assessment methodologies have been designed to be applied at a single spatial scale, usually the reach or segment scales, and avoiding the catchment context.

In this paper we present an integrated, multi-scale set of hydromorphological indicators of river systems within their catchments that has been developed within the EU FP7 project REFORM (REstoring rivers FOR effective catchment Management) (Gurnell et al., 2014). Within this project, a process-based European framework for river hydromorphology (hereafter called the REFORM framework) has been developed, and indicators aimed to support the assessment of human pressures, processes and morphological responses at each spatial scale have been identified (see Gurnell et al., 2015a for an overview).

The novelty of our approach is the holistic, process-based formulation of hydromorphological indicators of rivers to support assessment and monitoring of river conditions, and their functional integration across scales. Following delineation and characterisation of a catchment and its spatial units (landscape units, river segments, river reaches and geomorphic and smaller units), indicators are extracted across these spatial units and a temporal analysis of their changes over recent (e.g. last 20 years) and historical (e.g. last 100 years) time frames is also undertaken. The indicators are selected to represent key processes and features at each spatial scale, so that the present and past cascade of these processes and their propagation through a catchment can be identified. This process-based multi-scale set of indicators provides an integrative approach to assessment of river conditions that enhances prospects for sustainable river rehabilitation and biological conservation (Fausch et al., 2002).

2. MULTI-SCALE INDICATORS OF RIVER CHARACTER AND DYNAMICS

2.1. Methodological approach

Our proposed indicators are a central component of the REFORM framework. In this framework, different spatial units are defined (i.e., catchment, landscape unit, river segment, reach, geomorphic unit, river element) and hydrologic and geomorphic attributes for their delineation and characterization are proposed. An overview of the framework, its spatial units and attributes, and how they are delineated and assessed from existing information and field surveys is provided by Gurnell et al. (2015a) in this special issue.

In researching appropriate hydromorphological indicators we tried to capture the diversity and patterns of river character and behaviour across the river system. First we identified the key hydromorphological processes governing river functioning at each spatial scale, giving emphasis to water and sediment production across the land surface (e.g. catchment, landscape unit scales), water and sediment transfer through the river network (e.g. river segment scale), river and floodplain character and adjustments within the valley constraints (e.g. reach scale) and the reciprocal interactions with aquatic and riparian-floodplain vegetation (e.g. reach and geomorphic unit scales). Then we created a list of hydromorphological attributes of rivers that characterise forms and responses to these processes at different scales. From an extensive list of potential hydromorphological characteristics and following indicator selection criteria suggested by Kurtz et al. (2001) and others (e.g. Dale and Beyeler, 2001; EEA, 2003; Niemeijer and Groot, 2008; James et al., 2012), we selected as "indicators" those which: i) presented most conceptual relevance in terms of assessed processes or were of high management relevance, ii) were the most feasible to implement in terms of data availability or collection, quality assurance and cost-effectiveness; iii) were predictable in their response to spatial and temporal changes of controlling factors; and iv) were interpretable and readily communicable.

Some of the selected indicators may be used as characterization or classification criteria (i.e. descriptive indicators) whereas the majority of them are intended to be used as assessment or monitoring criteria, indicating present river condition and allowing changes in status to be tracked over time (i.e. audit/assessment indicators) (Brierley et al., 2010). The descriptive indicators were mostly dictated by existing legal information requirements, such as the obligatory classification criteria of water bodies within the European WFD (e.g., size, relief and geology of the catchment). These indicators are invariant in time and express basic controls of catchment hydrological and geomorphological processes. In contrast, the audit indicators, used to assess or monitor river conditions, were selected as the most appropriate attributes to characterize dynamic forms or features of rivers that are expected to vary as a consequence of changes in natural disturbances and human interventions over time.

Complementary literature was used to support the selection of hydromorphological indicators of specific river components such as the flow regime (Richter et al., 1996; Olden and Poff, 2003), channel forms and processes (Ollero et al, 2011; Rinaldi et al., 2013; Fryirs and Brierley, 2013) and the riparian corridor (González del Tánago and García de Jalón, 2011; Aguiar et al., 2011). We also incorporated information from other research concerning detection of human impacts (e.g. Gergel et al., 2002) or assessment of geomorphic status altered by dams and reservoirs (Schmidt and Wilcock, 2008; Lobera et al., 2015). We also considered recent reviews of indicators, indices and methodologies for assessing river hydromorphology by Fernández et al. (2011) and Belletti et al. (2015a).

2.2. Hydromorphological considerations and indicators proposal

River reaches are the main focus of our approach, since this is the scale at which rivers are most often assessed, managed and rehabilitated. Informed by previous literature describing the multidimensionality of rivers and their hierarchical organization (see Gurnell et al. (2015a) for a review of recent literature on these topics), in our approach rivers are viewed as a continuous array of distinct reaches (i.e., identifiable portions of the river network exhibiting channel forms, assemblages of geomorphic units, mobility, type of adjustments and vegetation patterns that are significantly different from the surroundings) (see Figure 1). The sequence of reaches along the river network conforms to larger-scale hydromorphologic structures (i.e., river segments) which are identifiable by significant hydrologic and geomorphic discontinuities, primarily dictated by abrupt geologic changes or major tributary confluences (Benda et al., 2004). The sequence of segments that conforms the river network as a whole is set within the catchment, in which relatively homogeneous areas of similar topography and geology contain characteristic landforms and usually land cover (i.e. landscape units, as defined by Brierley and Fryirs, 2005). Meanwhile river segments would reflect the dominant hydrological exchange along the longitudinal continuum of the river, river reaches would better reflect the hydrological exchange along the lateral and vertical dimension of the river corridor. In this sense, river segments would represent the scale to which the influence of longitudinal connectivity on biological community structure could be adressed (i.e., river continuum concept (Vannotte et al., 1980), discontinuity concept (Ward and Stanford, 1983)), whereas river reaches would give emphasis on the influence of finer-scale lateral and vertical connectivity on biological community structures (e.g., flood pulse concept (Junk et al., 1986), flow pulse concept (Tockner et al., 2000), hyporheic corridor concept (Stanford and Ward, 1993)) (Poole, 2002).

This hydromorphological context conceptualizes the physical template in which habitat characteristics may be interpreted and the interactions between physical and biological processes properly assessed across scales (e.g. Fausch et al., 2002: Thorp et al., 2006; McCluney et al., 2014; Van Looy et al., 2013; Villeneuve et al., 2015). Pools and riffles according to Frissell et al. (1986) may be viewed as geomorphic units within reaches (i.e., micro-scale); river segments according to Benda et al. (2004) would be coincident with the proposed river segments (i.e., meso-scale); patch mosaics (Poole, 2002) or hydrogeomorphic patches and associated functional process zones (Thorp et al., 2006) would be in the range between reaches and segments (i.e., intermediate scales). Finally other larger scale approaches (e.g. domain process concept (Montgomery, 1999) or riverine macrosystems (McCluney et al., 2014) may be likely associated to landscape unit or catchment scales.

Table 1 shows the proposed hydromorphological indicators of the main processes and forms across spatial scales, and Figure 2 shows their causal relationships. To a certain extent, the patterns observed at each scale provide the boundary conditions for processes and forms at the next scale, in a hierarchical, self-organizing manner within which river habitats and biological organization may be examined (Habersack, 2000). Within such a hierarchical framework, state variables (i.e., indicators) at a particular scale govern processes at smaller scales which act as drivers for the state variables (i.e., indicators) at the smaller scales.

Catchment

Key hydromorphological processes at the catchment scale are water and sediment production within the specific biogeographic region in which the catchment is located. Hydromorphological indicators at this scale aim to identify broad properties of runoff and sediment production by the catchment, which subsequently will have a strong influence on river bio-physical processes and channel dimensions and patterns along the drainage network. Drainage area, climate, geology and land cover are the primary agents dictating the potential water and sediment production in the catchment. Annual runoff indicates the effectiveness with which the catchment converts rainfall to runoff arriving at the outlet, and when compared with precipitation over time may act as a warning of the hydrological influence of human interventions at a catchment scale, including changes in land-cover and land-uses (e.g. Mao and Cherkauer, 2009; García Ruiz and Lana-Renault, 2011; Morán-Tejeda et al., 2012).

Landscape Unit

Due to the relatively homogeneous topography and landforms within landscape-units, hydromorphological indicators at this scale may give more detailed information on runoff processes (i.e., rapid vs. delayed runoff) and sediment production (fine and coarse sediment) within the catchment. Information concerning the presence of exposed aquifers and permanent snow-ice cover, permeability of soils and parent materials, and land cover and land use may be indicative of water infiltration, storage and runoff pathways. Information on soil erosion rates and areas of coarse sediment exposure and potential movement (landslides and mass movements, steep bare hillslopes), indicate the production of sediment that may reach the river network and thus may be expected to influence the hydromorphological character and dynamics of rivers observed at finer spatial scales (see Table 1).

River segments

Key processes at the river segment scale predominantly relate to the flow and sediment regimes and their interactions with the valley setting of the river network. At this scale, indicators of the hydromorphological processes that transfer water and sediment produced at larger scales (i.e., catchment, landscape units), are addressed to inform (see Table 1) i) the flow regime and its properties, that control river energy, potential of flooding, and water availability during dry periods; ii) sediment delivery and transport to the segment, and the sediment budget or balance within the segment that strongly influences river channel adjustments and stability; iii) valley dimensions, which constrain lateral river adjustments and thus sensitivity to fluvial process changes, and, through the valley gradient, river flow energy; iv) riparian corridor characteristics and large wood production; and (v) major longitudinal obstructions to downstream flows of water and sediment.

Flow regime type (a detail of the typology used is provided by Rinaldi et al. (2015b) in this special issue), average annual flow, and magnitude and frequency of some specific extreme flows have been selected from the numerous indicators that can be extracted from the overall flow regime characteristics (Olden and Poff, 2003). In combination, they represent essential components of the natural flow regime and when recorded over time they accurately reflect the degree of hydrologic alteration (Richter et al., 1996; Poff et al., 1997; González del Tánago et al., 2015a). Sediment delivery and sediment transport represent fundamental controls on river stability (Simon and Rinaldi, 2006) and they determine at a larger extent the resilience of rivers to human impacts, such as dams and reservoirs (Schmidt and Wilcock, 2008; Reid et al., 2013; González del Tánago et al., 2015b). The connectivity of potential sediment sources (e.g. rocky exposed areas, steep bare land, gullies and badlands, areas of land use that may promote soil erosion) with channels (e.g. Fryirs and Brierley, 2007), together with evidence of net sediment accumulation or loss from the segment are indicative of sediment dynamics at this spatial scale (Simon and Rinaldi, 2006) that may help to explain forms and processes at finer spatial scales (Simon et al., 2000). Three types of valley are recognized (i.e., confined, partly confined and unconfined), according to which potential floodplain extent and functionality, and potential river channel and floodplain responses to external changes may be predicted (Brierley and Fryirs, 2005; Fryirs et al., 2007).

Physical hydromorphological characteristics of rivers at this scale are complemented by bio-geomorphic indicators of the riparian zones. Landscape metrics such as average riparian corridor width, the longitudinal continuity of riparian vegetation along the river, together with biological information related to the dominant riparian plant associations are indicative of the lateral river dynamism and frequently show the flow regulation effects of dams and reservoirs (Merrit and Cooper, 2000; Gordon y Meentemeyer, 2006; Aguiar et al., 2011). Mature trees bordering the river channel determine the potential supply of large wood, which is considered a significant structural and functional component of river ecosystems, influencing river and floodplain stability and morphological complexity (Collins et al., 2012; Osei et al., 2015).

River reaches

At the reach scale, the key hydromorphological processes considered are flooding, which drive lateral and vertical hydrological exchanges within the riparian and floodplain zones, and the dynamic adjustments that may arise within the reach under local constraints in response to flow and sediment regime changes or human interventions. Indicators at this scale include (see Table 1) i) channel type and dimensions (e.g., channel planform, active channel width), bed-sediment size and type and abundance of geomorphic-units; ii) river energy and evidences of channel adjustments; iii) flooding extent and floodplain inundation frequency; iv) riparian and aquatic vegetation features (e.g., coverage, age structure), wood amount and the abundance of vegetation-dependent geomorphic units, all illustrative of the degree of reciprocal interactions among fluvial processes and vegetation; and (v) indicators of the main human constraints on lateral connectivity and river channel adjustments. These indicators reflect current morphological character and dynamism of river systems and their contemporary or historic change have frequently been associated with human interventions. Shifts in channel planform and bank profiles, changes in the types and abundance of geomorphic units or absence of pioneer vegetation recruitment have been related to coarse sediment removal by gravel mining (Surian and Rinaldi, 2003; Belleti et al., 2015b), fine sediment addition from erosion of agricultural land (e.g. Grabowski and Gurnell, 2015), channelization (Wyżga et al., 2012), urbanization (Chin, 2006) or flow regulation by dams and reservoirs (Lobera et al., 2015; González del Tánago et al., 2015b).

2.3. Applications

As previously described, the hydromorphological indicators are a central feature of the REFORM framework for assessing the hydromorphology of rivers, within which the different spatial units (i.e., catchment, landscape units, segments, reaches) have first to be delineated and characterized. The approach is deliberately open-ended so that it can be adapted to local environmental conditions and management issues, and can make the most effective use of available data sets.

Indicators may play different functions, documenting relevant information on river hydromorphology status and serving as instruments to monitor drivers and policy responses (Rapport and Hilden, 2013). Indicators are quantified at each spatial scale under current conditions to investigate present processes, forms and human pressures (audit function). In this way, they provide comprehensive baseline data from which river condition assessments, river trajectories and a clear understanding of pressure-response (i.e., cause-effect) relationships may be defined. When the same indicators are quantified at different historical conditions, hydrological alteration and morphological adjustments or changes over time may be assessed, and information on whether the system is functioning appropriately for its hydromorphologic type may be inferred (assessment function). Under similar pressures or impacts, different evolutionary trajectories may be observed in different reaches as a consequence of distinct local resistance and resilience conditions (Brierley and Fryirs, 2005; Reid et al., 2013; González del Tánago et al., 2015b). These differences should guide selection of further reach-specific management options and rehabilitation measures. Apart from providing relevant knowledge across scales to identify the nature of major pressures and impacts and the river responses to them as cause-effect relationships (conceptual function of indicators), hydromorphological indicators may further contribute to support policy-relevant information (instrumental function). Hydromorphological indicators may help in identifying and defining thresholds that could potentially contribute to define hydromorphologic reference conditions according to the river type; in addition to their utility to inform managers, stakeholders and the public of the consequences of water and land use policies on river hydromorphologic status (EEA, 2003; Rapport and

Hilden, 2013); and their contribution to the design and implementation of alternative and sustainable water and land use policies, including water resources management (e.g. environmental flows, King et al. 2015), soil conservation measures (e.g. green infrastructure, riparian buffer-strips creation) and landscape planning (e.g. urban planning and floodplain rehabilitation).

3. CASE STUDY: THE RIVER FROME (UK)

To illustrate the utility of the indicators summarised in Table 1 in developing understanding of a river's hydromorphology, this section presents a case study of their application to the River Frome catchment, southern England. Further applications of the REFORM framework and its indicators can be found in Belletti et al. (2015b) and González del Tánago et al. (2015b).

Tables 2, 3, 4 and 5 present a selection of the indicators evaluated for the Frome that represent key properties of its past and present character at catchment, landscape unit, segment and reach scales. More detailed information on the Frome and its hydromorphology are presented in Grabowski and Gurnell (2015) and Gurnell and Grabowski (2015) and the full application of the REFORM framework to the Frome is available in Grabowski and Gurnell (2014). The catchment, three landscape units, six segments and seventeen reaches of the river Frome are illustrated in Figure 3. Although all indicators listed in Table 1 were evaluated for all spatial units, for clarity and brevity, the following case study description is confined to a set of key indicators at landscape unit scale and finer, and to three example reaches (4, 5 and 6) located in two river segments (2 and 3) within two landscape units (1 and 2).

Catchment scale.-

The river Frome has a catchment area of 459 km2 and an average runoff coefficient is 0.52, reflecting average annual precipitation and runoff of 968 and 507 mm, respectively (Table 2). At this scale, two key hydromorphologically-relevant properties are apparent. The catchment is dominated by calcareous rocks which extend across 60% of the area, and the land cover is dominated by agriculture (Table 2). Based on the Corine level 1 land cover classes, there is no evidence of significant land cover change over time.

Landscape Unit scale.-

Three landscape units were identified within the Frome catchment, based primarily upon differences in its subdued topography, underlying geology, and land use. Some example indicators for two of these landscape units are presented in Table 3. Both landscape units are underlain almost entirely by aquifers, and have highly permeable soils. By considering the more detailed Corine level 2 and 3 land cover data at this scale, the potential impact of land cover on runoff production is indicated. Areas of rapid (i.e. % paved or compacted area, % urban fabric, % industrial, commercial, transport units, % open spaces with little or no vegetation) and delayed (i.e. % glaciers and perpetual snow, % large surface water bodies, % forests, % wetlands) runoff production are very limited, reflecting the predominantly agricultural nature of the catchment. A more detailed inspection of the Corine data reveals 26% arable and 72% pasture cover in landscape unit 1 and 55% arable and 39% pasture cover in landscape unit 2, demonstrating different agricultural activities in the two landscape units. Based on land cover information from the UK Countryside Surveys of 1990, 2000 and 2007 with classes aggregated to match those of Corine, a slight increase in the area of rapid runoff production at the expense of the intermediate class is apparent in recent decades as a result of expansion of the built-up area, whereas the delayed runoff (approximately

2% forest) has changed little. No coarse sediment source areas are present but the average rate of soil erosion (extracted from the Pan-European Soil Erosion Risk Assessment map (PESERA), which estimates soil erosion from topographic, climatic, soil and land cover data) in landscape unit 2 is three times that of landscape unit 1, reflecting the higher cover of arable agriculture in the former. Although few changes were identified in the Frome based on the indicators listed in Table 3, further analysis of agricultural census data indicated considerable intensification of agriculture (i.e. increased crop yields and animal densities and changes in the crops and animals produced) over the last 100 years (Grabowski and Gurnell, 2015). This pursuit of additional indicators of local importance for the Frome illustrates how the development of relevant catchment-specific indicators can be extremely informative.

Segment scale.-

The River Frome main stem was subdivided into six segments. Table 4 presents key indicators for segments 2 and 3, in which the three selected reaches (4, 5 and 6) are located, although flow regime indicators are calculated for river gauging stations located in segments 1 and 5 (and 6 for longer-term changes), since none are present in segments 2 and 3. As indicated by the geological indicators at catchment and landscape scale, the River Frome flow regime is groundwater-fed. This is confirmed by its ‘perennial stable’ or ‘perennial superstable’ flow regime (see Rinaldi et al., 2015b for flow regime typology). The flow regime has tended to become more stable over the last 40 to 50 years, based on analysis of a long flow record from segment 6. Flows are extremely reliable, with a high baseflow index that is increasing, and modest-sized flood flows. The river is unconfined and has a very low valley gradient and so very low stream power to move sediment. Eroded soil is indicated to be delivered at a rate of approximately 3.7 and 4.4 tonnes per river kilometre per year from the area within 500 m of the river’s edge into segments 2 and 3 respectively. As a result of agricultural intensification, it is estimated that sediment delivery has probably increased steadily over the last 100 years. Based upon the indicators of flow, sediment delivery, valley and river gradient, and river channel size, and various scenarios of bed material composition (from field surveys) and bedload transport formulations, SIAM modelling (see Grabowski and Gurnell, 2015) indicates that both segments currently have an aggrading sediment budget, with accumulation of predominantly sand and finer material within the channel, since gravel is rarely mobilised. Blocking structures (mainly long-established weirs) add to a tendency for fine sediment retention within the river channel. The average width of the riparian corridor is quite large, but this is the width of the envelope that contains all remnants of true riparian vegetation. Along the Frome true riparian vegetation is present as small isolated patches surrounded by agricultural land, and as a result, the proportion of river edge bordered by mature (mainly riparian) trees is quite small in length and usually narrow, and in segment 3 the patches of riparian vegetation are generally mature, suggesting that no significant riparian woodland regeneration is occurring.

Reach scale.-

The River Frome main stem was subdivided into seventeen reaches, and key indicators are listed for three example reaches (4, 5 and 6) in Table 5. The indicators are grouped to summarise the type and dimensions of channel and floodplain, and the evidence for current hydromorphological function and human alteration; current function and artificiality of the riparian corridor; and contemporary and historical hydromorphological adjustments.

The channel and floodplain types, channel dimensions and sediment size indicators reflect the low energy, baseflow-dominated flow regime and fine sediment dominated load identified at the segment scale. The sinuous and anabranching river types are inherently stable with fine sediment floodplains, and with sand-gravel or gravel-sand bed material indicative of gravel lag deposits infiltrated and often overlain by sand and finer sediment deposits.

In terms of the current hydromorphological function, some geomorphic units typical of the river channel and floodplain types are present. The extent of eroding and depositing banks indicates widespread lateral channel dynamics. In-channel geomorphic units (vegetated bars, benches, islands) occur in all three reaches, indicating some bed sediment dynamics but also considerable sediment retention, and these units are more extensive in reach 4 than in reaches 5 and 6. These and other vegetation-related geomorphic units are present, as would be expected on this low energy river, but are only abundant in reach 4, where tree and wood-related units dominate, in comparison with frequent aquatic plant dominated units in reaches 5 and 6. Given this wide range of indicators of dynamics on this very low energy river, all reaches are given a hydromorphological function assessment of good out of potential assessments of good, intermediate and poor.

The selected reaches show poor longitudinal continuity as a result of the presence of several intermediate and low blocking structures, but good lateral continuity, as a result of very limited channel reinforcement, a wide erodible corridor and access for floodwater to the entire floodplain. In combination, these lead to an adjustment potential assessment of intermediate and an artificiality assessment of some significant artificial elements.

Only reach 4 shows a good cover of riparian vegetation within the riparian corridor. Reaches 4 and 5 show some elements of each riparian vegetation age class, giving them a fairly balanced age structure assessment, but reach 6 shows no evidence of riparian woodland regeneration. Data were only available for the presence of wood and fallen trees in the channel, which is at best occasional and so the wood budget is assessed as severely degraded. As a result, the three reaches achieve riparian corridor function assessments of partial, very limited and very limited function, for reaches 4, 5 and 6, respectively.

Indicators generated by reconstructions of historical change are highly subject to the quantity and type of information that is available (Grabowski et al., 2014), and this is certainly the case for the Frome. Historical reconstruction of lateral dynamics depended entirely upon topographic maps, because the changes were too small in most reaches to be properly characterised by the short period of a few decades for which air photographs are available. However comparison of the channel bank positions recorded on the earliest and most recent *cica* 1:2,500 scale Ordnance Survey maps revealed channel narrowing in all three reaches since 1960-1975, complementing the contemporary indicators of fine sediment aggradation and the development of fine sediment geomorphic units within the river channel. Indicators of longer term bed incision or aggradation were derived from field survey. There is no field evidence of significant bed incision (e.g. exposure of bed sediment in the banks, exposure of infrastructure foundations) or aggradation (e.g. significant and widespread burial of the gravel river bed under finer sediment deposits). This reach scale evidence of significant lateral but little vertical historical channel adjustment links with indicators of increasing fine sediment production, delivery, and in-channel retention within mid-channel and marginal, vegetation associated landforms at both the reach and larger spatial scales.

Overall, it appears that increases in fine sediment production and delivery to this extremely low energy river are resulting in gradual channel narrowing driven mainly by the development of vegetation-associated landforms (vegetated lateral and mid-channel bars, lateral benches, islands), which is leading to a reduction in channel capacity in the absence of any significant bed level adjustments. For further details of these changes, the associated landforms and possible future channel adjustments under different scenarios, see Grabowski and Gurnell (2015) and Gurnell and Grabowski (2015).

4 UNDERSTANDING HYDROMORPHOLOGICAL CHANGES AT MULTIPLE SCALES: AN ESSENTIAL CONTEXT FOR RIVER MANAGEMENT

This paper has developed the idea of using hydromorphological indicators across different space and time scales to develop understanding of how catchments and their river networks function. The indicators form part the REFORM framework that is designed to support sustainable river management (Gurnell et al., 2015). Both the framework and the indicators are flexible and open-ended, representing an approach to developing understanding of a particular catchment that makes best use of locally-available information, and is moulded to local environmental circumstances. Throughout, we have attempted to convey the concepts behind the development of indicators and their sequential interpretation from larger to smaller spatial scales. We have illustrated this approach using the catchment, two landscape units, two segments and three reaches of the River Frome in southern England, and referred further examples in this issue (Belletti et al., 2015b and González del Tánago et al., 2015b).

The causal chain shown in Figure 2 may serve as a general framework to explore interactions between catchment and river network conditions and river adjustments and changes over time, by considering selected indicators at the relevant scale. In an up-scaling approach, explanatory pathways of river adjustments or degradation at reach scale (e.g. narrowing, channel incision, aggradation) may be established following potential causes at segment scale (e.g. coarse sediment deficit, fine sediment surplus, increase/decrease of sediment transport capacity etc., that could be promoted by flow regulation by dams and reservoirs, channelization works, gravel mining, Belletii et al., 2015b; González del Tánago et al., 2015a); and/or potential causes at landscape unit or catchment scale (e.g. increase of forest land, erosion control measures, land cover changes, climate change, González del Tánago et al., 2015b). Alternatively, within a down-scaling analysis, predictions of river responses at the reach scale may be achieved by progressively linking to hydrological changes at catchment scale (e.g. urban development) with potential consequences at the segment scale (e.g. increased amount of rapid runoff, increased peak flows, imbalance between transport capacity and sediment supply) and potential adjustments at the reach scale (e.g. channel widening/narrowing, incision/aggradation, reduction of soil moisture, riparian vegetation changes, Chin, 2006).

Using indicators to infer or describe processes and pressures and to track their spatial linkages and temporal changes is essential to designing reach-scale management strategies that are cost-effective and sustainable. For example, the very simple analysis presented for the river Frome has revealed that at the reach scale there is a historical trend of channel narrowing and the accumulation of fine sediments within landforms in the channel. This can be linked to the response of a low energy river that is blocked by numerous weir and bridge structures, and to a history of agricultural intensification at the landscape unit scale. These circumstances are elaborated by Grabowski and Gurnell (2015), but additional aggravating issues revealed by our analysis include the lack, at the segment scale, of a functioning riparian buffer zone, that would retain fine sediments through the process of floodplain aggradation and would contribute wood and other tree features which could induce channel adjustment dynamics to accommodate the fine sediment load.

Gaining knowledge of the functioning of a particular catchment requires active interaction with indicators to generate more locally-informative indicators that pinpoint space and time linkages, and it also requires the application of numerical models where relevant data are unavailable or issues are too complex for an empirical indicator-based approach. Perhaps the most important point is to realise the wealth of historical information that can often be exploited to quantify indicators that reveal locally relevant processes.

Lastly, it is crucial to recognise that rivers have continuously changed, often abruptly, and that such changes will continue as reaches adjust to past changes at larger scales and to future changes, not least climate change. These changes can be investigated through the use of indicators as suggested in this paper, and can be refined using modelling techniques, to form the starting point for designing any river interventions. Information on the current condition of a reach is useful, but it is only a small part of the story if sustainable management strategies are to be designed and implemented in appropriate locations. Thus, exploring hydromorphological indicators across spatial and temporal scales as is presented in this paper represents an essential step towards the design and evaluation of sustainable river management and rehabilitation strategies.

ACKNOWLEDGEMENTS

The work leading to this paper received funding from the EU's FP7 programme under Grant Agreement No. 282656 (REFORM). The Indicators were developed within the context of REFORM deliverable D2.1, therefore all partners involved in this deliverable contributed to some extent to their discussion and development. We acknowledge Vanesa Martínez-Fernández for her assistance in creating Figure 1.

REFERENCES

Abbe TB, Montgomery DR (2003) Patterns and processes of wood debris accumulation in the Queets river basin, Washington. Geomorphology 51: 81–107.

Aguiar FC, Fernandes MR, Ferreira MT (2011) Riparian vegetation metrics as tools for guiding ecological restoration in riverscapes. Knowledge and Management of Aquatic Ecosystems (402), 21.

Barquín J, Martínez-Capel F (2011) Assessment of physical habitat characteristics in rivers, implications for river ecology and management. Limnetica, 30(2): 159-168.

Beechie TJ, Sear DA, Olden JD, Pess GR, Buffington JM, Moir H, Pollock MM (2010) Process-based principles for restoring river ecosystems. BioScience 60(3): 209-222.

Belletti B, Rinaldi M, Gurnell AM, Buijse AD, Mosselman E (2015a) A review of assessment methods for river hydromorphology. Environmental Earth Sciences 73(5): 2079-2100.

Belletti B, Nardi L, Rinaldi M (2015b) Diagnosing problems induced by past gravel mining and other disturbances in Southern European rivers: the Magra River, Italy. Aquatic Sciences, this volume.

Benda L, Poff, NL, Miller D, Dunne T, Reeves G, Pess GR, Pollock M (2004) The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54(5): 413-427.

Brierley G, Fryirs K (2005) Geomorphology and River Management: Applications of the River Styles Framework. Balckwell Publishing, Australia.

Brierley G, Fryirs K, Cullum C, Tadaki M, Huang HQ, Blue B (2013) Reading the landscape. Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. Progress in Physical Geography 37(5): 601-621.

Brierley G, Reid H, Fryirs K, Trahan N (2010) What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. Science of the Total Environment 408(9): 2025-2033.

Chessman BC (1995) Rapid assessment of rivers using macroinvertebrates: a procedure based on habitat-specific sampling, family level identification and a biotic index. Australian Journal of Ecology 20(1): 122-129.

Chin A (2006) Urban transformation of river landscapes in a global context. Geomorphology 79: 460-487.

Church M. (2002) Geomorphic thresholds in riverine landscapes. Freshwater biology 47(4): 541-557.

Collins BD, Montgomery DR, Fetherston KL, Abbe TB (2012) The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. Geomorphology 139–140: 460–470.

Corenblit D, Tabacchi E, Steiger J, Gurnell AM (2007). Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth-Science Reviews 84(1): 56-86.

Dale VH, Beyeler SC (2001) Challenges in the development and use of ecological indicators, Ecological Indicators 1(1): 3-10.

Dean DJ, Schmidt JC (2011) The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region. Geomorphology 126(3): 333-349.

Eaton BC, Millar RG, Davidson S (2010) Channel patterns: Braided, anabranching and single-thread. Geomorphology 120: 353-364.

Elosegi A, Sabater S (2013) Effects of hydromorphological impacts on river ecosystem functioning: a review and suggestions for assessing ecological impacts. Hydrobiologia 712:129-143.

European Commission (EC) (2000) Directive 2000/60/EC (Water Framework Directive). Official Journal of the European communities, 22 December 2000.

European Environmental Agency (EEA) (2003) Environmental Indicators: Typology and Use in Reporting. European Environmental Agency. Copenhagen.

Fausch KD, Torgersen CE, Baxter CV, Li HW (2002) Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes a continuous view of the river is needed to understand how processes interacting among scales set the context for stream fishes and their habitat. BioScience 52(6): 483-498.

Fehér J, Gáspár J, Szurdiné-Veres K, Kiss A, Kristensen P, Peterlin M, Globevnik L, Kirn T, Semerádová S, Künitzer A, Stein U, Austnes K, Spiteri C, Prins T, Laukkonen E, Heiskanen AS (2012) Hydromorphological alterations and pressures in European rivers, lakes, transitional and coastal waters. Thematic assessment for EEA Water 2012 Report. European Topic Centre on Inland, Coastal and Marine Waters, Prague, ETC/ICM Technical Report 2/2012.

Fernandes MR, Aguiar FC, Ferreira MT (2011) Assessing riparian vegetation structure and the influence of land use using landscape metrics and geostatistical tools. Landscape and Urban Planning 99(2): 166-177.

Fernández D, Barquín J, Raven P.J (2011) A review of riverhabitat characterization methods: indices vs. characterisation protocols. Limnetica 30(2): 217-234.

Frissell CA, Liss WJ, Warren CE, Hurley MD (1986) A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management 10(2): 199-214.

Fryirs K A, Arthington A, Grove J (2008). Principles of river condition assessment. In: Brierley GK, Fryirs KA (eds) River Futures: An Integrative Scientific Approach to River Repair. Island Press, Washington DC, p, 101-124.

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

Fryirs KA., Brierley GJ (2013) Geomorphic Analysis of River Systems. An approach to reading the landscape. Willey-Blackwell Publications, Chichester.

Gaeuman D, Schmidt JC, Wilcock PR (2005) Complex channel responses to changes in stream flow and sediment supply on the lower Duchesne River, Utah. Geomorphology 64(3): 185-206.

García Ruiz JM, Lana-Renault N (2011) Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean región.A review. Agriculture, Ecosystems and Environment 140: 317-338.

García-Ruiz JM, López-Moreno JI, Vicente-Serrano SM, Lasanta–Martínez T, Beguería S (2011) Mediterranean water resources in a global change scenario. Earth-Science Reviews 105(3): 121-139.

Gendaszek A S, Magirl CS, Czuba CR (2012) Geomorphic response to flow regulation and channel and floodplain alteration in the gravel-bedded Cedar River, Washington, USA. Geomorphology 179: 258-268.

Gergel SE, Turner MG, Miller JR, Melack JM, Stanley EH (2002) Landscape indicators of human impacts to riverine systems. Aquatic Sciences 64(2): 118-128.

González del Tánago M, García de Jalón D (2011) Riparian Quality Index (RQI): A methodology for characterising and assessing the environmental conditions of riparian zones. Limnetica 30(2): 235-254.

González del Tánago M, García de Jalón D, Román M (2012) River restoration in Spain: theoretical and practical approach in the context of the European Water Framework Directive. Environmental management 50(1): 123-139.

González del Tánago M, Bejarano MD, García de Jalón D, Schmidt JC (2015a) Biogeomorphic responses to flow regulation and fine sediment supply in Mediterranean streams (the Guadalete River, southern Spain). Journal of Hydrology, 528, 751-762.

González del Tánago M, Martínez-Fernández V, García de Jalón D (2015b) Diagnosing problems produced by flow regulation and other disturbances in

Southern European rivers: The Porma and Curueño rivers (Duero Basin, NW Spain). Aquatic Sciences, this volume.

Gordon E, Meentemeyer RK (2006) Effects of dam operation and land use on stream channel morphology and riparian vegetation. Geomorphology 82: 412-429.

Grabowski RC, Gurnell AM (2014) Hydromorphological assessment of the Rievr Frome (UK): a lowland Northern European river. In B. Blamauer, B. Belletti , D. García De Jalón, M. González del Tánago, R.C. Grabowski, A.M. Gurnell, H. Habersack, M. Klösch, P. Marcinkowski, V. Martínez-Fernández, L. Nardi, T. Okruszko and M. Rinaldi (2014) Catchment Case Studies: Full Applications of the Hierarchical Multi-scale Framework. Deliverable 2.1, Part 3, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656, pages 5-181, downloadable from http://www.reformrivers.eu/results/deliverables.

Grabowski RC, Gurnell AM (2015) Diagnosing problems of fine sediment delivery and transfer in lowland, Nothwest European catchments: The Frome catchment, southern England. Aquatic Sciences, this volume.

Grabowski RC, Surian N, Gurnell AM (2014) Characterizing geomorphological change to support sustainable river restoration and management. WIREs Water, doi:10.1002/wat2.1037.

Graf WL (2006) Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology, 79(3), 336-360.

Grant GE, Schmidt JC, Lewis SL (2003) A geological framework for interpreting downstream effects of dams on rivers. In: O´Connor JE, Grant GE (eds.) A peculiar river. Water Science and Application 7. American Geophysical Union, Washihgton DC, pp 203-219.

Gurnell AM, Belletti B, Bizzi S, Blamauer B, Braca G, Buijse AD, Bussettini M, Camenen B, Comiti F, Demarchi L, García De Jalón D, González Del Tánago M, Grabowski RC, Gunn IDM, Habersack H, HendriksD, Henshaw A, Klösch M, Lastoria B, Latapie A, Marcinkowski P, Martínez-Fernández V, Mosselman E , Mountford JO, Nardi L, Okruszko T, O'Hare MT, Palma M, Percopo C. Rinaldi M, Surian N, Weissteiner C, Ziliani L (2015a) A hierarchical framework for developing understanding of river behaviour. Aquatic Sciences, this volume.

Gurnel, AM, Corenblit D, García de Jalón D, González del Tánago M, Grabowski RC, O'Hare MT, Szewczyk M. (2015b) A Conceptual Model of Vegetation-Hydrogeomorphology Interactions within River Corridors. River Research and Applications, in press.

Gurnell AM, Gonzalez del Tánago M, Rinaldi M, Grabowski R, Henshaw A, O'Hare M, Belletti B, Bujise AD (2014) - *Development and Application of a Multi-scale Process-based Framework for the Hydromorphological Assessment of European Rivers.* In: Lollino G, Arattano M, Rinaldi M, Giustolisi O, Marechal JC, Grant G (Eds), Engineering Geology for Society and Territory, Volume 3, Proceedings IAEG XII Congress, Springer International Publishing Switzerland, DOI: 10.1007/978-3-319-09054-2_71, 339-342.

Gurnell AM, Grabowski RC (2015) Vegetation-hydrogeomorphology interactions in a low-energy, human-impacted river. River Research and Applications, in press.

Gurnell AM, O'Hare JM, O'Hare MT, Dunbar MJ, Scarlett, PM (2010) An exploration of associations between assemblages of aquatic plant morphotypes and channel geomorphological properties within British rivers. Geomorphology 116(1): 135-144.

Gurnell AM, O'Hare MT, O'Hare JM, Scarlett P, Liffen TMR (2013) The geomorphological context and impact of the linear emergent macrophyte, Sparganium erectum L.: a statistical analysis of observations from British rivers. Earth Surface Processes and Landforms 38(15): 1869-1880.

Gurnell AM, Petts GE, Hannah DM, Smith BPG, Edwards PJ, Kollmann J, Ward JV, Tockner K (2001) Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms 26(1): 31-62.

Habersack HM (2000) The river-scaling concept (RSC): a basis for ecological assessments. Hydrobiologia 422/423: 49-60.

Horn JD, Joeckel RM, Fielding CR (2012) Progressive abandonment and planform changes of the central Platte River in Nebraska, central USA, over historical timeframes. Geomorphology 139-140: 372-383.

Hughes F, González del Tánago M, Mountford JO (2012) Restoring Floodplain Forest in Europe. In Stanturf J et al. (eds.), A Goal-Oriented Approach to Forest Landscape Restoration, World Forests, Springer Science+Business: 393-422.

James CA, Kreshner J, Samhouri J, O¨Neil S, Levin PS (2012) A methodology for evaluating and ranking water quantity indicators in support of ecoystem based management", Environmental management, 49(3): 703-719.

Junk W. Bayley PB, Sparks RE (1986) The flood pulse concept in river-floodplain systems. Canadian special publication of fisheries and aquatic sciences, 106(1): 110-127.

Karr JR.(1981) Assessment of biotic integrity using fish communities. Fisheries 6: 21-26.

Karrenberg S, Edwards PJ, Kollmann J (2002) The life history of Salicaceae living in the active zone of floodplains. Freshwater Biology 47(4): 733-748.

King AJ, Gawne B, Beesley L, Koehn JD, Nielsen DL, Price A (2015) Improving Ecological Response Monitoring of Environmental Flows. Environmental management, 55(5): 991-1005.

Kurtz JC, Jackson LE, Fisher, WS (2001) Strategies for evaluating indicators based on guidelines from the environmental protection Agency's office of research and development. Ecological Indicators 1(1): 49-60.

Liébault F, Piégay H (2002) Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France. Earth Surface Processes and Landforms 27(4): 425-444.

Liu Y, Zheng BH, Fu Q, Wang LJ, Wang M (2012) The selection of monitoring indicators for river water quality assessment. Procedia Environmental Sciences, 13: 129-139.

Lobera G, Besné P, Vericat D, López-Tarazón JA, Tena A. Aristi, Díez JR, Ibisate A, Larrañaga A, Elosegui A, Batalla R J (2015) Geomorphic status of regulated rivers in the Iberian Peninsula. Science of The Total Environment 508: 101-114.

Mao D, Cherkauer KA (2009) Impacts of land-use change on hydrological responses in the Great Lakes region. Journal of Hydrology 374: 71-82.

Martín-Vide JP, Ferrer-Boix C, Ollero A (2010) Incision due to gravel mining: Modeling a case study from the Gállego River, Spain. Geomorphology 117(3): 261-271.

McCluney KE, Poff NL, Palmer MA, Thorp JH, Poole GC, Williams BS, Williams MR, Baron JS (2014) Riverine macrosystems ecology: sensitivity, resistance, and resilience of whole river basins with human alterations. Frontiers in Ecology and the Environment 12(1): 48-58.

Meitzen KM, Doyle M W, Thoms MC, Burns CE (2013) Geomorphology within the interdisciplinary science of environmental flows. Geomorphology 200: 143-154.

Merritt DM, Cooper DJ (2000) Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River Basin, USA. Regulated Rivers: Research & Management 16(6): 543-564.

Montgomery DR (1999) Process domains and the river continuum. Journal of the American Water Resources Association, 35(2): 397-410.

Montgomery DR, Buffington JM (1998) Channel processes, classification, and response. In: Naiman, RJ, Bilby RE (eds.) River Ecology and Management.-Lessons from the Pacific Coastal Ecoregion. New York: Springer-Verlag, 13-42.

Morán-Tejeda E, Ceballos-Barbancho A, Llorente-Pinto J M, López-Moreno J I (2012) Land-cover changes and recent hydrological evolution in the Duero Basin (Spain). Regional Environmental Change *12*(1): 17-33.

Niemeijer D, de Groot RS (2008) A conceptual framework for selecting environmental indicator sets. Ecological Indicators 8(1):14-25.

O'Hanley JR (2011) Open rivers: barrier removal planning and the restoration of free-flowing rivers. Journal of Environmental Management, 92(12): 3112-3120.

Olden JD, Poff NL (2003) Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19: 101-121.

Ollero A, Ibisate A, Gonzalo L.E., Acín V, Ballarín D, Díaz E, Domenech S, Gimeno M, Granado D, Horacio J, Mora D, Sánchez M (2011) The IHG index for hydromorphological quality assessment of rivers and streams: updated versión. Limnetica 30(2): 255-262.

Osei NA, Gurnell AM & Harvey GL (2015) The role of large wood in retaining fine sediment, organic matter and plant propagules in a small, single-thread forest river. Geomorphology 235: 77-87.

Pander J, Geist J (2013). Ecological indicators for stream restoration success. Ecological indicators 30: 106-118.

Philips JD (2002) Sources of nonlinear and complexity in geomorphic systems. Progress in Physical Geography 26(3): 339-361.

Poff, NL, Allan, JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg, J. C. (1997) The natural flow regime. BioScience, 769-784.

Polvi LE, Wohl EE, Merritt DM (2011) Geomorphic and process domain controls on riparian zones in the Colorado Front Range. Geomorphology 125(4): 504-516.

Pont D, Piégay H, Farinetti A, Allai, S, Landon N, Liébault F, Dumont B, Richard-Mazet A (2009) Conceptual framework and interdisciplinary approach for the sustainable management of gravel-bed rivers: the case of the Drôme River basin (SE France). Aquatic sciences 71(3): 356-370.

Poole GC (2002) Fluvial landscape ecology: addressing uniqueness within the river discontinuum. Freshwater Biology 47(4): 641-660.

Poole GC (2010) Stream hydrogeomorphology as a physical science basis for advances in stream ecology. Journal of the North American Benthological Society 29(1): 12-25.

Rapport DJ, Hildén M (2013) An evolving role for ecological indicators: From documenting ecological conditions to monitoring drivers and policy responses. Ecological Indicators 28: 10-15.

Reid HE, Brierley GJ, McFarlane K, Coleman SE, Trowsdale S (2013) The role of landscape setting in minimizing hydrogeomorphic impacts of flow regulation. International Journal of Sediment Research 28(2): 149-161.

Richards K, Brasington J, Hughes F (2002) Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy. Freshwater Biology 47(4): 559-579.

Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10: 1163–1174.

Rinaldi M (2003) Recent channel adjustments in alluvial rivers of Tuscany, Central Italy. Earth Surface Processes and Landforms 28(6): 587-608.

Rinaldi M, Surian N, Comiti F, Bussettini M (2013) A method for the assessment and analysis of the hydromorphological condition of italian streams: The morphological quality index (MQI). Geomorphology 180–181(0): 96-108.

Rinaldi M, Surian N, Comiti F, Bussettini M (2015a) A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology, doi: 10.1016/j.geomorph.2015.05.010.

Rinaldi M, Gurnell AM, González del Tánago M, Bussettini M, Hendricks D (2015b) Classfication and characterization of river morphology and hydrology to support management and restoration. Aquatic Sciences, this volume.

Schmidt JC, Wilcock PR (2008) Metrics for assessing downstream effects of dams. Water Resources Research 44, W04404.

Shields Jr, F.D, Copeland R R, Klingeman PC, Doyle MW, Simon A (2003). Design for stream restoration. Journal of Hydraulic Engineering 129(8): 575-584.

Simon A, Curini A, Darby SE, Langendoen EJ (2000) Bank and near-bank processes in an incised channel. Geomorphology 35(3): 193-217.

Simon A, Rinaldi M (2006) Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79(3): 361-383.

Singh RK, Murty HR, Gupta,SK, Dikshit AK (2009) An overview of sustainability assessment methodologies. Ecological indicators 9(2): 189-212.

Sparovek G, Ranieri SBL, Gassner A, De Maria IC, Schnug E, dos Santos RF, Joubert A (2002) A conceptual framework for the definition of the optimal width of riparian forests. Agriculture, ecosystems & environment 90(2): 169-175.

Stanford JA, Ward JV (1993) An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. Journal of the North American Benthological Society: 48-60.

Stromberg JC, Beauchamp VB, Dixon MD, Lite S J, Paradzick C (2007) Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. Freshwater Biology 52(4): 651-679.

Surian N, Rinaldi M (2003) Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50(4): 307-326.

Thomson JR, Taylor MP, Fryirs KA, Brierley GJ (2001) A geomorphological framework for river characterization and habitat assessment. Aquatic Conservation: Marine and Freshwater Ecosystems 11(5): 373-389.

Thorp JH, Thoms MC, Delong M D (2006) The riverine ecosystem synthesis: biocomplexity in river networks across space and time. River Research and Applications 22(2): 123-147.

Tockner K, Malard F, Ward JV (2000) An extension of the flood pulse concept. Hydrological processes 14(16-17): 2861-2883.

Van Looy K, Tormos T, Souchon Y (2014) Disentangling dam impacts in river networks. Ecological indicators 37: 10-20.

Vannote RL, Minshall, GW, Cummins KW, Sedell JR, Cushing CE (1980) The river continuum concept. Canadian journal of fisheries and aquatic sciences 37(1): 130-137.

Vaughan IP, Diamond M, Gurnell AM, Hall KA, Jenkins A, Milner NJ, Naylor LA, Sear DA, Woodward G, Ormerod SJ (2009) Integrating ecology with hydromorphology: a priority for river science and management. Aquatic Conservation Marine and Freshwater Ecosystems 19:113–125.

Vericat D, Batalla RJ (2006). Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. Geomorphology 79(1): 72-92.

Villeneuve B, Souchon Y, Usseglio-Polatera P, Ferréol M, Valette L (2015) Can we predict biological condition of stream ecosystems? A multi-stressors approach linking three biological indices to physico-chemistry, hydromorphology and land use. Ecological Indicators 48: 88-98.

Vogel RM (2011) Hydromorphology. Journal of Water Resources Planning and Management 137: 147-149.

Ward JV (1989) The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society: 2-8.

Ward JV, Tockner K, Arscott DB, Claret C (2002) Riverine landscape diversity. Freshwater Biology 47(4): 517-539.

Ward JV, Stanford JA (1983) The serial discontinuity concept of lotic ecosystems. Dynamics of lotic ecosystems 10: 29-42.

Wyżga B, Zawiejska J, Radecki-Pawlik A, Hajdukiewicz H (2012) Environmental change, hydromorphological reference conditions and the restoration of Polish Carpathian rivers. Earth Surface Processes and Landforms 37(11): 1213-1226.

Table 1.- Set of hydromorphological indicators representative of key processes, features and pressures at spatial scales from catchment to river reach.

SPATIAL UNIT	***KEY PROCESSES / FEATURES***	***INDICATORS*** *(indicative units)*	***FUNCTION (+)***	***HYDROMORPHOLOGICAL RELEVANCE AND RIVER MANAGEMENT IMPLICATIONS***
CATCHMENT	Water production	Catchment area (km^2)	D	Governs the magnitude of hydrological processes at a broad scale. Effective catchment area may be altered by large water transfers, causing significant changes in runoff
		Annual runoff (mm)	D, A	Indicative of the general hydrologic response of the catchment. When compared with annual precipitation over time, may reflect the influence of climate or land cover changes (e.g., García Ruiz et al., 2011)
		Geology (% area WFD classes)	D	A permanent physical control of hydrological processes at broad scale (Grant et al., 2003)
		Land cover (% area CORINE level 1 classes)	D, A	A physical control of hydrological processes that may change over time (e.g., García-Ruiz and Lana-Renault, 2011)
LANDSCAPE UNIT	Runoff production /retention	Exposed aquifers, permanent snow-ice cover (% area)	D	A permanent physical controls of hydrologic response, indicative of high precipitation storage capacity determining delayed runoff
		Soil-parent material permeability (% classes)	D	Reflects hydrologic behaviour of land surface influencing predominant patterns and pathways of runoff, including relative magnitude of baseflows
		Rapid, intermediate, delayed runoff production areas (% area falling into each classes based on land cover and use types)	D, A	Land cover and land use potential to produce rapid runoff and high river flows associated with bare soils, agriculture intensification, urban areas (e.g., Chin, 2006); to encourage water infiltration and retention to produce delayed runoff supporting baseflows. Land cover changes towards increasing forest land have been related to hydrologic decline and morphological channel changes (e.g., Morán-Tejeda et al., 2012; González del Tánago et al.,2015b)
		Large surface water bodies (% area)	D, A	Whether natural lakes, reservoirs or artificial water bodies, their cover is indicative of flow storage with impacts on runoff response

	Fine sediment production	Soil erosion rates (t,ha^{-1}, year^{-1})	A	Amounts of fine sediments released by soil erosion for potential delivery to the river network and then may contribute to adjustments in channel form and bed sedimentary structure (e.g., Grabowski and Gurnell, 2015).
	Coarse sediment production	Coarse sediment source areas (% area with unstable slopes, gullies, etc.)	D, A	Active sources of coarse sediments for potential delivery to the river network where they influence channel morphology and behaviour. Their reduction by farm abandonment and afforestation works in mountain areas contribute to the sediment deficit downstream from dams and reservoirs (e.g., Liébault and Piégay, 2002; Pont et al., 2009).
RIVER SEGMENT	River flow regime and extreme values	Flow regime type *	D, A	A major control on the functions of river ecosystems (Poff et al., 1997), whose magnitude and temporal characteristics are frequently altered by flow regulation by dams and reservoirs, and major water abstractions.
		Average annual flow (m^3 s^{-1}), Baseflow index (%)	D, A	Indicates magnitude of discharge and importance of baseflow contribution
		Magnitude of maximum annual flows of geomorphic interest (e.g.,1.5, 2, 10 year floods) (m^3 s^{-1})	A	Peak flows of relatively short recurrence intervals (i.e., bankfull discharge, effective discharge) have strong influence on channel size, are a key criterion used in river assessment and design (Shields et al., 2003) and are frequently reduced by dam implementation and flow regulation (Graf, 2006)
		Timing of maximum flows (Julian day)	A	An important property of the natural flow regime, that is crucial for riparian vegetation recruitment, the life cycles of many aquatic and riparian organisms, and the control of invasive species (Stromberg et al., 2007)
		Magnitude of 1-day, 7-days and 30-days minimum flows (m^3 s^{-1})	A	Indicates duration of soil moisture stress for plants, low oxygen and high water chemical concentrations, dehydration in animals (Richter et al., 1996), and is frequently altered by flow regulation, particularly in association with irrigation.
		Timing of minimum flow period (Julian period)	A	A further important property of the natural flow regime, with similar relevance to the timing of maximum flows
		Eroded soil delivery (t year km^{-2})	A	Indicates the potential supply of finer sediments from areas close to the river that influence the rivers wash load.
		Suspended sediment transport	A	The wash and suspended sediment load transported by the river determines

	Sediment delivery and transport regime	(mg l^{-1}, t year^{-1} km^{-2})		water turbidity, which impacts on aquatic organisms, and contributes to channel adjustments and physical habitat clogging. Suspended load dominated systems have limited capacity to rework their boundaries and are highly exposed to aggradation and vegetation encroachment (e.g., Dean and Schmidt, 2011)
		Bed load transport (t year^{-1} km^{-2})	A	The bedload transported by the river is a main component of channel planform and bedform dynamics. It is frequently altered by the trapping effect of reservoirs (e.g., Vericat and Batalla, 2006) and gravel mining (e.g., Rinaldi, 2003)
		Sediment budget (Sediment Outputs – Inputs within the segment: > 0: Loss, degradation; =0: Balanced; <0: Gain, storage)	A	The deficit or surplus of sediment within the segment may lead, respectively, to bed incision and/or bank erosion or to bed and/or bank aggradation (e.g., Simon and Rinaldi, 2006; Schmidt and Wilcock, 2008; Grabowski and Gurnell, 2015). It may assess the impacts of land use changes affecting the sediment regime between tributaries
	Valley features	Valley confinement (Confined, Partly confined, Unconfined)	D	Primary control on river channel adjustments and characteristics including the potential river channel planform types that may be present (Brierley and Fryirs, 2005; Rinaldi et al., 2015b)
		Valley gradient (m m^{-1}, %)	D	Controls the maximum feasible channel slope, and then influences river flow energy and potential to transport sediment
		Valley width (m), River confinement (or entrenchment) index	D	Indicate the maximum lateral extent of potential fluvial processes (i.e., flooding, alluvial forest development), and the degree to which the river is confined within its valley (e.g., Polvi et al., 2011).
	Riparian corridor size, functions and wood delivery potential	Size of riparian corridor (average width, m)	A	Refers to envelope enclosing all apparently functioning riparian (woodland) vegetation. Indicative of spatial extent / magnitude of hydromorphological interactions with vegetation, and potential riparian buffer functions as filters, sediment sinks and sources (Sparovek et al., 2002)
		Longitudinal continuity / fragmentation of riparian vegetation along river edge (% of river length)	A	Refers to extent to which riparian (woodland) vegetation extends along the river channel edges. Indicates the degree to which riparian functions, including wood delivery, are maintained along the segment. Fragmentation and disruption of continuity is frequently associated with agriculture or urban development (e.g., Fernandes et al., 2011).
		River channel edges bordered by mature trees	A	Indicates potential for the recruitment of large wood to the river

		Dominant riparian plant associations	D, A	Supports diagnosis of the naturalness of the riparian vegetation and the presence of exotic or invasive species.
	Disruption of longitudinal continuity	Number of major blocking structures (dams, large weirs, etc, can be separated into high or intermediate impact according to their size and functioning)	A	Indicates the frequency and intensity of major interruptions to water flow and sediment transport and barriers to fish migration. The intensity of their impact is proportional to the height of the structural barrier and the way of the reservoir management. Prioritization for their removal to enhance river connectivity has been deeply studied by O´Hanley (2011).
RIVER REACH	Channel types and dimensions	River channel and floodplain types **	D, A	The main synthetic indicators of channel form and processes
		Planform properties (Sinuosity index, braiding index, anastomosing index) ***	A	Indicative of dominant channel processes and river adjustments. Changes in sinuosity, braiding or anastomosing index values are indicative of flow or sediment supply alterations (e.g., Gendaszek et al., 2012)
		Channel dimensions Channel bankfull width, depth (m)	A	Indicative of the capacity of the river channel to accommodate flows. Changes in the active channel width closely reflects land use changes and flow regulation by dams and reservoirs (Graf, 2006)
		Channel slope ($m\ m^{-1}$, %)	A	A major control (with discharge) on river flow energy and thus the ability to transport sediment and rework channel boundaries Closely related to channel planform (Eaton et al., 2010)
		Bed and bank sediment size (descriptive category , or D_{50}, cm)	D, A	The sediments bounding the river channel and thus act as a control on river size, dynamics, type and geomorphic units
		Geomorphic units: abundance and type of channel and floodplain units	D, A	Indicative of river energy and sediment processes. Typical assemblages of geomorphic units are associated with different river channel and floodplain types and so providing an indication of degree of natural function. Geomorphic units are also indicative of changes in flow and/or sediment availability and channel adjustments. Such changes are often a consequence of flow regulation or land cover changes (e.g., Lobera et al., 2015)
	Flooding extent	% of floodplain accessible by flood water, floodplain inundation frequency	A	Indicative of the potential lateral connectivity between the river and its floodplain and the riverine landscape heterogeneity (Ward et al., 2002). Frequency with which floodplain flow disturbances occur

	River energy and channel adjustments	Specific stream power at 'bankfull' discharge (W m^{-2})	A	Indicative of available river energy for sediment entrainment and transport and thus for channel and geomorphic unit adjustments
		Extent of eroding/aggrading banks (% active channel length)	A	Reflect bank processes of erosion and construction indicative of contemporary adjustments. Bank profiles are indicative of main bank erosion processes by hydraulic action or mass failure (Brierley and Fryirs, 2005), and vertical adjustments in bed level (incision, aggradation) (e.g., Simon et al., 2000)
		Lateral bank movement (m year^{-1})	A	Indicative of longer term bank erosion / aggradation resulting channel migration, widening or narrowing
		Number, extent of bare gravel bars, and vegetated gravel bars / benches / islands	A	Bare gravel bars are active depositional forms that are indicative of connectivity of sediment supply and sometimes active accumulation of sediment. Vegetated gravel bars, benches and islands are relatively immobile depositional forms where vegetation has stabilised and often induced aggradation of the surface. Where they are abundant, they indicate vegetation encroachment and channel narrowing, which is frequently promoted by flow regulation (e.g., Horn et al., 2012; Lobera et al., 2015; González del Tánago et al., 2015a,b).
		Bed incision / aggradation rates (m, cm y^{-1})	A	Channel bed incision is frequently associated with gravel mining, channelization works and damming (e.g., Simon and Rinaldi, 2006, Martín-Vide et al., 2010). Aggradation is frequently associated with changes of land cover or management leading to soil erosion (i.e., increase of sediment supply) or flow regulation (i.e.,decrease of sediment transport capacity) (e.g., Gaeuman et al., 2005)
	Riparian Vegetation succession and encroachment	Proportion of riparian corridor under riparian vegetation (% coverage)	A	Indicates the proportion of the potential corridor that has a functioning riparian vegetation cover
		Age structure of dominant plant associations (% old, mature, young forest, Salicacea recruitment)	A	Reflects landform diversity associated to flood disturbance and channel mobility (Richards et al., 2002). Indicates riparian forest sustainability under current conditions (i.e., potential for recruitment, growth and turnover of riparian trees) and functioning of rejuvenating and maintenance mechanisms (Corenblit et al., 2007). Salicacea species are the more frequent pioneer species colonizing exposed sediments in floodplain habitats (Karrenberg et al., 2002)
		Riparian vegetation patchiness (form index) and average size of	A	Reflects riparian vegetation structure and fragmentation associated to soil moisture availability and flood disturbance. Increasing vegetated patch size may

		patches (m^2)		indicate vegetation encroachment likely associated to flow regulation, whereas decreasing vegetation coverage and patch size may imply hydrologic decline by groundwater abstraction, land drainage, flow regulation, climate change
		Lateral functional zones (% area of riparian corridor)	A	Presence of a lateral gradient from proximal, flood disturbance-dominated to distal soil moisture-dominated zones (Gurnell et al., 2015b), reflects long-term functioning of riparian vegetation – fluvial process interactions.
	Aquatic vegetation	Aquatic plant coverage (% river channel bed) Number of aquatic plant morphotypes	A	Indicative of river energy and hydraulic conditions and plant influence on channel roughness, flow conveyance, and retention and stabilisation of fine sediments within the channel (Gurnell et al., 2010, 2013). Increases in cover or associated geomorphic units over time indicate vegetation encroachment and channel narrowing, which is frequently due to reductions in discharge and flow velocity. Number of morphotypes reflect plant diversity
		Aquatic plant dependent geomorphic units (absent, occasional, present, abundant)	A	Indicate extent of contemporary geomorphic adjustments induced by aquatic plants.
	Large wood	Large wood and fallen trees in channel and riparian corridor (absent, occasional, present, abundant)	A	Reflects longitudinal and lateral connectivity within the river system and degree of human wood removal. Large wood retains fine sediment, organic matter and plant propagules (Osei et al., 2015) and stabilises floodplains (Abbe and Montgomery, 2003; Collins et al., 2012).
		Wood budget (good, moderate, degraded, severely degraded)	A	Quantity of wood present in comparison with the potential quantity in the absence of human management, indicates the degree to which wood impacts on the river ecosystem are artificially degraded
		Large wood and riparian tree dependent geomorphic units (absent, occasional, frequent, abundant)	A	Indicate extent of landforms and associated physical habitats induced by the presence of large wood and trees, particularly within the river channel (Gurnell et al, 2001, Abbe and Montgomery, 2003).
		% channel length with bank revetments, embankments, artificial levees	A	Indicative of human pressures and impacts preventing bank erosion and lateral channel mobility and adjustments, and thus altering the lateral dimension of the river ecosystem and the potential of riparian functions. A complementary

				indicator is % potentially erodible channel banks.
	Constraints on channel adjustments and lateral and vertical connectivity	Average width of erodible corridor (m, channels widths)	A	Indicative of the width of the corridor that could potentially be eroded because not stabilised by revetments, embankments, artificial levees and other forms of human reinforcement or control.
		Number and size of channel blocking structures (stated at segment unit scale)	A	Indicative of the severity of human interventions providing obstructions to within-reach longitudinal continuity of water, sediment and biota
		% channel bed reinforced % paved or sealed floodplain	A	Indicative of severity of human interventions affecting vertical bed level adjustment and bed sediment mobilisation, and connectivity with groundwater and the hiporheic
		% channel and floodplain affected by gravel extraction or dredging	A	Indicative of human pressures that may explain incision processes and sediment deficit downstream (Rinaldi, 2003)
		Intensity of riparian forest management and wood removal	A	Indicative of human interventions in the natural functioning of riparian woodland altering wood delivery and wood dependent geomorphic units

(+) Main function of the indicator as: (D): Descriptive criterion, no expected to change over time; or (A) audit and assessment criterion, expected to change over time in response to natural or human-induced process changes or direct human interventions

*Flow regime types are described elsewhere in this special issue by Rinaldi et al. (2015b)

**River channel and floodplain types are described elsewhere in this special issue by Rinaldi et al. (2015b).

***Braiding /Anastomosing Index: Average number of active channels separated by bars/islands measured at a minimum of 10 cross sections.

Table 2 Hydromorphological indicators for the River Frome catchment, southern England at the catchment scale

Indicator	**Value**[1]
Catchment area (km^2)	459
Annual runoff (mm)	507
Geology (WFD types)	
% siliceous	40%
% calcareous	60%
% organic	0%
% mixed /other	0%
Land cover (Corine level 1)	
% forest and semi-natural areas	11%
% wetlands	0%
% artificial surfaces	4%
% agricultural areas	86%

1 no evidence for significant change in land cover at (Corine level 1 classes) in last 70 years

Table 3 Hydromorphological indicators for landscape units (LU) 1 and 2 of the River Frome catchment (A slight increase in the area of rapid runoff production has been observed at the expense of intermediate production due to a small expansion in built-up areas over the last 80 years)

Indicator	LU1	LU2	Change
Exposed aquifers (% area)	98	85	No change
Highly permeable soil substratum (% area)	73	98	No change
Large surface water bodies (% cover)	0	0	None present
Land cover / runoff production (based on Corine level 2 and 3[1] and UK Countryside Survey[2] land cover data)			
rapid runoff production area (%)	0[1]	4[1]	Slight increase[2]
intermediate runoff production area (%)	97[1]	94[1]	Slight decrease[2]
delayed runoff production area (%)	2[1]	2[1]	No change
Soil erosion (t. ha^{-1}. year^{-1})	0.09	0.28	No data
Coarse sediment source areas (% area)	0	0	No data

Table 4 Hydromorphological indicators for segments 2 and 3 (with flow regime data for segments 1 and 5 because there are no flow gauging stations in segments 2 and 3).

Indicator	Segment 1	Segment 5	Change between 1966-85 and 1992-2011, in Segment 6
RIVER FLOW REGIME AND EXTREMES (1992-2011)			
Flow regime type*	Perennial super-stable	Perennial stable	Change from perennial stable to perennial superstable
Average annual flow (m^3/s)	0.18	3.30	No change
Baseflow index	53.64	49.69	Increase from 40% to 59%
Annual floods of different return period			
$Q_{pmedian}$	0.62	11.71	Not calculated
Q_{p2}	0.65	11.41	Not calculated
Q_{p10}	1.12	20.00	Not calculated

Indicator	Segment 2	Segment 3	Change
Specific stream power (Q median of maximum one day flow, $W.m^{-2}$)	17.4	13.1	Insufficient data
SEDIMENT DELIVERY AND TRANSPORT REGIME			
Eroded soil delivered (t/year; t/km/year)	14.0, 3.7	31.5, 4.4	Increase inferred from agricultural census data
Sediment budget (modelled)	gain (all sand and finer)	gain (all sand and finer)	Increase inferred from agricultural census data
VALLEY FEATURES			
Valley gradient (m/m)	0.005	0.003	No change
Valley confinement	Unconfined	Unconfined	No change
River confinement	13.77	20.07	No change
RIPARIAN CORRIDOR SIZE, FUNCTIONS AND WOOD DELIVERY POTENTIAL			
Average riparian corridor width (m)	122	227	Minimal change
Continuity of riparian vegetation along river edge	30%	27%	Minimal change
Age structure of riparian vegetation	Balanced	Mature	No data
River channel edges bordered by mature trees	14%	24%	Minimal change
DISRUPTION OF LONGITUDINAL CONTINUITY (MAJOR BLOCKING STRUCTURES)			
High	0	0	No change
Medium	3	3	No change

* one of nine possible regimes defined by Rinaldi et al. (2015b)

Table 5 .-Hydromorphological indicators and assessments for reaches 4, 5, and 6 of the River Frome

River Reach (Landscape Unit, River Segment)	**4 (1, 2)**	**5 (2, 3)**	**6 (2, 3)**
CHANNEL AND FLOODPLAIN bed sediment size, and TYPE AND DIMENSIONS			
Reach slope ($m.m^{-1}$)	0.006	0.003	0.004
River channel slope ($m.m^{-1}$)	0.006	0.002	0.004
(Main) channel bankfull width (m)	6.5	9.1	13.9
(Main) channel bankfull depth (m)	1.15	1.45	0.97
(Main) channel width:depth ratio	5.6	6.9	14.5
Specific stream power			
Bed sediment size	Sand/Gravel	Gravel/Sand	Gravel/Sand
Bank sediment size	Earth (Silt/Sand)	Earth (Silt/Sand)	Earth (Silt/Sand)
River Type*1	Sand-gravel, sinuous (unconfined)	Sand-gravel, sinuous (unconfined)	Sand-gravel, anabranching (unconfined)
Floodplain Type (condition) *2	Lateral migration, backswamp (highly degraded)	Lateral migration, backswamp (highly degraded)	Anabranching, organic rich (highly degraded)
HYDROMORPHOLOGICAL FUNCTION			
Presence of channel / floodplain geomorphic units typical of river channel / floodplain type	Some	Some	Some
Bed covered by vegetated bars, benches, islands	10-15%	10%	5%
Extent of eroding banks + laterally aggrading banks	44%	55%	30%
Abundance of aquatic-plant dependent geomorphic units	Occasional	Frequent	Frequent
Abundance of large wood and tree dependent geomorphic units	Abundant	Occasional	Occasional
Hydromorphological function assessment	**Good**	**Good**	**Good**
HYDROMORPHOLOGICAL ALTERATION / ARTIFICIALITY			
Number low blocking structures	1	2	2
Number intermediate blocking structures	3	3	0
Number high blocking structures	0	0	0
Longitudinal continuity assessment	**Poor**	**Poor**	**Intermediate**
Flooplain accessible by flood water	100%	100%	100%
Width of erodible corridor (channel widths)	14	22	17
Lateral continuity assessment	**Good**	**Good**	**Good**
Potentially erodible (not reinforced) channel banks	97%	95%	97%
Potentially erodible (not reinforced) channel bed	96%	95%	97%
Adjustment potential assessment	**Intermediate**	**Intermediate**	**Intermediate**
Artificiality assessment	**Some artificial elements**	**Some artificial elements**	**Some artificial elements**
RIPARIAN CORRIDOR FUNCTION / ARTIFICIALITY			
Proportion (%) riparian corridor under riparian vegetation	58	5	21

Lateral functional zones	Absent	Absent	Absent
Proportion riparian corridor under mature, intermediate, early growth riparian vegetation (%, %, %)	19, 7, 74 (balanced)	77, 23, 0 (balanced)	100, 0, 0 (mature)
Presence of fallen trees (in channel)	occasional	absent	occasional
Presence of large wood (in channel)	occasional	occasional	occasional
Wood budget (in channel)	Severely degraded	Severely degraded	Severely degraded
Riparian corridor function assessment	**Partial**	**Very limited**	**Very limited**
HYDROMORPHOLOGICAL ADJUSTMENT			
Contemporary adjustment			
Bed covered by major mid channel bars and islands (%)	Y	N	N
Bed covered by sand and finer sediment (%)	60	44	27
Geomorphic evidence for channel narrowing	N	Y	Y
Geomorphic evidence for channel widening	N	N	N
Historical adjustment			
Change in main channel width 1960/75-2013	-4%	-12%	-16%
Geomorphic evidence for channel bed incision or aggradation	N	N	N
Hydromorphological adjustment assessment	**Bed aggrading**	**Narrowing**	**Narrowing**

*[1] one of 22 types defined by Rinaldi et al. (2015b)

*[2] one of 12 types defined by Rinaldi et al. (2015b)

Figure 1.- Spatial scales considered in the identification of hydromorphological processes and indicators. According to catchment and landscape unit attributes (i.e., size, relief, geology, land cover), different amounts of water and sediments are produced and delivered to the river network. Longitudinal connectivity along river segments determines water and sediment transport downstream. Lateral and vertical dimensions at reach scale govern the predominant pathways of exchange of water and sediments, and the resulting hydromorphological character and functioning of the river system.

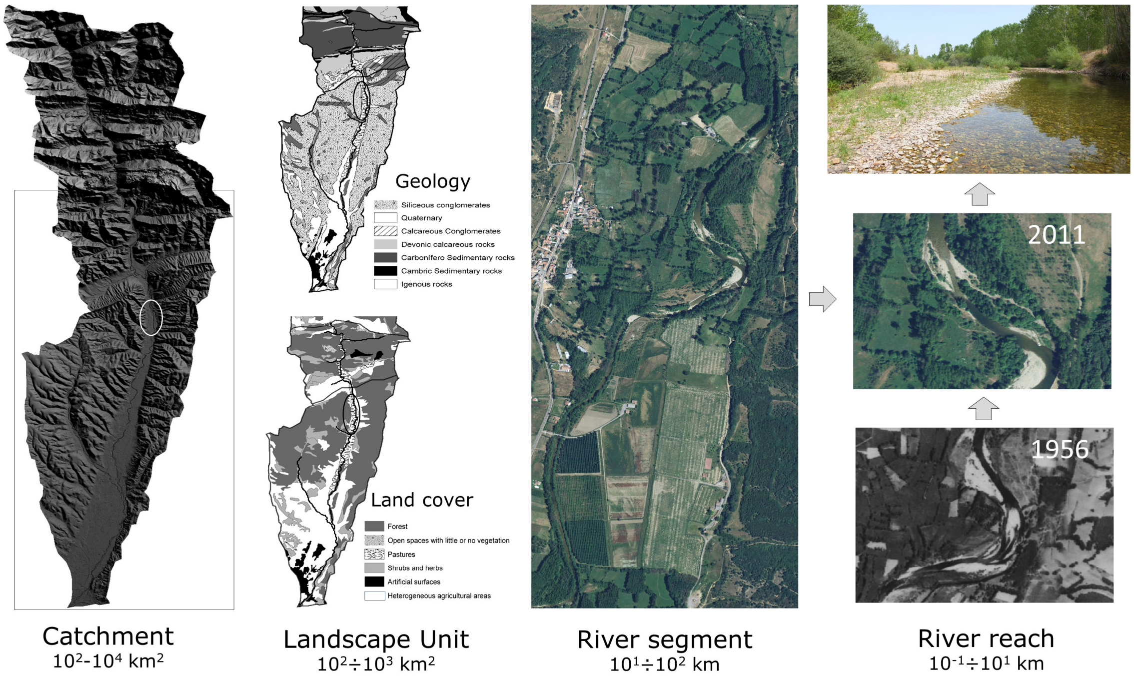

Figure 2.- Hierarchical and causal chain of hydromorphological indicators at different spatial scales, showing their interplay and cascade influence as bordering conditions for hydromorphological processes towards smaller scales.

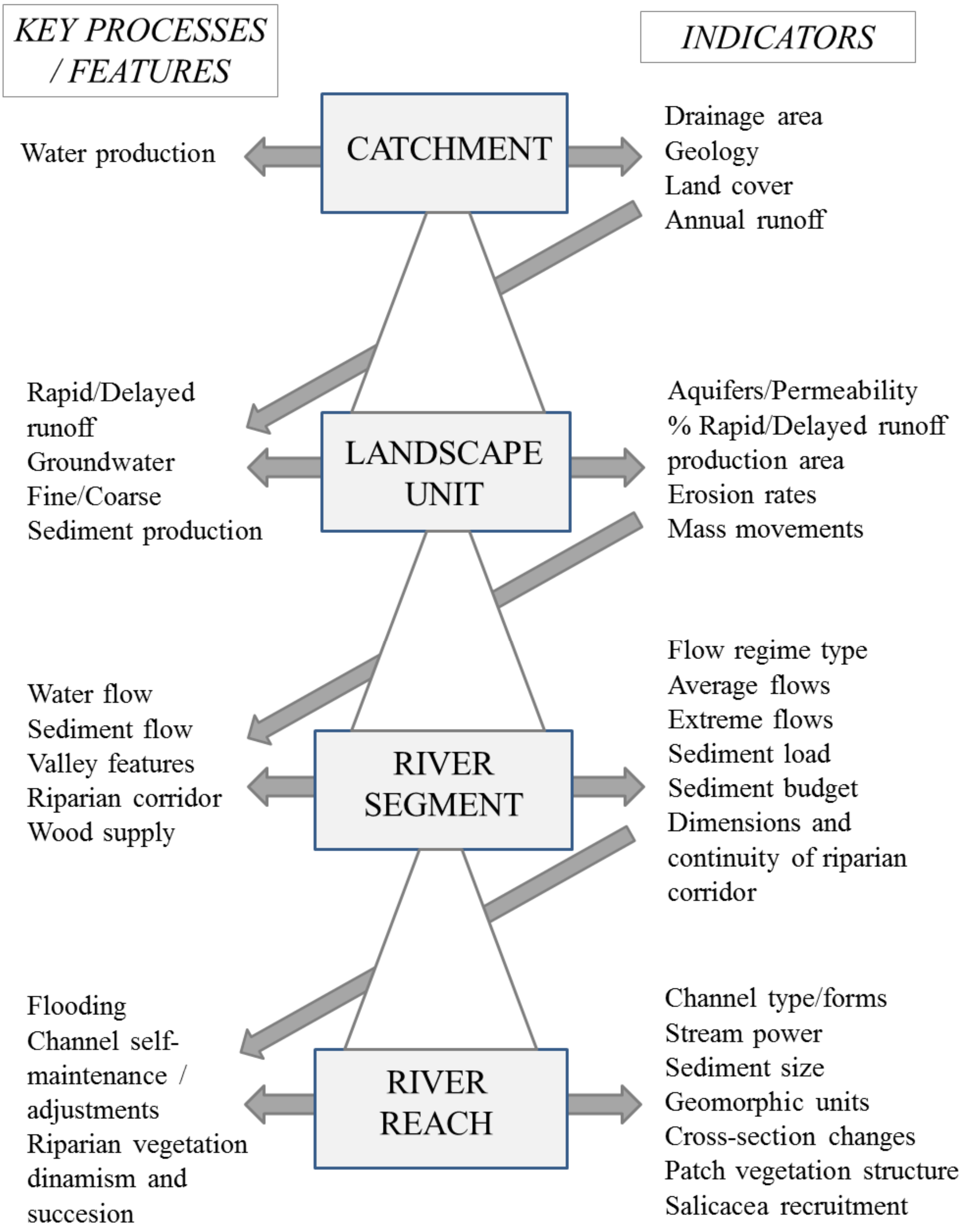

Figure 3.- Delineation of the catchment, three landscape units, six segments and seventeen reaches of the river Frome, UK.