A review of methods for river hydromorphological assessment

B. Belletti [a,]*, M. Rinaldi [a], A.D. Buijse[b], A.M. Gurnell[c], E. Mosselman[b,d]

[a] *Department of Earth Sciences, University of Florence, Italy*

[b] *Deltares, Netherlands*

[c] *Queen Mary University of London, UK*

[d] *Delft University of Technology, the Netherlands*

* Corresponding author: Via S.Marta 3, 50139, Firenze, Italy, Tel: ++390554796225; Fax: ++39055495333; E-mail: barbara.belletti@unifi.it

Abstract

Several hydromorphological assessment methods have been developed in different countries during recent decades, with notable differences in their aims, scales, and approaches. Although these methods are increasingly applied to support river management, the strengths and limitations of the different types of methods have been insufficiently investigated. The main objective of this review is to provide a critical analysis of currently available hydromorphological assessment methods, identifying their main strengths, limitations, omissions, the potential for integration of different approaches, and the need for further improvements.

To address these aims, methods have been grouped into four categories of hydromorphological assessment: (1) physical habitat assessment; (2) riparian habitat assessment; (3) morphological assessment; (4) assessment of hydrological regime alteration.

The general characteristics and information recorded by 121 methods are reviewed, allowing for a comparative analysis of the four assessment categories. ~~Based on this comprehensive review, strengths and limitations have been identified for each of the four categories of hydromorphological methods.~~ The main gap in most methods is insufficient consideration of physical processes. Thus, an integrated hydromorphological analysis is recommended, where the morphological ~~(3)~~ and hydrological ~~(4)~~ components are the key parts for the classification of hydromorphological conditions. Besides, physical ~~(1)~~ and riparian habitat ~~(2)~~ methods allow for a better characterization and improved potential linkages with ecological conditions.

Keywords

Hydromorphology, Physical habitats, Riparian habitats, Hydrological regime, Morphological alteration

Introduction

In recent decades, hydromorphology has been developed as an umbrella discipline that links hydrology and geomorphology, and places the consideration of physical stream characteristics and processes at the centre of river management and restoration (Newson and Large 2006; Vaughan et al. 2009). Within Europe, it has developed rapidly and numerous methodologies have been proposed following the introduction of the EU Water Framework Directive (WFD; European Commission 2000), which requires the incorporation of hydromorphology into the assessment and monitoring of all European water bodies, including consideration of hydrological regime (i.e., quantity and dynamics of water flow and connection to groundwater bodies), river morphology (i.e., channel dimensions and mobility, river bed structure and substrate calibre, and the structure of the riparian zone), and river continuity.

Hydromorphological assessment can be defined as an evaluation and classification of both hydrological and geomorphological stream conditions. It ~~Hydromorphological assessment~~ includes those ~~consists of a suite of~~ methods and procedures that identify and characterize hydromorphological features in order to assess river conditions. The many existing ~~operational~~ methods ~~that have been developed for application in different countries~~, vary widely in terms of their ~~their underlying~~ concepts, ~~and~~ aims, ~~the~~ spatial scales ~~at which they are applied~~, ~~the~~ collected data ~~that are collected,~~ and outputs ~~the indicators that are derived from the data~~.

Towards the end of the 20th century, hydromorphological assessment mainly focussed upon types and abundances of physical habitats (e.g., Platts et al. 1983; Plafkin et al. 1989; Raven et al. 1997, 2002). This was because physical habitats were recognized as an important component in ecological studies that aimed at explaining distributional patterns of organisms, and the composition and structure of biological communities (Fernández et al. 2011). During the last decade, it has been recognised that broader *river condition assessments* are needed that go beyond an inventory of physical habitats to include the measurement of “pressure” or “response” variables with a stronger emphasis on river dynamics and processes (Fryirs et al. 2008). However, integration of the full range of disciplinary approaches necessary to assess river conditions (hydrology, geomorphology, water quality, biology, ecology) in a robust way remains a challenge.

There have been a number of recent reviews of hydromorphological assessment methods that emphasise river habitat characterization (e.g., Weiss et al. 2008; Fernández et al. 2011), and there have also been attempts to standardise these habitat-based methods (CEN 2002; Parsons et al. 2004). However, many new methods~~,~~ employing a wider range of geomorphological concepts and approaches~~,~~ have been proposed in the last decade.~~ Furthermore,~~ Indeed ~~although ~~hydromorphological assessment is now carried out by many public agencies, particularly within the European Union as a part of implementation of the WFD~~,~~. Nevertheless in many cases there is still an insufficient awareness of the limitations and strengths of different methods, and of how they should be integrated to ensure a robust assessment. In response to these needs, an extensive review analysis of existing hydromorphological methods (Rinaldi et al. 2013b) has been carried out in the context of REFORM (REstoring rivers FOR effective catchment Management; http://www.reformrivers.eu/), a collaborative EU project targeted towards development of guidance and tools to make river restoration and mitigation measures more cost-effective. The review takes recent published reviews, mainly focussed on river habitat characterization, as its starting point (Raven et al. 2002; McGinnity et al.

2005; Weiss et al. 2008; Fernández et al. 2011). It represents an extension of the review of Fernández et al. (2011), which incorporated 55 mainly habitat-based assessment methods that have been developed worldwide, by incorporating a total of 121 methods. It synthesizes the results, identifying and discussing the main strengths, limitations and gaps in existing methods, and~~ in order to~~ proposes future directions for hydromorphological assessment. It also touches briefly ~~ression~~ on methods specifically developed in Europe, in relation to the implementation of the WFD. The review does not aim to discuss the scientific principles and concepts that underlie hydromorphological and river condition assessments, since these are reported in other recent reviews (e.g., Fryirs et al. 2008), but it aims to compare and discuss methods in a critical way, starting from the knowledge and expertise of the authors.

~~**Methods, categories and properties of hydromorphological assessments**~~ **Scope of the review**

~~In this section the meaning of *hydromorphological assessment* in the context of this review is defined; some broad types of assessment are identified; and the characteristics that were extracted for each hydromorphological assessment method are described.~~

~~Hydromorphological assessment can be defined as an evaluation and classification of both hydrological and geomorphological stream conditions. This review takes previously published, recent reviews, mainly focussed on river habitat characterization, as its starting point (Raven et al. 2002; McGinnity et al. 2005; Weiss et al. 2008; Fernández et al. 2011). Specifically, it represents an extension of the~~

~~review of Fernández et al. (2011), which incorporated fifty-five mainly habitat-based assessment methods that have been developed worldwide.~~

The range of application of the methods considered in this review varies from those applicable to small, wadeable streams to those suited to relatively large, non-wadeable rivers. It is restricted to physics-based assessments, i.e., methods that address all or some of the physical elements required for a hydromorphological evaluation. Therefore, methods for the assessment of longitudinal fish continuity are not included, as they have a biological focus, although they were included in the broader review of Rinaldi et al. (2013b). It also excludes physical habitat simulation models and environmental flows methods, as they differ in structure and approach from the truly hydromorphological (i.e., hydrological *and* geomorphological) assessments considered here. Indeed, habitat simulation and environmental flow methods aim to identify~~,~~ habitats and flow requirements respectively~~,~~ needed to achieve and/or maintain a specified river condition (Arthington 1998; King et al. 2008), rather than to directly assess hydromorphological condition, alteration and pressures. For some examples of habitat modelling approaches see Rinaldi et al. (2013b), and for environmental flows, refer to Arthington (1998), King et al. (2008) and to the recent review of Poff and Zimmerman (2010).

The 121 methods reviewed, are listed in Table 1. ~~included in this review~~. ~~Each method was systematically analyzed, drawing mainly on information found in scientific papers and, where available, technical reports. In some cases, additional information was requested from authors or practitioners who were directly involved in the development and/or use of specific methods.~~

(Table 1)

Categories of Methods

An initial inspection of these hydromorphological methods four broad categories of assessment, although a sharp delineation is difficult and some overlap between types inevitably exists. These were identified based on the main focus and objectives of each method, which were reflected in the spatial scale of application (Fig. 1). A temporal trend is apparent in the development and application of different approaches (Fig. 2). The earliest assessment methods started to appear at the beginning of the 1980s. Until the end of the 1990s, proposed methods can mainly be described as physical habitat survey procedures~~, with only a few examples of morphological methods~~. This first phase reflects the progressive development of river restoration techniques, which initially consisted of rather small-scale, localized interventions for habitat improvement. The introduction of the WFD marked a notable increase in the number of new methods developed in Europe, but most of these continued to be physical habitat surveys. Only in recent years, a significant increase in morphological and hydrological methods occurred, as a consequence of the increasing need to use catchment-wide and process-oriented approaches for implementing river restoration projects.

(Figure 1)

(Figure 2)

Methods for physical habitat assessment

This category includes~~ From the early 1980s~~ methods and protocols for the survey, characterization, and classification of physical habitat elements which can~~ were developed which can~~ be described as river habitat surveys or physical habitat assessments (e.g., Platts et al. 1983; Plafkin et al. 1989; Raven et al. 1997; Ladson et al. 1999; National Environmental Research Institute 1999; LAWA 2000, 2002a, b). These focus mainly on instream habitats or microhabitats, but generally they also include some consideration of riparian habitats. ~~They often provide one or more indices that attempt to evaluate deviation from some reference condition. ~~Methods that aim to evaluate the overall functioning of the stream (e.g., method 39; Table 1) by including information on ecology-related features, are also included in this category, although they are not strictly habitat survey methods. Seventy-three physical habitat assessment methods were identified, illustrating that this type of assessment remains the most common approach for assessing the hydromorphological state of a river (Table 1, Fig. 2).

Methods for riparian habitat assessment

Riparian zones~~ systems~~ are an integral component of riverine systems, since their lateral and vertical~~ form and vegetation~~ structures depend upon hydromorphological processes. However, the development of specific methods for assessing riparian ~~ecosystem ~~conditions is relatively recent (Fig. 2). Some indicators of riparian conditions are often included in one of the other types of assessment methods, but this particular category consists of methods that are specifically designed for the characterization of habitats in the riparian zone (e.g., Munné and Prat 1998), including some assessments of wetland ecosystem functioning (methods 74, 78; Table 1). Fifteen riparian habitat methods were identified (Table 1).

Methods for morphological assessment

This category includes methods with the following distinctive characteristics differing from the category of physical habitat assessment: (1) they make a broader evaluation of river conditions including assessing channel forms, geomorphic adjustments, and human alterations; (2) the spatial scale is typically the ‘reach’ scale, i.e. a variable length with sufficiently homogeneous morphological characteristics and boundary conditions.

Following the development of physical habitat assessment methods, this type of broader assessment of river conditions has emerged, particularly during the last decade (Fig. 2). In this regard, Fryirs et al. (2008) suggest that a clear distinction should be made between a *river audit* and a *river condition assessment*. A *river audit* permits assessment of river status by generating~~es~~ information on the presence and frequency of physical habitats and their characteristics~~,~~. ~~while~~ A *river condition assessment* is a broader evaluation which places greater emphasis on physical processes, and aims to measure both pressure and response variables (i.e., hydromorphological and biological indicators) as a basis for developing a clearer understanding of the cause-effect relationships that regulate observed changes in system conditions. The ‘morphological assessment’ category contains methods that can be described as *river condition assessments*. A total of 22 methods were identified (Table 1).

Methods for the assessment of hydrological regime alteration

This category encompasses a further, independent, group of methods~~ area of progress~~ that produce hydrological assessments, particularly the development of specific indicators of hydrologic alteration (method 118; Table 1; Richter et al. 1996; Poff et al. 2003), which can support assessments of the alteration of the natural hydrological regime. The output of these assessments is usually an index of the degree of deviation from unaltered conditions. As previously noted, the related *environmental flows methods* are not included in this review because their specific aim is an evaluation of flow requirements for aquatic ecosystems and species, rather than a direct assessment of the flow regime and its alterations (Arthington 1998; King et al. 2008; Poff and Zimmerman 2010)~~ provide extensive reviews of environmental flow methods. In our review,~~ A total of 11 hydrological methods were identified (Table 1).

~~Survey of method characteristics and recorded features~~ Methodology

Each method was analyzed, drawing mainly on information found in scientific papers and, where available, technical reports. In some cases, additional information was requested from authors or practitioners who were directly involved in the development and/or use of specific methods.

In a similar manner to previous reviews (in particular Fernández et al. 2011), the type (category) of each assessment method was identified, and then (a) the characteristics of the method~~;~~, (b) the features that were recorded, and, when appropriate, (c) the river processes that were assessed, were extracted. The types of extracted information are summarised in Table 2 (a more detailed description is reported in Rinaldi et al. 2013b). The way in which these three main types ((a) to (c)) of information were collected, differed slightly across the different assessment categories. In particular, information regarding the hydrological regime assessment methods (HRA) differed from the first three categories (i.e., PH, RH, M):

(a) Method characteristics. These concerned data collection methods or sources (e.g., field survey, remote sensing, etc.); the type of method (e.g., qualitative characterization, assessment by a quantitative index); whether the method makes use of some type of reference conditions; the spatial scale of the assessment, including the zones of the river corridor that were surveyed; and the temporal scales of investigation. There are several approaches used to define reference conditions, including: (i) empirical data from reference sites; (ii) historical information (i.e. some historical state is assumed as a reference condition); (iii) modelled; (iv) theoretical; (v) based on expert judgement; (vi) based on the historic range of variability or evolutionary sequence and ergodic reasoning (Brierley and Fryirs 2005). For hydrological assessment methods, additional information was collected concerning the predictive ability of the assessment, whether methods make a direct link to ecology, and the particular strengths of a method (i.e., ease of application, ability to use variable data series lengths, ability to be applied both to gauged and ungauged catchments, inclusion of an assessment of pressures *a priori*).

(b) Recorded features. These represent the core of the review, since they highlight differences between the categories of assessment. In the case of physical habitat, riparian habitat, and morphological assessment, they comprise lists of hydromorphological features recorded in various portions of the river corridor (instream, banks, riparian areas, floodplain). For the hydrological assessment methods, these include metrics of hydrological characterization, alteration and pressures.

(c) River processes. These are only relevant to the first three categories of assessment, and provide information on whether any specific physical river process is included in the evaluation (e.g., longitudinal, lateral and vertical continuity, bank processes, channel adjustments).

(Table 2)

A comparative analysis of hydromorphological assessment methods

Based upon the characteristics, information, and, where relevant, river processes incorporated within each assessment, the following sections provide a summary of the properties of the assessment methods within each of the four categories (physical habitat, riparian habitat, morphological, hydrological regime alteration).

The percentage of methods within each category covering the different characteristics, recorded features and river processes is summarized in Table 2, Fig. 3 and Fig.4.

Methods for physical habitat assessment

~~The percentage of physical habitat, riparian habitat, and morphological assessment methods that incorporate particular aspects or features is summarised (Fig. 3 and Table 2).~~

~~This reveals that~~ Most physical habitat assessments are based on extensive field surveys. Maps and remote sensing techniques are also frequently used for preliminary reconnaissance of the river and to allow for reach identification.

~~In general,~~ 78% of physical habitat assessment methods generate one or more indices that evaluate hydromorphological condition. These indices are usually derived from the inventory of recorded features (e.g., 12, 31; note numbers refer to methods listed in Table 1), although some methods also aim at evaluating the overall functioning of the stream (6% of methods), by including information on ecology-related features (e.g., method 39; Table 1).Some form of reference conditions are also explicitly incorporated in 58% of the reviewed methods.

The spatial scale of most physical habitat assessments is rather small, coinciding with what might be described as a *site* scale, i.e. a river length in the order of a few hundred meters. The longitudinal length of each site or reach may be either fixed (e.g., 500 m) or variable, in the latter case the length reflects larger scale characteristics (e.g., geology and climate, presence of longitudinal discontinuities, etc.). All reviewed methods focus on the channel; most include the river banks and riparian areas; but less than 75% extend to the surrounding floodplain. Concerning their temporal scale, all reviewed methods assess the present state of the river at the time of survey, while very few include information on recent or historical river conditions (45; Table 1).

Regarding the features that are recorded, channel features usually include channel dimensions, dominant bed sediment size and composition, channel forms and morphological units (e.g., number of riffles and pools), and artificial features (e.g., dams, weirs, culverts, deflectors, etc.). The physical structure of the banks and the presence of artificial elements are the most commonly recorded feature of riverbanks and riparian zones. Land use and the presence of fluvial forms (e.g., oxbow lakes, wetlands) are the most commonly-recorded floodplain features. Information on large scale catchment and valley characteristics is rarely included, and hydrological information is only provided to characterize the condition at the time of the survey (e.g., estimation of discharge). However, in some countries (e.g., Australia), the hydrological assessment is more detailed and considers several properties of the river regime (e.g., Ladson et al. 1999; Parsons et al. 2004).

In relation to river processes, longitudinal and lateral continuity are often assessed based on the presence of artificial features, while only 12% of ~~a few~~ methods include some consideration of channel adjustments (i.e., widening/narrowing, aggradation/degradation).

(Figure 3)

Methods for riparian habitat assessment

As for physical habitats, the assessment of riparian habitats is mainly undertaken using extensive field assessment protocols, while the use of maps and remote sensing is rare (Fig. 3; Table 2; but see method 87, Table 1).

The assessment approach varies, ranging from the use of indices or quality classes to the application of inventory protocols often including sampling of vegetation community composition (e.g., 75, 84; Table 1). A relatively low proportion (40%) of the methods makes explicit use of reference conditions (e.g., 87; Table 1).

Riparian habitat assessment is usually undertaken at the *reach* scale, which is larger than the *site* scale that is generally employed in river habitat assessments. The area or length that is surveyed is variable and has relatively homogenous vegetation characteristics. Similar to physical habitat assessment, the temporal scale of investigation is restricted to the time of the survey.

In terms of the recorded features, these methods focus on banks and riparian zones. About 50% of the investigated methods record channel features, and mainly focus on the width of the channel in relation to vegetated areas such as islands and vegetated bars, and artificial features. The vegetation features most commonly assessed include vegetation structure, species coverage, and species composition, with a special emphasis on the presence and abundance of non-native species (particularly in European methods). Some methods place emphasis on the temporal dynamics of vegetation pattern (i.e., evidence of vegetation regeneration, for example, in terms of the presence of seedlings).

~~While~~ Most of the methods evaluate longitudinal and lateral vegetation continuity ~~(~~which provides insights into the lateral connectivity between the riparian area and its river and floodplain~~),~~. Only a small proportion attempt to relate the riparian habitat to physical processes.

Methods for morphological assessment

As for the previous categories, field survey is the predominant method of data-gathering, but morphological assessments make more extensive use of remote sensing data and maps (73%; Fig. 3, Table 2).

Morphological methods are mainly used for ~~aimed at providing~~: (i) an evaluation framework of river conditions (e.g., 97, 103; Table 1); (ii) an assessment supported by one or more indices (e.g., 102, 110; Table 1); or (iii) an assessment directed towards restoration design (e.g., 92; Table 1). Some methods provide a risk assessment of existing pressures rather than an analysis of morphological conditions (e.g., 104; Table 1). In some case the assessment provides a morphological characterization that is included in broader protocols for evaluating the river or watershed conditions (e.g., 96, 99; Table 1). Lastly, some morphological methods are used in combination with the assessment of other ecosystem components to provide an evaluation of the overall river conditions (Healey et al. 2012). 64% of methods include the use of reference conditions.

Compared to the previous categories, morphological assessment is generally carried out at a larger spatial scale, which could still be termed the *reach* scale, i.e. a length in the order of a few kilometres with sufficiently homogeneous morphological characteristics and boundary conditions. In most cases (>80%), the assessment concerns the entire river corridor (i.e., channel, banks, riparian zones, and floodplain). In a temporal context, a larger proportion of these methods take account of recent and historical channel adjustments through the use of maps and remote sensing.

Compared to physical habitat methods, the assessment of channel features is more focussed on channel pattern and physical variables, but less on the survey of instream habitats (e.g., instream vegetation, large wood accumulations, flow types). Although some characterization of bed sediment is incorporated within most methods, relatively few methods attempt to evaluate substrate structure alterations such as armouring and clogging (or embeddedness) (see methods 105, 109, 110; Table 1). Bank morphology, artificial features in the riparian zone, and floodplain forms and features are considered to some extent by most of the morphological methods. More than 80% evaluate hydrological alterations, although usually only in qualitative terms. Many also include some consideration of river processes, including sediment continuity, bank erosion, and channel adjustments.

Methods for the assessment of hydrological regime alteration

The main characteristics of this category of assessment are summarised in Figure 4~~3~~ and Table 2.

This type of assessment mainly involves the processing of existing hydrological data series or the use of modelled data. Numerical models are required when data are not available or to fill gaps in incomplete data series (e.g., 120; Table 1). Maps and remote sensing can be used to support the evaluation of human pressures at the catchment scale or for characterizing the river or catchment (50% of methods). Field measurements of river discharge may be included in the assessment (e.g., 115; Table 1), particularly for ungauged reaches (e.g., 120; Table 1).

Most of the methods produce a final single index or multiple indices. Given their predictive ability, some are used to build scenarios for evaluating the success of restoration or the impact of specific river changes (e.g., 117; Table 1). Reference conditions are often used, and consist of undisturbed or pre-impact conditions based on existing data or on modelling results (64% and 27%, respectively).

The spatial scale of application varies widely from the reach (the most common scale) to the segment (i.e., a macro-reach of tens of kilometres) or to the entire catchment.

46% of methods link explicitly with ecological components. For example they may assess the ecological response to changes in the hydrological regime in order to evaluate the present ecological status (114; Table 1).

Concerning the recorded features, almost all make use of river discharge data. In the cases where field data are required, cross-sections, flow velocity and depth are generally measured (e.g., 115; Table 1). Some methods (e.g., 112; Table 1) also combine watershed land use characteristics (e.g., coverage, density) with hydrological data. Almost all are based on the five main components of the flow regime: discharge magnitude, frequency, duration, timing, rate of change (Richter et al., 1996, Poff et al., 2003). Some also evaluate temporal variability (i.e., annual/seasons, inter-annual/climatic changes) (e.g., 116; Table 1).

In terms of assessed pressures, the effects of impoundments, water abstractions and diversions are commonly evaluated, while none of the reviewed methods assess the effects of hydro-peaking from power generation plants.

(Figure 4)

Strengths, limitations and gaps in assessments

Based on the above review of existing assessment techniques, this section identifies strengths and limitations within each of the four categories (Table 3). This is supported by the authors' expert opinion on the pros and cons of the methods implemented and applied by EU countries within the context of the WFD.

(Table 3)

Methods for physical habitat assessment

These methods have a number of strengths. They provide a framework within which habitat units can be efficiently inventoried and sampled, and so ~~such that~~ they are useful for characterizing the range of physical habitats that are present, their heterogeneity and ~~thus~~ the contemporary physical structure of ecosystems. Additionally, these methods often inventory some features of ecological relevance, which are not addressed within the other categories, such as the presence of refuge areas, organic matter, shading, etc. (e.g., 12, 40; Table 1). Therefore, they are potentially helpful in establishing links between morphology and ecological conditions and communities~~. In particular, characterization of physical habitats can be useful in~~ (e.g., supporting explanation of the distribution patterns of organisms, the composition and structure of biological communities or aspects of ecosystem functioning). Finally, ~~because~~ some of these methods have been used quite widely across Europe (e.g., method 12, Table 1, and similar procedures developed in other countries), ~~they~~ allowing for comparison of data and results from different regions. Nevertheless, physical habitat assessments have several shortcomings. First, these methods have long been considered to be equivalent to hydromorphological assessment, but they are now recognised to represent only one component of a hydromorphological evaluation, which is mainly the occurrence of habitats. Indeed, when physical habitat methods are used with the aim of understanding physical processes and causes of river alterations, they generally fail (e.g. Fryirs et al. 2008, Entwistle et al. 2011).

More specifically, the spatial scale of investigation (i.e., the *site* scale of few hundred meters)~~, which in most cases is rather small (*site* scale) and of a fixed length of the order of a few hundred meters,~~ is usually inadequate for the accurate diagnosis and interpretation of the causes of any morphological alteration. This is because physical site conditions commonly originate~~ stem~~ from processes and causes that operate at larger spatial scales (e.g., Frissel et al. 1986; Brierley and Fryirs, 2005).

Additionally, physical habitat assessment methods require very detailed site-specific data collection, such that their application to large numbers of water bodies may be impractical. These methods also make limited use of geomorphological approaches ~~methods~~ other than field surveys (Table 2; Fig. 3). The expansion of these assessments to incorporate remotely sensed data and GIS analysis, would permit wider spatial and temporal scales of analysis, and~~, as a consequence,~~ more informative assessments. As a consequence, observations tend to be viewed in a static way, rather than placing them in the temporal context within which channel processes operate and river channels adjust. This ~~is considered to be the main~~ primary limitation ~~of physical habitat assessment methods, because it~~ prevents the development of a sound understanding of hydromorphological responses to pressures (i.e., cause-effect relationships), which is essential for identifying and subsequently implementing appropriate rehabilitation actions (Kondolf et al. 2003; Fryirs et al. 2008).

The use of reference conditions based on statistical analyses of empirical data is also questionable. Selection of a sufficient and representative number of reference sites can be problematic, given that many different morphological typologies should be represented. The choice of *natural* sites is also prone to errors, because sites without artificial elements could still be morphologically altered by disturbances occurring in other parts of the river network (upstream or downstream) or that may have occurred in the past. Moreover, ~~the tendency is to define high status/reference conditions on the basis of the presence and abundance of features. As a result,~~ these procedures tend to ~~implicitly~~ identify high status conditions with maximum morphological diversity for all types of rivers, failing to recognize that in some cases the *natural* geomorphic structure of a particular stream type may be very simple whereas in other cases it may be more complex (Barquín et al. 2011; Fryirs 2003).

Additional limitations can be identified in the way that physical habitat methods characterize channel forms and morphological units. These concern a notable gap in the terminology used to describe morphological units in most habitat surveys when compared to the present state of the art in fluvial geomorphology. For example, most refer only to riffles and pools when describing configuration of the river bed, probably because~~. This may be related to the fact that~~ most habitat survey methods have been developed to address small single-thread, sand-bed or gravel-bed rivers. As a result, there is incomplete consideration, for example, of the wide variety of bed morphologies found in steep, mountain, cobble- or boulder-bed streams, where other morphological units may occur (cascades, rapids, glides, step-pools, etc.). ~~On the other hand,~~ Although considerable progress has been made recently in the description and terminology associated with morphological units found in mountain streams (e.g., Halwas and Church 2002; Comiti and Mao 2012), this post-dates the development of most physical habitat assessment methods, and has been insufficiently incorporated by updating these methods. The variety of bed morphologies found in large lowland rivers is also poorly incorporated (e.g., dune-ripple morphologies). Similarly, morphological units found in rivers with complex, transitional or multi-thread patterns (i.e., braided or wandering) are not adequately covered, although some effort has been made recently to represent some of these morphologies (including ephemeral or temporary streams typical of some Mediterranean regions in Southern Europe; e.g., 54, Table 1). In the case of large rivers with complex morphologies (e.g., many piedmont Alpine rivers), field surveys alone are inadequate to characterize channel forms and morphological units, and so the incorporation of remote sensing techniques is essential. Furthermore, considerable progress has been achieved recently in developing new procedures whereby the identification and analysis of individual landforms (geomorphic units) is set in a more appropriate spatio-temporal framework (e.g., Fryirs and Brierley 2013; Brierley et al. 2013), but this type of approach has not been incorporated into any of the analysed methods.

Methods for riparian habitat assessment

Many of the strengths and shortcomings of physical habitat assessments also apply to riparian habitat assessments since they ~~Methods devised for assessing riparian habitats~~ usually adopt a similar approach. ~~As a result, many of the strengths and shortcomings of physical habitat assessments also apply to riparian habitat assessments.~~ However, riparian habitat assessments also have some specific strengths, since they integrate well with physical habitat assessments by extending their coverage from the river channel into the riparian zone, and also giving more emphasis to vegetation, particularly riparian vegetation. Therefore, they are extremely important in accomplishing a requirement of the WFD, which is to give consideration to vegetation as a key biological as well as hydromorphological element.

While most of these methods are based on field survey and some are still focussed on the *site* scale, others make use ~~can be well integrated with other hydromorphological components in terms~~ of other information sources and approaches (e.g., integrated use of remote sensing and field survey) and a larger spatial scale (*reach*) that can be integrated with other hydromorphological methods allowing for an overall river condition assessment (e.g., 87; Table 1).

Despite these specific strengths, many riparian habitat assessments are essentially an inventory of habitats and vegetation conditions observed along a portion of river. As a result, there is limited consideration of the processes generating riparian conditions and the causes of alteration at larger spatial and temporal scales.

~~Moreover~~ This type of assessment is not yet widely used. In the U.S., riparian assessment is often coupled with the assessment of wetland ecosystem functioning (e.g., 78; Table 1). In Europe, most methods have been developed in Mediterranean countries (e.g., Spain, Italy), where flashy flow regimes and ephemeral, multi-channel patterns (incorporating vegetated islands) are more frequent, determining a more complex riparian forest structure. This regional bias means that the validity of many of the techniques is uncertain if they were to be applied to other climatic, hydrological and morphological conditions. Additionally a regional bias could also exist in terms of ~~it should be considered that different~~ human impacts ~~may have acted on riparian vegetation in different contexts~~ (e.g., the predominance of water abstraction and sediment budget changes in southern European countries in comparison with the predominance of vegetation management / removal and pollution in northern ones).

Methods for morphological assessment

Compared to the previous two categories, these methods make use of a more robust geomorphologically-based approach by integrating information drawn from remote sensing and field survey, with a stronger consideration of physical processes at appropriate spatial and temporal scales. Such an approach goes beyond an inventory of forms to support the development of a better understanding of cause-effect relationships.

In most cases the basic spatial unit for the application is the *reach* scale, commonly a few kilometres in length, where reaches are identified in a geomorphologically-meaningful way, as sections of river along which present boundary conditions are relatively uniform. ~~This is a spatial scale that is defined in a geomorphologically-meaningful way.~~

Additionally, some methods account explicitly for the temporal component by incorporating a historical analysis of channel adjustments to provide insights into the timing and causes of alterations and into potential future geomorphic changes (e.g., 110; Table 1). Understanding evolutionary trajectories and past changes is an important component when assessing contemporary river conditions. Morphological indicators should take account of how rivers have changed through time (Brierley and Fryirs 2005; Fryirs et al. 2008). Some of these strengths could also be interpreted to some degree as limitations. Physical processes are generally more difficult to assess~~.~~ ~~Evaluating the correct functioning of processes is certainly a more difficult task~~ than a simple inventory of existing forms. A rigorous evaluation of processes requires the collection of measurements at different times and process rates (e.g., bank erosion or deposition), quantitative modelling or analyses of changes in the process regime (e.g., alterations in sediment transport or water discharge regime), all of which are unlikely to be feasible within the context of a relatively rapid hydromorphological assessment. For practical reason, recorded indicators of processes are thus often generated from a static visual assessment ~~(in the field or based on remotely-sensed information)~~ of the occurrence or not of active processes (observed in the field or based on remotely-sensed information). In other cases, the evaluation is indirectly based on the presence of artificial elements, which are inferred to have significant impacts on some processes. For example, the simple presence of transverse structures is often assumed to alter sediment fluxes and continuity, without any quantitative evaluation of the magnitude of their effects. Even though some morphological assessment methods explicitly account for the temporal component by considering channel adjustments (i.e., changes of channel form through time), this analysis is often prone to errors because it is difficult and requires specialist expertise, specific analyses (e.g., GIS analysis of channel planimetric changes), as well as high spatial and temporal resolution data. ~~Furthermore, the definition of the temporal interval of analysis can be questionable because it is constrained by the quality and timing of the historical data sources.~~The definition of a reference state for morphological conditions is even more problematic than for the other categories. Some morphological assessments implicitly incorporate the assumption that the past state is a reference condition. However, where a more rigorous approach is attempted, a common vision of reference conditions is lacking (Bertoldi et al. 2009; Dufour and Piégay 2009; Rinaldi et al. 2013a), leading to the application of non-harmonized definitions of reference conditions.

The focus of morphological assessments is generally on fluvial forms and processes at wider spatial and temporal scales than physical habitat assessment, but ~~even though these methods account for river processes in terms of longitudinal and lateral continuity,~~ the vertical component of river continuity (i.e., the connection to groundwater) is still poorly considered (Table 2; Fig. 3). Limited attention is also given to a systematic inventory of the morphological units and assemblages that characterize a given morphology and are useful for ecosystem characterization, These ~~k of morphological inventory~~ combine to be a severe limitation when morphological assessment is used alone.

Lastly, these methods evaluate morphological conditions exclusively in terms of physical forms or processes, without any inferences concerning their consequences or implications in terms of ecological state. This means that a high morphological quality is not necessarily related to a good ecological state, although this is most likely the case, since many authors suggest that functioning of physical processes and *dynamic equilibrium* promote ecosystem diversity and functioning (e.g., habitat heterogeneity; Tockner and Ward 1999; Rinaldi et al. 2013a). However a clear relation between some of the morphological indicators used in these methods and biological responses is currently lacking.

Methods for the assessment of hydrological regime alteration

The main strength of this category of assessment is that it makes use of well-defined indicators based on quantitative assessments, statistical analyses or physics-based models. For example, most methods employed within Europe are based on some or all of the Indicators of Hydrologic Alteration (IHA) proposed by Richter et al. (1996) and Poff et al. (2003).

The drawback is that such indicators and models generally require large data sets and long-time series, which are often not available. In particular, applying these methods to ungauged streams is problematic. If models are applied when data are not available or incomplete, the uncertainties that can affect the estimation should be carefully considered.

A further critical issue is defining the unaltered (*natural*) reference hydrological regime. This requires a sufficiently mostly non-existant long data series ~~dating~~ from pre-impact conditions. Assuming that 'pre-impact' data series related to a particular intervention (e.g. dam construction) represent *natural* conditions is rarely appropriate, particularly in Europe where river systems and their hydrological regime have been affected over many centuries by numerous and continuing alterations at a catchment scale (Rinaldi et al. 2013c).

Indicators of hydrological alteration are usually based, at best, on daily discharges. This prevents the analysis of hydrological alterations that occur at shorter time scales, such as hydropeaking (as well as thermopeaking), that have very important effects on ecological communities (e.g., Paetzold et al. 2008; Person and Peter 2012). Specific indicators or models for analyzing hydropeaking are needed. Recent progress has been made to develop integrating approaches and key indicators to assess hydrological alterations due to hydropower impacts (e.g., Zolezzi et al. 2009; Meile et al. 2011). These should be incorporated to further improve hydrological assessment methods.

Like other categories, the effects of groundwater alterations are generally not included apart from an indirect assessment through low-flow analyses. Groundwater systems are an important component of riverine ecosystems and ~~so~~ methods are needed to incorporate them into assessments in a more detailed way.

Because of the above limitations, the practical use of these methods for supporting hydromorphological assessment is still modest ~~limited~~. An alternative and more feasible approach might be an analysis of existing hydrological pressures, based on the presence and type of impacts and causes of alteration (e.g., 112, 121; Table 1). However, it can be extremely difficult to correctly evaluate the effects of a given pressure in the absence of a quantitative analysis of hydrological data. Merging of these two types of approach has been achieved in relation to developing *environmental flow* methods, but with the aim of defining flow requirements for the proper biological functioning together with the human needs (e.g., Arthington 1998; King et al. 2008), rather than to assess regime alteration alone.

Methods implemented by EU countries in the context of the WFD

Finally, we briefly focus on the methods which have been formally approved or are commonly used (but without formal approval) by European countries to implement the WFD, because the choice of the methods and outcome of the assessments strongly influences decision-making on ecological status and the need for rehabilitation programmes. A more detailed analysis of these methods is provided by Rinaldi et al. (2013b). Each method is included in one of the previously defined categories (Fig. 5a), revealing that physical habitat assessment methods prevail (31, 37, 38, 40, 44, 54, 60, 61, 64, 65, 68, 70, 73, 77; Table 1), followed by morphological methods (101, 104, 105, 109, 110; Table 1), while the use of riparian habitat and hydrological alteration methods is very limited (77 and 120, respectively; Table 1). For this analysis~~ aim~~, an adaptation of RHS to Portugal (Raven et al. 2009; Ferreira et al. 2011) has also been included within the physical habitat assessment methods, while the three different versions of the German method have been counted only once (the overall LAWA, corresponding to methods 31, 37, and 38 in Table 1).

In most EU countries (with the exception of France and Italy) physical habitat assessments are the only methods used for the hydromorphological assessment in the context of the WFD. The limitations of each category of methods have been previously discussed, but the following points summarise current general limitations in the application of hydromorphological assessment methods within the EU:

1) A lack of consideration of physical processes is the most important omission in currently-used hydromorphological assessment methods. This omission ~~is an important limitation because a characterization of physical habitats alone is insufficient to develop ~~limits development of a proper understanding of the causes of alterations and responses to them (i.e., cause-effect). Such an understanding is essential if appropriate rehabilitation actions are to be implemented (Kondolf et al. 2003; Fryirs et al. 2008).

2) ~~Due to the widespread availability of methods for physical habitat assessment and their relative simplicity, in most cases this approach has been identified as an appropriate procedure for the stream hydromorphological assessment required by the WFD. Limitations of this category of method have been previously discussed, but~~ Although informative, physical habitat assessment is only one component of an

overall hydromorphological assessment. At present, few EU countries attempt to incorporate other components into a fully integrated hydromorphological assessment.

3) There is also currently no integration of the physical (hydromorphological) aspects with other components (i.e., water quality, biology, ecology) to give a genuinely interdisciplinary approach to overall river condition assessment (Fryirs et al. 2008) .

4) For future hydromorphological assessment and monitoring, a more integrated use of more components is required to achieve an overall assessment, and a stronger ~~additional~~ emphasis within hydromorphology on morphological and hydrological methods would be beneficial.

To place these EU WFD-related assessments into a broader context and allow a more general comparison of the use of the four categories of methods worldwide, the distribution of method categories including all European methods (i.e., not only those implemented for the WFD) as well as other non-European methods is plotted in Figure 5b. It confirms that the most widely used category of methods worldwide is the physical habitat assessment, followed by a recent increase in the development and application of more morphological methods. Exceptions are South-Africa, where morphological assessments prevail, and Australia, where it seems that more interest is allocated to riparian habitats.

(Figure 5)

Concluding remarks and recommendations for future developments

The analysis of hydromorphological assessment methods presented in this paper builds on existing reviews (Raven et al. 2002; Mc Ginnity et al. 2005; Weiss et al.

2008; Fernández et al. 2011). However, this review has extended previous reviews and ~~has~~ provided new insights, which can be summarised as follows.

Most previous reviews have a specific focus on European methods (e.g., Raven et al. 2002; Weiss et al. 2008), as they were mainly aimed at supporting the selection of methods suitable for the implementation of the WFD. This paper started from a wider geographical perspective (similar to Fernández et al. 2011), and then focussed briefly on European WFD-related assessments.

~~Partly related to the previous point,~~ Most previous reviews focus on physical habitat assessment, as they have often been seen to be synonymous with hydromorphological assessment. In this paper the review is wider, with the aim of identifying and critically assessing the strengths and limitations of the various categories, and providing suggestions for further progress in this area of assessment.

Starting from the identified limitations and gaps, future developments need to incorporate physical processes into hydromorphological assessment methods; this aspect becomes extremely relevant in the context of dynamic rivers, such as those of southern Europe. This can be achieved by wider implementation of methods for morphological rather than just physical habitat assessment in order to increase the capability to assess geomorphic processes.

The assessment of morphological processes and alterations should be included in an appropriate spatial hierarchical framework and scaling methodology, emphasizing relevant spatial units and temporal scales, and identifying key controlling factors at each spatial scale as well as appropriate morphological indicators.

Finally, the development of a framework for integrated hydromorphological analysis is recommended, where the morphological and hydrological components (including vegetation as a morphological driver) are key parts of the evaluation and classification of hydromorphological state and quality. An important issue for the future is to combine an integrated hydromorphological assessment with other ~~Hydromorphological analysis should then be better integrated with the other~~ components of the river system. A combined and integrated assessment of morphology, hydrology, water quality, biology and ecology would provide the most effective evaluation of river conditions.

In this respect, it is worth recalling that the various methodological categories identified in this review, reflect different conceptual approaches and disciplines (e.g., hydrology, geomorphology, biology), and that application of each specific approach requires training and some basic expertise. Application of assessment methods without the necessary background and skill can represent a serious limitation in promoting a truly integrated analysis of a river system.

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TABLE CAPTIONS

Table 1 Summary of hydromorphological assessment methods included in this review. Method categories: PH = physical habitat assessment; RH = riparian habitat assessment; M = morphological assessment; HRA = hydrological regime alteration assessment. Ch = method characteristics; Fe = recorded features; Rp = river processes (n.a.: not applicable). The last three columns (Ch, Fe, Rp) express the percentage of elements of each category of information (described in detail in Table 2) accounted for by each method.

Table 2 Summary of types of information collected for each of the categories of assessment: PH, physical habitats; RH, riparian habitats; M, morphological assessment; HRA, hydrological regime alteration. Codes in the third column correspond to those reported in Figures 3, and 4. The percentage of methods, for each category (i.e., PH, RH, M, HRA), considering a specific type of characteristic, feature and process is also reported. The values (in %) refer each time to the sum of methods for one category, the type of information not being an alternative choice (i.e., each method can adopt one or more type of characteristic, feature, process). “/” means that the specific characteristic, feature or process has not been analyzed for the specific category

Table 3 Summary of strengths and limitations for each method category: PH = physical habitat assessment; RH = riparian habitat assessment; M = morphological assessment; HRA = hydrological regime alteration assessment

Table 1

	Category	Year	Country	Acronym	Key reference	Ch	Fe	Rp
1	PH	1983	US	MESC	Platts et al. (1983)	47	56	33
2	PH	1987	Austria	Werth	Werth (1987)	59	48	17
3	PH	1989	Austria	WatercSt	Spiegler et al. (1989)	53	59	17
4	PH	1989	US	QHEI	Rankin (1989)	59	63	33
5	PH	1992	Sweden	RCE	Petersen (1992)	47	33	33
6	PH	1993	Australia	SRS	Anderson (1993)	59	41	33
7	PH	1993	Belgium	SEvalW	Schneiders et al. (1993)	47	33	17
8	PH	1994	Belgium	SK	Wils et al. (1994)	35	11	0
9	PH	1996	Austria	GEBD (RSR)	Buhmann and Hutter (1996)	59	56	17
10	PH	1996	France	Qualphy	Denortier and Goetghebeur (1996)	59	63	33
11	PH	1996	US	RSAT	Galli (1996)	41	41	17
12	PH	1997	England	RHS	Raven et al. (1997)	53	67	50
13	PH	1997	Poland	EcomorphEval	Ilnicki and Lewandowski (1997)	47	41	33
14	PH	1997	US	FFHSIP	Overton et al. (1997)	41	33	17
15	PH	1997	US	VSMM	US Env. Protection Agency (1997)	59	52	33
16	PH	1998	Austria	AssRivSt	Muhar and Jungwirth (1998)	59	67	50
17	PH	1998	Austria	RATyrol	BUWAL (1998)	41	26	17
18	PH	1998	Denmark	DSFI	Danish Env. Protection Agency (1998)	35,3	7	0
19	PH	1998	France	SEQ-P	Agences de L´Eau (1998)	59	63	33
20	PH	1998	Switzerland	ModConc	Liechti et al. (1998)	41	37	33
21	PH	1998	US	MCSH (NAWQA)	Fitzpatrick et al. (1998)	47	37	0
22	PH	1998	US	RHVSA-EMAP	Lazorchak et al. (1998)	41	37	0
23	PH	1999	Australia	ISC	Ladson et al. (1999)	65	30	33
24	PH	1999	Denmark	Aarhus	Kaarup (1999)	47	18	17
25	PH	1999	Denmark	NPHI	National Env. Research Institute (1999)	47	37	0
26	PH	1999	Denmark	PhysSC	Skriver et al. (1999)	41	41	0
27	PH	1999	US	PHC (EMAP)	Kaufmann et al. (1999)	41	41	0
28	PH	1999	US	RBP	Plafkin et al. (1989); Barbour et al. (1999)	59	56	33
29	PH	2000	Australia	HPM	Davies et al. (2000)	59	48	17
30	PH	2000	England	MesoH	Tickner et al. (2000)	41	11	0
31	PH	2000	Germany	LAWA-FS-MToL	LAWA (2000)	59	48	50
32	PH	2000	US	WCE	Oregon Watersh. Enhanc. Board (2000)	71	52	33
33	PH	2001	Austria	NÖMORPH	Freiland Umeltconsulting (2001a, b)	59	41	17
34	PH	2001	Germany	BfG – WW	Bundesanstalt für Gewässerkunde (2001)	47	56	50
35	PH	2001	US	SCA	Yetman (2001)	47	48	50
36	PH	2001	US	SRHRAP	Starr and McCandless (2001)	41	41	33
37	PH	2002	Germany	LAWA-FS-SToL	LAWA (2002a)	59	52	50
38	PH	2002	Germany	LAWA-OS	LAWA (2002a, b)	53	37	50
39	PH	2002	Italy	IFF	Siligardi et al. (2002)	59	37	17
40	PH	2002	Spain	IHF	Pardo et al. (2002)	41	18	0
41	PH	2002	Sweden	BiotopeMap	Hallde´n et al. (2002)	65	44	17
42	PH	2002	US	HHEI	Ohio Env. Protection Agency (2002)	59	30	0
43	PH	2002	US	MinHWCP	Minnesota Pollution Control Ag. (2002)	41	44	17
44	PH	2003	Denmark	DHQI	Pedersen and Baattrup-Pedersen (2003)	71	41	17
45	PH	2003	England	GeoRHS	Environment Agency (2003)	59	48	67
46	PH	2003	US	MNHWA	Crowe and Kudray (2003)	47	26	33
47	PH	2004	Australia	AusRivAs-PAP	Parsons et al. (2004)	65	70	50
48	PH	2004	England	URS	Davenport et al. (2004)	53	56	50
49	PH	2004	Germany	GSI	Feld (2004)	59	52	17
50	PH	2004	US	BURP	Idaho Dep. Env. Quality (2004)	53	37	17
51	PH	2004	US	SEvalAH	Kansas Dep. of Widelife and Parks (2004)	53	37	33
52	PH	2004	US	VSGA	Vermont Ag. of Natural Resources (2004)	53	63	67
53	PH	2004	US	WSAss	US Env. Protecion Agency (2004)	47	44	33
54	PH	2005	Italy	CARAVAGGIO	Buffagni et al. (2005)	59	70	50
55	PH	2005	Portugal	HCI	Oliveira and Cortes (2005)	53	26	0
56	PH	2005	US	NWHI	Wilhelm et al. (2005)	41	22	17
57	PH	2006	Czech Rep.	EcoRivHab	Matoušková (2006)	65	52	33
58	PH	2006	Spain	HIDRI	Munné et al. (2006)	71	59	17
59	PH	2006	US	SIH	US Forest Service (2006)	53	44	50
60	PH	2007	Netherlands	Handboek HYMO	Dam et al. (2007)	53	41	67
61	PH	2007	Slovakia	HAP – SR	Lehotský and Grešková (2007)	59	63	67

Table 1 continued

	Category	Year	Country	Acronym	Key reference	Ch	Fe	Rp
62	PH	2008	South Africa	IHI	Kleynhans et al. (2008)	53	41	33
63	PH	2009	NZ	SHAP	Harding et al. (2009)	53	59	17
64	PH	2009	Poland	MHR	Ilnicki et al. (2009)	59	56	33
65	PH	2009	Slovenia	SI_HM	Tavzes and Urbanic (2009)	53	67	50
66	PH	2009	US	SCS-SH	Maine Dep. of Env. Protection (2009)	59	48	50
67	PH	2009	US	SVAP	US Dep. of Agricolture (2009)	53	59	67
68	PH	2010	Austria	HYMO	Mühlmann (2010)	47	41	50
69	PH	2010	China	USM	Xia et al. (2010)	41	44	50
70	PH	2010	France	CarHyCE	ONEMA (2010)	35	44	33
71	PH	2010	US	MBSS	Stranko et al. (2010)	47	52	17
72	PH	2011	Ukraine	UA-FS	Scheifhacken et al. (2011)	47	48	17
73	PH	2012	Ireland	RHAT	Murphy and Toland (2012)	65	67	67
74	RH	1995	US	HGM	Smith et al. (1995)	35	7	17
75	RH	1998	Italy	BSI & WSI	Braioni and Penna (1998)	59	67	0
76	RH	1998	Quebec	IQBR	Saint-Jacques and Richard (1998)	35	22	0
77	RH	1998	Spain	QBR	Munné and Prat (1998); Munné et al. (2006)	47	33	17
78	RH	1998	US	PFC	Prichard et al. (1998)	29	41	50
79	RH	2000	US	RWA	Oregon Watersh. Enhanc. Board (2000)	47	22	17
80	RH	2000	US	VRRA	Winward (2000)	41	15	17
81	RH	2003	US	VARH	Ward et al. (2003)	35	41	33
82	RH	2005	Australia	RARC	Jansen et al. (2005)	35	22	0
83	RH	2005	Australia	TRARC	Dixon et al. (2005)	35	22	0
84	RH	2006	Spain	IVF	Munné et al. (2006)	47	41	0
85	RH	2007	South Africa	VEGRAI	Kleynhans et al. (2007)	47	30	0
86	RH	2010	Spain	RFV	Magdaleno et al. (2010)	47	22	0
87	RH	2011	Spain	RQI	González DT and García DJ (2011)	47	63	50
88	RH	2012	Australia	RVC_RCI	Healey et al. (2012)	47	22	17
89	M	1984-86	US	CEMs	Schumm et al. (1984); Simon and Hupp (1986)	29	29	67
90	M	1994	US	SCRS	Harrelson et al. (1994)	41	48	33
91	M	1995	US	RGAs	Ministry of Env. (1999); Simon and Downs (1995)	59	41	33
92	M	1996	US	NCD	Rosgen (1996)	53	52	33
93	M	1998	England	FA	Environment Agency (1998)	65	81	83
94	M	1998	England	SRH	Thorne (1998)	53	70	50
95	M	2000	South Africa	GI	Rowntree and Wadeson (2000)	71	56	33
96	M	2000	US	CMA	Oregon Watersh. Enhanc. Board (2000)	65	26	33
97	M	2005	Australia	RSF	Brierely and Fryirs (2005)	65	56	67
98	M	2005	South Africa	GAI	Kleynhans et al. (2005)	53	44	83
99	M	2006	Spain	HIDRI-P1	Munné et al. (2006)	41	11	0
100	M	2006	US	WARSSS	Rosgen (2006)	53	56	67
101	M	2007	Czech Republic	HEM	Langhammer (2007)	71	48	50
102	M	2007	Spain	IHG	Ollero et al. (2007)	59	63	83
103	M	2008	England	GAP	Sear et al. (2008)	59	81	83
104	M	2008	France	SYRAH-CE	Chandesris et al. (2008)	47	37	100
105	M	2008	Scotland	MImAS	UK Technical Advisory Group (2008)	59	52	67
106	M	2009	Poland	RHQ	Wyżga et al. (2009)	65	56	83
107	M	2009	US	SAP	Starr (2009)	53	48	50
108	M	2009	US	SCS-RGA	Maine Dep. of Env. Protection (2009)	65	22	50
109	M	2010	France	AURAH-CE	Valette et al. (2010)	41	18	17
110	M	2013	Italy	MQI	Rinaldi et al. (2013)	65	59	83
111	HRA	1998	US	RVA	Richter et al. (1996)	32	54	n.a.
112	HRA	2000	US	HCA	Oregon Watersh. Enhanc. Board (2000)	36	41	n.a.
113	HRA	2005	Scotland	DHRAM	Black et al. (2005)	46	54	n.a.
114	HRA	2005	South Africa	HAI	Kleynhans et al. (2005)	39	41	n.a.
115	HRA	2006	Spain	QM-HIDRI	Munné et al. (2006)	39	18	n.a.
116	HRA	2006	US	HIT	Henriksen et al. (2006)	29	50	n.a.
117	HRA	2008	Taiwan	HMA	Shiau and Wu (2008)	46	54	n.a.
118	HRA	2009	US	IHA	The Nature Conservancy (2009)	25	59	n.a.
119	HRA	2010	Spain	IAHRIS	Martínez SM and Fernández Yuste (2010)	39	54	n.a.
120	HRA	2011	Italy	IARI	ISPRA (2011)	57	68	n.a.
121	HRA	2012	Australia	HS_RCI	Healey et al. (2012)	50	54	n.a.

Table 2

Categories of information		Type	Code	PH (73)	RH (15)	M (22)	HRA (11)
(a) Method characteristics						%	
Source of information / Data collection methods		- Map/Remote sensing	M/RS	60	33	73	55
		- Field survey or measurement	FS	99	93	91	9
		- Rapid field assessment	RF	34	27	9	/
		- Modelling	MO	10	0	5	91
		- Existing database or data series	ED	/	/	/	100
Type of method/assessment		- Characterization/Inventorying	CI	66	33	50	/
		- Assessment by index	IN	78	73	59	/
		- General assessment/Design	GA	6	0	50	/
		- Simple index	SI	/	/	/	36
		- Multiple index	MI	/	/	/	46
		- Modelling status	MS	/	/	/	18
		- Expert judgment	EJ	/	/	/	27
River typology		- No river typology	NT	/	/	/	64
		- River typology/type	RT	/	/	/	0
Reference conditions		- Use of reference conditions	RC	58	40	64	/
		- Known reference conditions	KR	/	/	/	64
		- Reconstructed reference conditions	RR	/	/	/	27
Spatial scale	Longitudinal	- Fixed length	FI	37	33	9	/
		- Length vs. width	CW	18	7	14	/
		- Variable length	VA	47	60	64	/
	Lateral	- Channel	CH	100	53	100	/
		- Banks/Riparian zone	B/RZ	95	93	96	/
		- Floodplain	FP	71	53	86	/
		- Catchment	CA	/	/	/	18
		- River	RI	/	/	/	36
		- Reach	RE	/	/	/	91
		- Section	SE	/	/	/	36
Temporal scale		- Present (last year)	P	100	100	100	/
		- Recent (1-10 year)	R	3	7	36	/
		- Historical (10-50 year)	H	6	7	46	/
		- Monthly	M	/	/	/	55
		- Daily	D	/	/	/	82
		- Hourly	H	/	/	/	0
		- Other	O	/	/	/	27
Predictive ability		- Pressure change	PC	/	/	/	18
		- Restoration success	RS	/	/	/	18
		- No prediction	NO	/	/	/	27
Link to ecology		- Link to ecology	LE	/	/	/	46
Strengths/Gaps of the method		- Easy to apply	EA	/	/	/	18
		- Variable data series length	DL	/	/	/	18
		- Gauged / Ungauged stations	G/U	/	/	/	36
		- A priori pressure assessment	AP	/	/	/	55

Table 2 – Continued

Categories of information	**Type**	**Code**	**PH (73)**	**RH (15)**	**M (22)**	**HRA (11)**
(b) Recorded features				%		
Channel features	- Channel pattern	CP	55	13	82	/
	- Channel form	CF	78	27	86	/
	- Channel dimension	CD	84	33	73	/
	- Flow type	FT	36	7	27	/
	- Substrate	SB	85	20	82	/
	- Physical parameters	PP	/	/	32	/
	- In-channel vegetation	IV	62	20	27	/
	- Woody debris	WD	62	27	50	/
	- Artificial features and structures	AF	75	27	77	/
Banks / Riparian zone features	- Bank profile/shape	BP	66	27	82	/
	- Bank material	BM	33	20	36	/
	- Riparian vegetation structure	VS	71	93	64	/
	- Riparian vegetation continuity	VC	52	67	32	/
	- Riparian vegetation width	VW	38	53	27	/
	- Species composition	SP	/	73	18	/
	- Species coverage/distribution	SC	/	80	/	/
	- Vegetation regeneration	VR	/	60	/	/
	- Riparian soil	RS	/	20	/	/
	- Artificial features and structures	AF	73	47	77	/
	- Land use	LU	63	53	46	/
Floodplain features	- Fluvial forms	FF	34	13	46	/
	- Floodplain dimensions	FS	/	/	41	/
	- Floodplain features	FD	/	/	32	/
	- Land use	LU	67	40	46	/
Large scale characteristics	- Large scale pressure	LS	49	13	68	/
	- Hydrological regime/Discharge	HR	70	27	82	/
	- Valley form	VF	49	7	64	/
Hydrological conditions	- Flow regime	FR	/	/	/	91
	- Discharge	DI	/	/	/	91
	- Change in depth	CD	/	/	/	9
	- Velocity	VE	/	/	/	9
	- Shear stress	SS	/	/	/	0
	- Other	O	/	/	/	27
Metrics of flow regime	- Magnitude	MG	/	/	/	73
	- Frequency	FR	/	/	/	64
	- Duration	DU	/	/	/	82
	- Timing	TI	/	/	/	91
	- Rate of change	RC	/	/	/	55
	- Minimum flow	MI	/	/	/	82
	- Maximum flow	MA	/	/	/	82
	- Annual variability	AV	/	/	/	36
	- Inter-annual variability	IV	/	/	/	46
	- Intermittent flow	IF	/	/	/	9
Pressure assessed	- Flow diversion	FD	/	/	/	73
	- Groundwater interaction	GW	/	/	/	64
	- Hydropeaking	HP	/	/	/	0
	- Impoundment	IM	/	/	/	82
	- Lateral/Vertical adjustment	CA	/	/	/	0
	- Large scale pressure	LS	/	/	/	36
(c) River processes				%		
River processes	- Longitudinal continuity	LC	56	7	55	/
	- Lateral continuity	TC	49	40	68	/
	- Large scale sediment connectivity	SC	/	/	36	/
	- Bank erosion/stability	BE	59	27	82	/
	- Channel adjustments	CA	12	7	82	/
	- Vertical connection (groundwater)	GW	/	/	18	/

Table 3

	Strengths	**Limitations**
PH	1. Framework for habitat inventory 2. Ecological relevance 3. Widely used	1. Small and usually fixed spatial scale 2. Detailed, time-consuming data collection 3. Limited use of geomorphological methods and remote sensing 4. Static approach 5. Local assessment of ‘natural’ state, which corresponds to feature presence/absence 7. Outdated terminology and incomplete coverage of morphological units (and channel patterns)
RH	1. Focus on riparian zone and vegetation 2. Recent development of hymo integrating approaches (e.g., remote sensing, reach scale) Including strengths of PH	1. Limited consideration of processes 2. Poorly developed/used (e.g., mainly in the Mediterranean areas of EU) Additional limitations, as for PH methods
M	1. Robust geomorphological-based approach 2. Use of geomorphologically-meaningful spatial scale (i.e., reach) 3. Account for temporal component	1. Physical processes difficult to assess rigorously 2. Temporal component difficult to assess 3. Several definitions of reference state 4. Assessment of vertical continuity not explicitly included 5. Limited consideration of physical habitats 6. Lack of linkages with biological components
HRA	Robust approaches (indicators)	1. Need for a large dataset and long-time series 2. Difficult to define unaltered hydrological regime 3. Short time scales not included (e.g., hydropeaking) 4. Groundwater alteration not included

FIGURES CAPTIONS

Fig. 1 Spatial context, spatial scales and overlap between assessment method categories. PH: physical habitat assessment; RH: riparian habitat assessment; M: morphological assessment; HRA: hydrological regime alteration assessment

Fig. 2 Timing of the introduction of four categories of assessment methods (121 assessment methods included). PH: physical habitat assessment; RH: riparian habitat assessment; M: morphological assessment; HRA: hydrological regime alteration assessment

Fig. 3 Analysis of (a) the method characteristics; (b) the recorded features; (c) the processes incorporated in the reviewed physical habitat (PH), riparian habitat (RH), and morphological (M) assessment methods. For the definition of the codes recorded on the vertical axes see Table 2

Fig. 4 Analysis of (a) the method characteristics; (b) recorded features incorporated in the reviewed methods of assessment of hydrological regime alteration (HRA). For the definition of the codes reported on the vertical axes see Table 2

Fig. 5 Number of reviewed methods, sub-divided according to the assessment category, used by: (a) European countries for the implementation of the Water Framework Directive; (b) European (in general, not only for the WFD) and non-EU countries, where “Others” refers to Canada and Quebec, China, New Zeeland, Switzerland, Ukraine. Method categories: PH = physical habitat assessment; RH =

riparian habitat assessment; M = morphological assessment; HRA = hydrological regime alteration assessment