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A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI)

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ABSTRACT

A new index has been developed for the hydromorphological assessment of Italian rivers. The method was designed to comply with the EU Water Framework Directive requirements, but its use can be extended to other applications in river management. The evaluation of stream morphological quality is preceded by a phase of river segmentation, consisting of an initial division of the network into river reaches with homogeneous morphological characteristics. The evaluation procedure consists of a set of 28 indicators, which were defined to assess longitudinal and lateral continuity, channel pattern, cross section configuration, bed structure and substrate, and vegetation in the riparian corridor. These characteristics are analyzed in terms of geomorphological functionality, artificiality, and channel adjustments. Indicators, classes, and the scoring system were defined based on expert judgement. The scoring system leads to the definition of the Morphological Quality Index (*MQI*). Application of the method to 102 river reaches covering a wide range of physical conditions and human pressures of Italian streams enabled the testing of the overall methodology and the refinement of the indicators and scores. Limitations, strengths, and the applicability of the method are also discussed in the paper.
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1. Introduction

The EU Water Framework Directive (WFD; European Commission, 2000) introduced the term 'hydromorphology', which requires the consideration of any modifications to flow regime, sediment transport, river morphology, and lateral channel mobility. Following its introduction, hydromorphology has increasingly grown as a cross-disciplinary topic at the interface between hydrology, geomorphology, and ecology and has created new perspectives and opportunities to embed the consideration of physical processes in river management actions and strategies (Newson and Large, 2006; Vaughan et al., 2009).

Different definitions of hydromorphology have been used (e.g., CEN, 2002; Newson and Large, 2006; Maas and Brookes, 2009; Vogel, 2011), and several methods have been adopted for implementing the WFD in European countries—in most cases coinciding with physical habitat assessment procedures. These methods include, among others, the River Habitat Survey (RHS; Raven et al., 1997) and the German method (Lawa, 2000). Although the characterization of physical habitat elements is useful for ecological studies, the use of these methods for understanding the physical processes and causes of river alterations is affected by a series of limitations (Fryirs et al., 2008). Among such limitations, the following can be noted: (i) the spatial scale of investigation (coinciding with the site, with a length in the order of a few hundred meters) is usually inadequate for the accurate diagnosis and comprehension of any morphological alteration because physical site conditions commonly stem from processes and causes on a wider scale; (ii) the limited use of geomorphological methods (remote sensing, GIS analysis) other than field surveys, which would permit wider spatial and temporal scales of analysis; and (iii) the use of a static temporal perception, with a lack of specific consideration of channel processes and, specifically, of channel adjustments. The latter is probably the main limitation of physical habitat assessment methods, preventing a sound understanding of pressure–response (i.e., cause–effect) aimed at the implementation of rehabilitation actions (Kondolf et al., 2003a; Fryirs et al., 2008).

As a consequence of these weaknesses, an increasing effort has been made to develop methods based on a sounder geomorphological approach, with a stronger consideration of physical processes at appropriate spatial and temporal scales. The River Styles Framework (Brierley and Fryirs, 2005), the *SYRAH* (Système Relationnel d'Audit de l'Hydromorphologie des Cours d'Eau; Chandesris et al., 2008), the *IHG* (Indice Hydrogeomorfologico; Ollero et al., 2007, 2011), and the method proposed by Wyżga et al. (2010, 2012) are examples of morphological assessment procedures that are based on a geomorphological approach. Furthermore, several other geomorphic methodologies have been developed for different purposes, including the procedure proposed by Rosgen (1996) used as a basis for stream

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restoration, or a series of classification schemes accounting for channel adjustments and instability (e.g., Simon, 1989; Downs, 1994; Simon and Downs, 1995; Rosgen, 2006). Although the value of these methods is acknowledged, none of them was considered to fully satisfy a series of conditions for the WFD application to Italian streams. These conditions can be summarized as follows: (i) the method should include a quantitative evaluation procedure to classify the stream morphological quality; (ii) it should be directly applicable by competent authorities (i.e., public agencies, river basin managers); and (iii) it should be suitable for the Italian context, i.e., cover the full range of physical conditions, morphological types, degree of artificial alterations, and amount of channel adjustments. Therefore, the development of a new specific method for Italian streams was considered necessary.

In Italy, as in many other European countries, hydromorphological degradation is one of the major types and causes of a river's alteration because of a very high level of human pressures and the consequent channel adjustments (e.g., Surian and Rinaldi, 2003; Surian et al., 2009a,b). At the same time, hazards related to fluvial processes and channel dynamics are of great concern because of the high degree of urbanization in the territory. It is increasingly recognized that future management strategies need to balance environmental issues with socioeconomic needs and to merge conflicting objectives by integrative approaches (e.g., Brierley and Fryirs, 2008). In this perspective, the Italian National Institute for Environmental Protection and Research (ISPRA) has recently promoted a research program with the objective of developing an overall methodology for the hydromorphological analysis of Italian streams. This methodology, named *IDRAIM* (stream hydromorphological evaluation, analysis, and monitoring system), pursues an integrated analysis of morphological quality and channel dynamics hazards aimed at a harmonized implementation of both the WFD and the EU Floods Directive (European Commission, 2007). The Italian Environment Minister has recently issued the WFD monitoring and classification standards (MATTM, 2010), introducing the Morphological Quality Index (*MQI*) (in Italian: 'Indice di Qualità Morfologica' or *IQM*) described in this paper, which is part of *IDRAIM*, as a new and innovative protocol for stream morphological quality assessment.

The objective of this paper is to present the new evaluation method developed for the hydromorphological analysis of Italian streams, leading to the definition of the Morphological Quality Index (*MQI*), and to discuss its main limitations and strengths. Because the assessment of morphological quality, as well as that of biological or chemical stream characteristics, implies the definition of reference conditions, this issue will be addressed first in the next section.

2. Reference conditions

An assessment tool such as the *MQI* needs reference conditions against which the deviations of present geomorphic reach conditions are measured. In the last three decades, several studies have dealt with the issue of defining the geomorphic reference conditions of streams (e.g., Binder et al., 1983; Kern, 1992; Rhoads et al., 1999; Jungwirth et al., 2002; Brierley and Fryirs, 2005; Palmer et al., 2005; Dufour and Piégay, 2009; Burchsted et al., 2010). Those studies show that some debate on this topic still exists and a common vision of reference conditions is lacking. On the other hand, some concepts (e.g., guiding image, Palmer et al., 2005; evolutionary trajectory, Brierley and Fryirs, 2005) are largely accepted, meaning that a common ground has, in fact, been established. In this section the key ideas developed on this topic in recent years are summarized, and then reference conditions defined for the *MQI* will be explained.

Most fluvial systems in Europe (e.g., Petts et al., 1989; Billi et al., 1997; Comiti, 2012)—as well as in other continents (e.g., Montgomery, 2008)—have been affected by humans for several centuries or even thousands of years, rendering fluvial systems the result of a long interplay between climatic, geological, and human factors. This evidence led many authors to conclude that referring to a 'pristine' stream condition is neither feasible nor worthwhile (e.g., Kern, 1992; Rhoads and Herricks, 1996; Rhoads et al., 1999; Jungwirth et al., 2002; Downs and Gregory, 2004; Kondolf and Zolezzi, 2008; Piégay et al., 2008; Dufour and Piégay, 2009; Wyżga et al., 2012). Past stream conditions may be taken as examples of more natural conditions, but in many cases the naturalness of such past conditions is questionable. Recognition that fluvial systems have been affected by human impact for centuries and also that climate variability may have a significant role over such timescales (e.g., Bravard, 1989; Rumsby and Macklin, 1996) implies a dynamic view of fluvial systems. In such a view, each river reach has its own evolutionary trajectory in terms of channel morphology (e.g., Brierley and Fryirs, 2005). According to the evolutionary trajectory concept, a river is a complex system that adjusts its morphology to changes in boundary conditions, in particular to flows and sediment flux variations (Brierley et al., 2008; Dufour and Piégay, 2009).

Because fluvial systems are the result of continuous interplay between natural and human factors and because channel morphology in a specific reach may change through time, many authors have moved away from using the past as a reference condition. In fact, not only are past conditions not necessarily natural (e.g., more intense land degradation during the eighteenth and nineteenth centuries from agricultural activities), but they could also be of little practical use for river management and restoration. Because a fluvial system may have changed over time, referring to a past channel morphology that may reflect boundary conditions very different from the present ones would not be useful. This type of reasoning has been used by several authors, but with some differences. For example the 'leitbild' (e.g., Kern, 1992; Muhar, 1996) or 'guiding image' concept (e.g., Binder et al., 1983; Palmer et al., 2005) was built taking into account present environmental conditions (e.g., present catchment hydrology and geomorphology, human pressures). The reference conditions (i.e., leitbild or guiding images) are essentially defined by looking at the present and future conditions and constraints, aiming to identify the least degraded and most ecologically dynamic state that could exist at a given site given the regional (catchment) context (Palmer et al., 2005). Similarly, Brierley and Fryirs (2005) state that, in general, reference conditions are framed in terms of an expected state. Such an expected reference state represents the best conditions that can be attained by a river, altered by humans, given the prevailing catchment boundary conditions (Brierley and Fryirs, 2005). Recently a similar approach, taking into account the present environmental conditions in the catchment, was proposed by Wyżga et al. (2012) for defining reference conditions of Polish streams.

The approaches just mentioned have many aspects in common. Firstly, they refer to a dynamic state rather than to a static one, inasmuch geomorphic river conditions are viewed in the context of an inherent evolutionary tendency of the system (Brierley and Fryirs, 2005). Secondly, those works argue that river restoration should not aim to recreate past conditions. On the same line of thinking is the concept of 'naturalization', proposed by Rhoads and Herricks (1996) and by Rhoads et al. (1999) for human-dominated environments. It is also relevant to point out that the 'guiding image' or the 'expected state' is not used to assess deviation from a natural condition but rather to define goals for river restoration. In this respect, the work of Jungwirth et al. (2002) is valuable because it emphasizes that assessment can be a two-step process, i.e., firstly, deviations from natural conditions ('visionary leitbild') are assessed, followed by the identification of restoration goals ('practical leitbild'). The appropriateness of identifying river 'degradation' history before reasoning about possible restoration actions has recently been argued for Alpine rivers by Comiti (2012).

In the definition of reference conditions for the *MQI*, we have taken into account (i) several of the concepts described above (in particular the concept of evolutionary trajectory); (ii) the requirements of the WFD; and (iii) the specific context of Italian streams that have been affected by humans for a long period of time (e.g., Billi et al., 1997;

Surian and Rinaldi, 2003; Comiti, 2012). According to the WFD, the point of reference is given by 'undisturbed' conditions showing no or only 'very minor' human impacts (European Commission, 2003). As a consequence, reference conditions for the *MQI* were defined in order to measure the deviation from undisturbed or only very slightly disturbed geomorphic processes. The reference conditions for a given reach are defined considering three components, i.e., channel forms and processes, artificiality and channel adjustments (see also next sections). As for the first component, the reference conditions are given by the channel form and processes that are expected for the morphological typology (see below) under examination. For artificiality, the reference is given by the absence or only slight presence of human intervention in terms of flow and sediment regulation, hydraulic structures, and river maintenance activities. If elements of artificiality exist, they should produce only small negligible effects on the channel morphology and river processes. Finally, concerning channel adjustments, the channel could also be aggrading or incising in the long term (e.g. the last 100–200 years), but not going through major changes of channel morphology caused by human factors. Summarizing, the reference conditions for the *MQI* entail a river reach in dynamic equilibrium, where the river is performing those morphological functions that are expected for a specific morphological typology, and where artificiality is absent or does not significantly affect the river dynamics at the catchment and reach scale. Reaches that represent reference conditions may be very rare or even absent in the Italian context (Comiti, 2012). This is simply because the *MQI* is a tool to assess the deviation from undisturbed conditions and not a tool to set restoration goals. In this respect, reference conditions for the *MQI* are similar to the 'visionary leitbild' of Jungwirth et al. (2002), although those authors refer to historical morphological conditions. This is not the case for the *MQI* because a single morphological typology cannot be expected or predicted for a specific reach in the context of inherent evolutionary tendencies of the system. In other words, we may assume different channel typologies as a reference depending upon the different boundary conditions (i.e., changes at the catchment and reach scale), and not necessarily a return to a previous condition.

3. The Morphological Quality Index (MQI)

This section illustrates the various phases and components of the evaluation method, including the initial setting and segmentation, the definition of the indicators, the *MQI* calculation, and the scoring and classification system. Before describing the method, its main characteristics and innovative features are reviewed.

3.1. Main characteristics of the method

The main characteristics and innovative features of the *MQI* can be summarized as follows.

(i) The method is based on an expert judgement (i.e., a selection of variables, indicators, classes, and relative scores), deriving from the specific knowledge and experience of the authors. This reflects the use of a 'special' rather than a 'natural' classification scheme (Sneath and Snokal, 1973; Kondolf, 1995; Kondolf et al., 2003a).
(ii) The method was designed to comply with WFD requirements, but could be used for other purposes in river management.
(iii) Because the method is to be used by environmental or water agencies on a national level, it has been designed to be relatively simple and not excessively time consuming. However, its application should be carried out by trained people with an appropriate background and sufficient skills in fluvial geomorphology.
(iv) The method is based on the consideration of processes rather than only of channel forms. Aspects such as continuity in sediment and wood flux, bank erosion, lateral mobility, and channel adjustments are taken into account.
(v) The temporal component is explicitly accounted for by considering that an historical analysis of channel adjustments provides insight into the causes and time of alterations and into future geomorphic changes. Lack of consideration of the temporal component is considered as one of the main limitations of many of the other geomorphic classification schemes (Kondolf et al., 2003a). In this method, we explicitly include indicators of channel adjustments in the evaluation of river morphological quality.
(vi) Concerning the spatial scales, a hierarchical nested approach (Brierley and Fryirs, 2005) is adopted where the 'reach' (i.e., a section of river along which present boundary conditions are sufficiently uniform, commonly a few kilometres in length) is the basic spatial unit for the application of the evaluation procedure.
(vii) Morphological conditions are evaluated exclusively in terms of physical processes without any reasoning on 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 commonly the case. In fact, it is widely recognized that the geomorphic dynamics of a river and the functioning of natural physical processes spontaneously promote the creation and maintenance of habitats and ensure the ecosystems' integrity (e.g., Kondolf et al., 2003b; Brierley and Fryirs, 2005; Wohl et al., 2005; Florsheim et al., 2008; Fryirs et al., 2008; Habersack and Piégay, 2008).

3.2. General setting and segmentation

The first phase of the method is aimed at subdividing the river network into relatively homogeneous reaches, defined as sections of river along which present boundary conditions are sufficiently uniform (i.e., with no significant changes in valley setting, channel slope, imposed flow and sediment load; Brierley and Fryirs, 2005). Even though the identified river reaches will be the basic spatial unit for the application of the evaluation procedure, no attempts are made in this phase to characterize the reaches on the basis of their 'natural' or 'reference' conditions, as is the case in some physical habitat assessment method.

The segmentation is based on existing information (e.g., topographical and geological data) and remote sensing data analyzed by GIS, and represents a guided, sufficiently flexible, and adaptive procedure rather than a rigid set of rules. Recent developments in automated spatial disaggregation and discretization of fluvial features (e.g., Alber and Piégay, 2011) could potentially be implemented for some steps of the procedure.

A summary of the procedure is reported in Table 1 and is synthetically described in this section (more details are reported in Rinaldi et al., 2012).

In step 1, a basic investigation of geology, geomorphology, climate, and the land use of the whole catchment is carried out. The result is the identification of physiographic units (equivalent to the 'landscape units' of Brierley and Fryirs, 2005). The river network is divided into segments, which are macroreaches defined by the intersection of channel network with physiographic units, and by possible additional factors (e.g., macrodifferences in valley setting).

In step 2, lateral confinement is analyzed in more detail, and three valley settings are differentiated (Brierley and Fryirs, 2005): confined, partly confined, and laterally unconfined channels. These terms are used in the sense of natural valley width confinement caused by hillslopes or ancient terraces, while artificial elements (e.g., bank protections, embankments, urban areas) are not considered as elements of confinement.

Lateral confinement is defined by measuring the "degree of confinement", that is the percentage of banks not directly in contact with the alluvial plain but with hillslopes or ancient terraces (Brierley and Fryirs, 2005), and "a confinement index", which is defined by the ratio between the alluvial plain width and the channel width (Rinaldi et al., 2012). Therefore, the classification of lateral confinement jointly takes

Table 1
Summary of the general setting and segmentation procedure.

Steps	Criteria	Outputs
Step 1: general setting and identification of physiographic units and segments	–Geological and geomorphological characteristics	*–Physiographic units* *–Segments*
Step 2: definition of confinement typologies	–Lateral confinement	*–Confinement typologies:* confined (*C*) partly confined (*PC*) unconfined (*U*)
Step 3: identification of morphological typologies	–Planimetric characteristics (sinuosity, braiding, and anastomosing indices)	*–Morphological typologies:* *Confined*: single thread, wandering, braided, anastomosed *Partly confined–unconfined*: straight, sinuous, meandering, sinuous with alternate bars, wandering, braided, anastomosed
Step 4: division into channel reaches	–Further discontinuities in hydrology, bed slope, channel width, alluvial plain width, bed sediment	*–Reaches*

into account the longitudinal extent along which the channel impinges on the valley margins and the lateral extent of the alluvial plain.

In step 3, channel morphology is analyzed in detail. Stream channels are classified into a series of typologies (Table 1 and Fig. 1), according to traditional classifications of river morphologies (e.g., Schumm, 1977; Church, 1992; Rosgen, 1994; Montgomery and Buffington, 1997), but taking into account the specific Italian context (e.g., Rinaldi, 2003; Surian and Rinaldi, 2003; Surian et al., 2009a). It is in fact recognized that classification systems work best as guides to river management when they are developed for specific physiographic regions (e.g., Palmer et al., 2005).

Partly confined and unconfined channels are classified based on their planimetric pattern, and divided into seven river morphologies (straight, sinuous, meandering, sinuous with alternate bars, wandering, braided, anastomosed). Confined channels are classified, at a first level, based on their planform only into single-thread, wandering, braided, and anastomosed (Rinaldi et al., 2012). A more detailed classification (second level) is required only for confined single-thread channels, which must also be characterized in terms of bed configuration following a simplified version of the Montgomery and Buffington (1997) classification (Fig. 1). However, this second level of classification is used only during the assessment procedure and does not affect river segmentation.

Step 4 considers additional discontinuities to further subdivide the stream reaches, including hydrological discontinuities (e.g., tributaries, dams), bed slope (particularly for confined reaches), or relevant changes in channel width, alluvial plain width, or bed sediment. The final product of this phase is the subdivision of the river network into reaches that are relatively homogeneous in terms of channel morphology, lateral confinement, hydrology, and other characteristics, reflecting no significant changes in the flow or sediment load (Brierley and Fryirs, 2005). These reaches, which are commonly a few kilometres in length, represent the elementary spatial units for the assessment of the morphological conditions.

3.3. Structure and key components of the evaluation procedure

The following aspects are considered for the assessment of the morphological quality of river reaches, consistent with CEN (2002) standards and WFD requirements: (i) continuity of river processes, including longitudinal and lateral continuity; (ii) channel morphological conditions, including channel pattern, cross section configuration, and bed substrate; and (iii) vegetation. These aspects are analyzed in terms of three components: (i) the geomorphological functionality of river processes and forms; (ii) artificiality; and (iii) channel adjustments.

Indicators of geomorphic functionality evaluate whether or not the processes and related forms responsible for the correct functioning of the river are prevented or altered by artificial elements or by channel adjustments. These processes include, among others, the continuity of sediment and wood flux, bank erosion, periodic inundation of the floodplain, morphological diversity in planform and cross section, the mobility of bed sediment, and processes of interaction with vegetation.

On the other hand, indicators of artificiality assess the presence and frequency of artificial elements or interventions as such, independently of their effects on processes. Therefore, artificial elements are accounted for in a twofold way, i.e., based on their function or their effects as noted by the functionality indicators (i.e., as elements preventing natural processes, for example, a bank protection that prevents lateral erosion) and based on their presence and density (i.e., artificial elements as such that are not expected in unaltered rivers, independently of their effects). In other terms, some elements have multiple effects on the various components of the evaluation (i.e., functionality and artificiality), and apparent repeated evaluations are actually useful in discerning the impact of these elements on the different components.

Finally, indicators of channel adjustments are included in the evaluation. Adjustments caused by human disturbances can shift within a fluvial system in space and time, so that an alteration in channel form and process may be related to disturbances that occurred in the past and/or in a different location of the watershed (Simon and Rinaldi, 2006). Channel adjustments focus on relatively recent morphological changes (i.e., about the last 100 years) that are indicative of a systemic

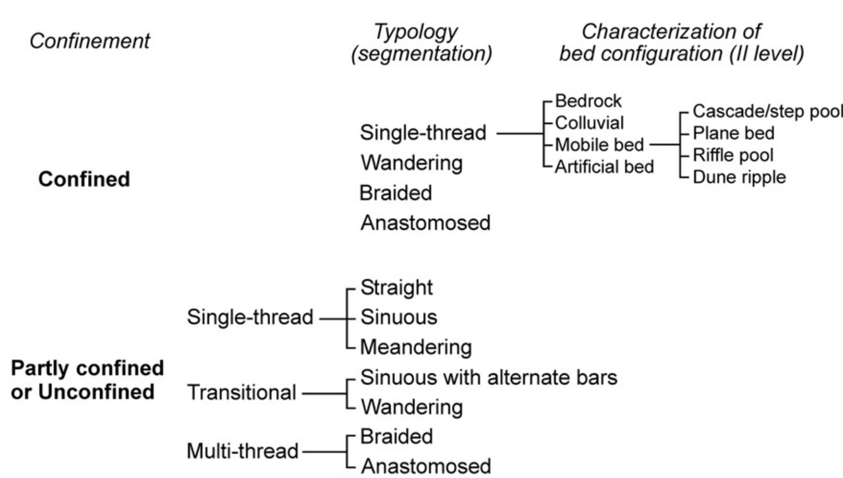

Fig. 1. Stream classification used during the step 3 of the segmentation phase.

instability related to human factors. In fact, human-induced disturbances greatly compress timescales for channel adjustments (e.g., Rinaldi and Simon, 1998; Simon and Rinaldi, 2006). However, channel changes that are not clearly related to human disturbances that occurred during this temporal frame (e.g., changes related to large floods) could be recognized and not considered as alteration. To this end, the information relative to the indicators of artificiality is useful (e.g., intense sediment removal activity or the presence of dams in the watershed that could be interpreted as causes of intense channel adjustments). As anticipated above, the historical river conditions (past 100 years) are not considered as a reference state (see previous section) but as a comparative situation to infer whether channel adjustments occurred over the last decades.

Although identification of the causes of channel adjustments may not always be straightforward, a simplified analysis of past evolution, like the one carried out in the evaluation procedure, allows one to distinguish in most of the cases between changes that are strictly related to human interventions and those that reflect natural tendencies of the channel (e.g., natural evolutionary trajectories related to climatic variations or channel response to large floods).

The overall evaluation is carried out by making a synergic use of two types of methods: GIS analysis (using available databases and remotely sensed data such as aerial photos and LiDAR DTMs) and field surveys. Channel adjustments are evaluated only for relatively large channels, i.e., rivers with a channel width >30 m, because this assessment (mostly based on a comparison of aerial photos) would be affected by large errors in narrower streams using standard photo resolution.

The spatial scale of application is a river reach, as identified during the initial phase of segmentation. However, alterations of flow and sediment discharge require information at the catchment scale on the types of interventions affecting these variables (i.e., dams, check dams, weirs, etc.). GIS analysis is carried out at the reach scale, while the field survey is focussed on a representative subreach (or 'site'). In terms of the implications for management, an assessment of the entire river is advisable to avoid missing the potential causes of systemic river instability and to enable a cause-and-effect basis for river management.

Regarding the timing of the assessment, the procedure should not be applied shortly after a large flood (e.g., flood with a return period >10–20 years). In fact, the effects of such events could strongly influence the interpretation of forms and processes. In such cases, the application of the *MQI* some years after the occurrence of the flood is advisable.

The *MQI* assessment includes only those hydrological aspects related to alterations of channel-forming discharges, i.e., those having significant effects on geomorphological processes. The overall changes in the hydrologic regime are analyzed separately by a specific index of hydrological alteration (IARI; ISPRA, 2009). This index is based on the thirty-three Indicators of Hydrologic Alteration (IHA; Richter et al., 1996; Poff et al., 1997), providing information on the possible alterations of five components of the hydrological regime (i.e., magnitude, frequency, timing, duration, rate of change). Using at least twenty years of monthly streamflow data, each of these metrics are analyzed against an unimpacted flow series. The integration of the hydrologic regime analysis with the *MQI* provides an overall hydromorphological assessment.

3.4. Indicators

The complete set of indicators (28) can be schematically represented by crossing the aspects (in rows) and components (in columns) described in the previous section (Table 2). Selection of the indicators used in the method is a part of the expert judgement of the authors, as more importance is implicitly assigned to those key elements than to the others that have not been selected (Kondolf, 1995).

During the segmentation phase, three classes based on channel confinement were differentiated: (i) confined channels (hereafter '*C*'); (ii) partly confined channels (hereafter '*PC*'); and (iii) unconfined channels (hereafter '*U*'). At this stage, instead of using a different evaluation form for each of these three classes, only two procedures were developed given that the same indicators can be used for partly confined and unconfined channels. This implies that some differences exist in the number and type of indicators for each of these two assessment procedures, as some of the indicators are specific for confined channels while they are not suitable for partly confined and unconfined, and vice versa. For example, presence and extension of a modern floodplain is not considered relevant in the case of confined channels, while it is an important feature either for partly confined and unconfined channels.

A summary of indicators, with assessed parameters, assessment methods, and ranges of application for each of them, is reported in Table 3.

The selection of indicators, parameters, and assessment procedures have been verified and improved during a testing phase, when the overall methodology was applied to 102 river reaches (see Section 3.7).

3.4.1. Indicators of geomorphological functionality

This set of indicators is used to assess whether channel form and processes are as expected according to the morphological typology under examination (morphological typology is defined in step 3 of the previous phase of "General setting and segmentation"). The general rule is to contextualize the indicator to the channel typology and the physical setting where the reach is located. For example, cross section variability (indicator *F9*) is evaluated in reference to the expected variability for that channel typology. A lack of cross section variability is not evaluated as an alteration in the case of channel morphologies characterized by natural cross section homogeneity (e.g., sinuous lowland rivers, with low gradients and/or low bedload).

Longitudinal continuity is assessed by one indicator (i.e., *F1*), which evaluates whether or not the natural flux of sediment and wood along the reach is decreased or intercepted by artificial barriers. Indicators of lateral continuity evaluate whether the expected lateral connectivity of water, sediment and wood are altered. A first indicator is the presence of a modern floodplain (*F2*), that is a surface that has been built under present regime conditions. A river in dynamic equilibrium builds a floodplain that is generally inundated for discharges just exceeding formative flows (return period of 1–3 years). Channel adjustments (e.g., incision) or artificial structures (e.g., levees) can disconnect the floodplain from the channel. Recently formed terraces, representing abandoned floodplains, are common and are typically the result of channel incision. Consequently, the modern floodplain generally occupies only a portion of the overall alluvial plain used during the step 2 for characterizing the valley setting. A preliminary delimitation of the modern floodplain is carried out by remote sensing, but field survey is fundamental to identify this surface, based on field evidences (e.g., the highest elevation of channel bars is generally very similar or slightly lower than the elevation of the modern floodplain).

Table 2
List of indicators as a function of the main aspects (continuity, morphology, vegetation) and components of assessment (functionality, artificiality, channel adjustments).

		Functionality	Artificiality	Channel adjustments
Continuity	–Longitudinal	F1	A1, A2, A3, A4, A5	
	–Lateral	F2, F3, F4, F5	A6, A7	
Morphology	–Channel pattern	F6, F7, F8	A8 (A6)	CA1
	–Cross section	F9	(A4, A9, A10)	CA2, CA3
	–Bed substrate	F10, F11	A9, A10, A11	
Vegetation		F12, F13	A12	

Table 3
Definition, assessed parameters, assessment methods, and ranges of application of each indicator.

Indicators and assessed parameters	Assessment methods	Ranges of application
F1—Longitudinal continuity in sediment and wood flux Presence of crossing structures (weirs, check-dams, bridges, etc.) that potentially may alter natural flux of sediment and wood along the reach	*Remote sensing* and/or *database of interventions*: identification of crossing structures; *field survey*: visual assessment of partial or complete interception (qualitative)	All typologies
F2—Presence of a modern floodplain Width and longitudinal length of a modern floodplain	*Remote sensing–GIS*: measurement of width and longitudinal length (quantitative); *field survey*: identification/checking of modern floodplain (qualitative)	*PC–U*; not evaluated in the case of mountain streams along steep (>3%) alluvial fans
F3—Hillslope–river corridor connectivity Presence and length of elements of disconnection (e.g., roads) within a buffer 50-m wide for each river side	*Remote sensing–GIS*: identification and measurement of length of disconnecting elements (quantitative); *field survey*: checking disconnecting elements (qualitative)	*C*
F4—Processes of bank retreat Presence/absence of retreating banks	*Remote sensing* and/or *field survey*: identification of eroding banks (qualitative)	*PC–U*; not evaluated in the case of straight – sinuous channels of low energy (lowland rivers, low gradients and/or bedload)
F5—Presence of a potentially erodible corridor Width and longitudinal length of an erodible corridor, i.e., area without relevant structures (e.g., bank protections, levees) or infrastructures (e.g., houses, roads)	*Remote sensing–GIS*: measurement of width and longitudinal length (quantitative)	*PC–U*
F6—Bed configuration–valley slope Identification of bed configuration (i.e., cascade, step pool, etc.) in case of presence of transversal structures and comparison with expected bed configuration based on valley slope	*Topographic maps*: mean valley slope (quantitative); *field survey*: identification of bed configuration (qualitative)	single-thread *C*; not evaluated for bedrock streams, and for deep streams when observation of the bed is not possible
F7—Forms and processes typical of the channel pattern Percentage of the reach length with alteration of the natural heterogeneity of forms expected for that river type caused by human factors	*Remote sensing–GIS*: identification and measurement of length of altered portions (quantitative); *field survey*: identification/checking (qualitative)	*PC–U*; wandering or multi-thread *C*
F8—Presence of typical fluvial forms in the alluvial plain Presence/absence of fluvial forms in the alluvial plain (e.g., oxbow lakes, secondary channels, etc.)	*Remote sensing* and/or *field survey*: identification and checking of fluvial forms (qualitative)	*PC–U*; evaluated only in the case of meandering rivers within a lowland plain physiographic unit
F9—Variability of the cross section Percentage of the reach length with alteration of the natural heterogeneity of cross section expected for that river type caused by human factors	*Field survey*: identification/checking (qualitative); *remote sensing–GIS*: identification and measurement of length of altered portions (quantitative)	All typologies; not evaluated in the case of straight, sinuous or meandering channels with natural absence of bars (lowland rivers, low gradients and/or low bedload)
F10—Structure of the channel bed Presence/absence of alterations of bed sediment (armouring, clogging, bedrock outcrops, bed revetments)	*Field survey*: visual assessment (qualitative)	All typologies; not evaluated for bedrock or sand-bed rivers, and for deep channels when observation of the bed is not possible
F11—Presence of in-channel large wood Presence/absence of large wood	*Field survey*: visual assessment (qualitative)	All typologies; not evaluated above the tree-line and in streams with natural absence of riparian vegetation
F1—Width of functional vegetation Mean width (or areal extension) of functional vegetation in the fluvial corridor potentially connected to channel processes	*Remote sensing–GIS*: identification and measurement of mean width of functional vegetation (quantitative)	All typologies; not evaluated above the tree—line and in streams with natural absence of riparian vegetation
F13—Linear extension of functional vegetation Longitudinal length of functional vegetation along the banks with direct connection to the channel	*Remote sensing–GIS*: identification and measurement of longitudinal length of functional vegetation (quantitative)	All typologies; not evaluated above the tree—line and in streams with natural absence of riparian vegetation
A1—Upstream alteration of flows Amount of changes in discharge caused by interventions upstream (dams, diversions, spillways, retention basins, etc.)	*Hydrological data*: evaluation of reduced/increased discharge caused by interventions (quantitative). In absence of available data, the assessment is based on presence of intervention and its use (qualitative)	All typologies
A2—Upstream alteration of sediment discharges Presence, type, and location (drainage area) of relevant structures responsible for bedload interception (dams, check-dams, weirs)	*Remote sensing–GIS* and/or *database of interventions*: identification of structures and relative drainage area (quantitative)	All typologies
A3—Alteration of flows in the reach Amount of alterations of discharge caused by interventions within the reach	See A1	All typologies
A4—Alteration of sediment discharge in the reach Typology and spatial density of structures intercepting bedload (check dams, weirs) along the reach	*Remote sensing–GIS* and/or *database of interventions*: identification and number of structures (quantitative)	All typologies
A5—Crossing structures Spatial density of crossing structures (bridges, fords, culverts)	*Remote sensing–GIS* and/or *database of interventions*: identification and number of structures (quantitative)	All typologies
A6—Bank protections Length of protected banks (walls, rip-raps, gabions, groynes, bioengineering measures)	*Remote sensing–GIS* and/or *database of interventions*: length of structures (quantitative)	All typologies
A7—Artificial levees Length and distance from the channel of artificial levees	*Remote sensing–GIS* and/or *database of interventions*: length and distance of structures (quantitative)	*PC–U*
A8—Artificial changes of river course Percentage of the reach length with documented artificial modifications of the river course (meander cutoff, relocation of river channel, etc.)	*Historical/bibliographic information* and/or *database of interventions* (quantitative)	*PC–U*
A9—Other bed stabilization structures Presence, spatial density and typology of other bed-stabilizing structures (sills, ramps) and revetments	*Remote sensing–GIS* and/or *database of interventions*: identification, number or length of structures (quantitative)	All typologies
A10—Sediment removal	*Database of interventions* and/or *information available by public agencies; field survey* and/or *remote sensing*: indirect evidence (qualitative)	All typologies; not evaluated in the case of bedrock streams

(continued on next page)

Table 3 (*continued*)

Indicators and assessed parameters	Assessment methods	Ranges of application
Existence and relative intensity of past sediment mining activity (from the 1950s, with particular focus on the last 20 years)		
A11—Wood removal Existence and relative intensity (partial or total) of in-channel wood removal during the last 20 years	*Database of interventions* and/or *information available by public agencies*; *field survey*: additional evidence (qualitative)	All typologies; not evaluated above the tree—line and in streams with natural absence of riparian vegetation
A12—Vegetation management Existence and relative intensity (selective or total) of riparian vegetation cuts during the last 20 years	*Database of interventions* and/or *information available by public agencies*; *field survey*: additional evidence (qualitative)	All typologies; not evaluated above the tree—line and in streams with natural absence of riparian vegetation
CA1—Adjustments in channel pattern Changes in channel pattern from 1950s based on changes in sinuosity, braiding, and anastomosing indices	*Remote sensing–GIS* (quantitative)	All typologies; evaluated only for large channels ($W>30$ m)
CA2—Adjustments in channel width Changes in channel width from 1950s	*Remote sensing–GIS* (quantitative)	All typologies; evaluated only for large channels ($W>30$ m)
CA3—Bed-level adjustments Bed-level changes over the last 100 years	*Cross sections/longitudinal profiles* (if available); *field survey*: evidence of incision or aggradation (qualitative/ quantitative)	All typologies; evaluated only for large channels ($W>30$ m) and where field evidence or information is available

Lateral continuity of sediment and wood flux is differentiated between confined and partly confined or unconfined channels. In the former case, the link between hillslopes and river corridor is evaluated (*F3*), as this is very important for the natural supply of sediment and large wood. In the case of partly confined and unconfined channels, bank erosion is the key process contributing to sediment supply, and is recognized as a positive attribute of rivers (Florsheim et al., 2008). A first indicator (*F4*) evaluates whether bank erosion processes occur as expected for a given river typology or whether a significant difference exists, such as absence caused by widespread bank control or, on the contrary, excessive bank failures related to the instability of the system (e.g., related to incision; Simon and Rinaldi, 2006). A second indicator (*F5*) assesses the presence and extension of a potentially erodible corridor (Piégay et al., 2005).

A second group of indicators concerns channel morphology, including aspects related to channel pattern, cross section, and substrate. A first indicator (*F6*) evaluates whether or not the presence of transversal structures (e.g., check-dams) has altered the expected bed configuration based on the mean slope of the reach (e.g., a formed cascade/step pool reach might feature plane–bed configuration as a consequence of the bed slope reduction caused by the structures). The following two indicators (*F7* and *F8*) qualitatively assess whether the active processes and resultant forms expected for a given morphological type in the channel and in the alluvial plain are present along the reach (e.g., a channelized meandering reach may not exhibit typical processes of that morphology).

Indicator *F9* evaluates the variability and heterogeneity of forms and surfaces in cross section expected for a given channel morphology.

The substrate conditions are assessed by a first indicator (*F10*) which takes into account possible alterations of the bed sediment, such as armoring, clogging, bedrock outcrops, or bed revetments. Clogging refers to an excess of fine sediments causing interstitial filling of the coarse sediments and potentially smothering the channel bed ('blanket': Brierley and Fryirs, 2005, or 'embeddedness': Sennatt et al., 2008). The presence and extension of clogging or armoring are assessed visually in the field, given that a quantitative evaluation is extremely time consuming or not feasible. For confined reaches, armoring is not considered to indicate an alteration because of its natural occurrence in steep, coarse-grained streams. A second indicator of substrate conditions (*F11*) concerns the presence of in-channel large wood, and evaluates whether altered conditions exist compared with the expected presence of large wood along the reach. Because of the difficulties in the assessment of expected LW storage values, only evidence of an almost complete lack of wood is considered as an alteration, but only if the reach cannot be considered a "transport" reach due to its natural morphological conditions (i.e., wide and deep channel relatively to dominant log size).

The last two indicators of functionality assess the mean width (or areal extension) and linear extension (*F12* and *F13*, respectively) of vegetation in the river corridor that is functional (i.e., woody vegetation as shrubs and trees) to a range of geomorphic processes such as flow resistance, bank stabilization, wood recruitment, sediment trapping. No ecological considerations are made on the type of vegetation (i.e., invasive species, etc.), but artificial plantations are ranked lower than natural woodlands for their reduced structural effectiveness. This evaluation is carried out by remote sensing and GIS analysis.

3.4.2. Indicators of artificiality

These consist of a set of indicators to assess artificial elements in the catchment and along the reach.

The first indicator (*A1*) is aimed at quantitatively assess alterations of channel-forming discharges and/or flows with higher return periods caused by interventions at the catchment scale (dams, diversions, spillways, retention basins, etc.). This evaluation is based on existing hydrological data. However, in case of the absence of available data, quantitative assessment is problematic, and a qualitative evaluation can be made based on existing pressures. Indicator *A3* is evaluated in the same way as *A1*, but refers to abstractions/releases along the reach analyzed.

The second indicator attempts to evaluate any upstream alteration of sediment discharges (*A2*). A rigorous, quantitative analysis of the alteration in sediment regime is not feasible, given the complexity and uncertainty of such analyses. Therefore, the evaluation is based on the assumption that relevant structures responsible for bedload interception in the catchment (dams, check-dams, weirs) have a significant effect on the sediment discharge supplied to the downstream reaches. This effect also depends on the drainage area upstream from the structures compared to the drainage area of the reach.

A following group of indicators (from *A4* to *A9*) accounts for the number, extent (spatial density), and typology of various types of artificial intervention (i.e., transversal and crossing structures, bank protections, artificial levees, artificial changes of river course, bed revetments). Therefore, the evaluation is much simpler than for the previous aspects, as these indicators do not require interpretation of processes or quantitative analyses, but just a measure of number or length of existing structures. However, in some cases, the availability of detailed information on existing structures can be limited. When databases on interventions are not available, detailed remote sensing, GIS analysis, and field surveys are required.

The last group of indicators of artificiality concerns maintenance interventions and the removal of sediment, large wood, and vegetation. Similarly to the previous group, these indicators require databases of

Table 4
Indicators of geomorphological functionality: description of classes and definition of scores.

Indicator	Classes	Score
F1	A—absence of alteration in the continuity of sediment and wood	0
	B—slight alteration (obstacles to the flux but with no interception)	3
	C—significant alteration (complete interception of sediment and wood)	5
F2	A—presence of a continuous (>66% of the reach) and wide floodplain (>*nW*, where *n* = 1 or 2 for wandering—braided or for single thread channels, respectively, and *W* = channel width)	0
	B—presence of a discontinuous (10 ÷ 66%) floodplain of any width or >66% but narrow	3
	C—absence of a floodplain or negligible presence (≤10% of any width)	5
F3	A—full connectivity between hillslopes and river corridor (>90%)	0
	B—connectivity for a significant portion of the reach (33 ÷ 90%)	3
	C—connectivity for a small portion of the reach (≤33%)	5
F4	A—presence of frequent retreating banks particularly along outer banks of bends	0
	B—infrequent retreating banks because impeded by bank protections and/or scarce channel dynamics	2
	C—complete absence of retreating banks, or widespread presence of unstable banks by mass failures	3
F5	A—presence of a potentially erodible corridor (EC) for a length >66% of the reach and wide (>*nW*, where *n* = 1 or 2 for wandering—braided or for single thread channels, respectively, and *W* = channel width)	0
	B—presence of a narrow (≤*nW*) potentially EC for >66%, or wide but for 33 ÷ 66% of the reach	2
	C—presence of a potentially EC of any width but for ≤33% of the reach	3
F6	A—bed forms consistent with the mean valley slope	0
	B—bed forms not consistent with the mean valley slope	3
	C—complete alteration of bed forms for the presence of an artificial bed	5
F7	A—absence (<5%) of alteration of the natural heterogeneity of forms expected for that river type	0
	B—alteration for a limited portion of the reach (≤33%)	3
	C—consistent alteration for a significant portion of the reach (>33%)	5
F8	A—presence of alluvial plain forms (oxbow lakes, secondary channels, etc.)	0
	B—presence of traces of alluvial plain forms (abandoned after the 1950s) but with possible reactivation	2
	C—complete absence of alluvial plain forms	3
F9	A—absence (≤5%) of alteration of the cross-section natural heterogeneity (width and depth)	0
	B—presence of alteration for a limited portion of the reach (≤33%)	3
	C—presence of alteration for a significant portion of the reach (>33%)	5
F10	A—natural heterogeneity of bed sediments and no significant clogging	0
	B—evident armouring (*PC–U* only) or clogging in various portions of the site	2
	C1—evident and widespread (>90%) armouring (*PC–U* only) or clogging, or occasional substrate outcrops (*PC–U* only)	5
	C2 - widespread substrate outcrops (>33% of the reach) (*PC–U* only) or widespread substrate alteration by bed revetments (>33% of the reach)	6
F11	A—presence of large wood	0
	C—absence or negligible presence of large wood	3
F12	A—wide connected functional vegetation (>*nW*, where *n* = 1 or 2 for wandering—braided or for single thread channels, respectively, and *W* = channel width)	0
	B—intermediate width of connected functional vegetation (0.5*W* ÷ *nW*)	2
	C—narrow connected functional vegetation (≤0.5 *W*)	3
F13	A—linear extension of functional vegetation >90% of maximum available length	0
	B—linear extension of functional vegetation 33 ÷ 90% of maximum available length	3
	C—linear extension of functional vegetation ≤33% of maximum available length	5

Table 5
Indicators of artificiality: description of classes and definition of scores.

Indicator	Classes	Score
A1	A—no significant alteration (≤10%) of channel-forming discharges and *Q* with return interval >10 years	0
	B—significant alteration (>10%) of *Q* with return interval >10 years	3
	C—significant alteration (>10%) of channel-forming discharges	6
A2	A—absence or negligible presence of structures of interception of sediment fluxes	0
	B1—presence of dams for drainage area 5 ÷ 33%, and/or weirs or check dams with total interception of bedload and drainage areas 33 ÷ 66%, and/or weirs or check dams with partial interception of bedload and drainage areas >33% (*plain/hills areas*) or >66% (*mountain areas*)	3
	B2—presence of dams for drainage area 33 ÷ 66%, and/or weirs or check dams with total interception of bedload and drainage areas >66%	6
	C1—presence of dams for drainage area >66%	9
	C2—presence of a dam at the upstream boundary of the reach	12
A3	A—no significant alteration (≤10%) of channel-forming discharges and *Q* with return interval >10 years	0
	B—significant alteration (>10%) of *Q* with return interval >10 years	3
	C—significant alteration (>10%) of channel-forming discharges	6
A4	A—absence of structures of sediment flux interception (dams, check dams, weirs)	0
	B—presence of open or consolidation check dams with relatively low density (≤1 every *n*, where *n* = 200 m in *mountain areas*, *n* = 1000 m in *hilly–plain areas*)	4
	C—presence of retention or consolidation check dams with relatively high density (>1 every *n*)	6
If the total density of transversal structures, including bed sills and ramps (see A9) is very high, i.e., >1 every 100 m in mountain areas, or >1 every 500 m in hilly–plain areas, add 12		
A5	A—absence of crossing structures (bridges, fords culverts)	0
	B—presence of some crossing structure (≤1 every 1000 m on average in the reach)	2
	C—presence of numerous crossing structures (>1 every 1000 m on average in the reach)	3
A6	A—absence or localized presence of bank protections (≤5% total length of the banks)	0
	B—presence of protections for ≤33% total length of the banks (sum of both banks)	3
	C—presence of protections for >33% total length of the banks (sum of both banks)	6
In case of extremely extended bank protections (>80%) add 12		
A7	A—levees absent or distant, or presence of levees close or in contact ≤10% total length of the banks	0
	B—medium presence of levees close and/or in contact (in contact ≤50% bank length)	3
	C—high presence of levees close and/or in contact (in contact >50% bank length)	6
In the case of extremely extended levees in contact (>80%) add 12		
A8	A—absence of artificial changes of river course in the past (meanders cut-off, channel diversions, etc.);	0
	B—presence of changes for ≤10% of the reach length	2
	C—presence of changes for >10% of the reach length	3
A9	A—absence of structures (bed sills/ramps) and absent or localised (≤5%) revetments	0
	B—limited presence of structures (≤1 every *n*, where *n* = 200 m for *mountain areas*, *n* = 1000 m for *plain/hills areas*) and or revetments (≤15% impermeable and/or ≤25% permeable)	3
	C1—presence of many structures (>1 every *n*) and/or significant bed revetments (≤33% impermeable and/or ≤50% permeable)	6
	C2—presence of impermeable bed revetments >33% and/or permeable revetments >50%	8
In the case of widespread bed revetment (>80%) add 12		
A10	*PC–U*:	0
	A—absence of recent (last 20 years) and past (from 1950s) significant sediment removal activities	
	B—moderate activities in the past (from 1950s) but absent during last 20 years, or absent in the past but present recently (last 20 years)	3
	C—intense activities in the past, or moderate in the past but present during last 20 years	6
		0

(continued on next page)

Table 5 (*continued*)

Indicator	Classes	Score
	C:	
	A—absence of significant sediment removal activities during the last 20 years	
	B—localized sediment removal activities during the last 20 years	3
	C—widespread sediment removal activities during the last 20 years	6
A11	A—absence of removal of woody material at least during the last 20 years	0
	B—selective cuts and/or clear cuts over ≤50% of the reach during the last 20 years	2
	C—total removal of woody material during the last 20 years	5
A12	A—no cutting interventions on riparian vegetation during the last 20 years	0
	B—selective cuts and/or clear cuts over ≤50% of the reach during the last 20 years	2
	C—clear cuts over >50% of the reach during the last 20 years	5

interventions and/or information by public agencies in charge of the river management, while field survey can provide additional evidence.

3.4.3. Indicators of channel adjustments

This set of indicators aims to assess channel adjustments (planimetric and vertical changes) which occurred over the previous decades. Only channel adjustments related to human pressures must be quantified, therefore it is crucial to identify controlling factors of such adjustments. Although channel adjustments are assessed using a simplified method, in most cases it should be possible to obtain a reliable interpretation of their causes by considering the magnitude of such adjustments, as well as type and frequency of human pressure at the catchment and reach scale. This latter information should be available from the analysis of the previous set of indicators (i.e., indicators of artificiality). Therefore, these indicators do not provide a detailed reconstruction of past channel evolution (i.e., channel evolutionary trajectory) but only an overall evaluation of past channel instability.

The evaluation of planimetric channel adjustments (i.e., *CA1* and *CA2*) is based on the comparison between aerial photos of the 1950s and those from the most recent available photos. Aerial photos of the 1950s were selected for two main reasons: (i) a first practical reason is the existence of a homogeneous (scale wise) Italian cover of aerial photos in 1954–1955 (IGM GAI) and similar coverages in many other regions suitable for this type of analysis, and antecedent aerial photos are not available on a national scale; (ii) for most Italian rivers, the most significant part of the planimetric adjustments over the last 100 years generally occurred from the 1950s to the early 1990s (Rinaldi and Simon, 1998; Surian and Rinaldi, 2003; Surian et al., 2009a).

Bed-level adjustments (incision or aggradation) are considered to be amongst the most relevant physical alterations affecting a number of processes (e.g., lateral connection with floodplain, alteration of in-channel habitats, etc.). This indicator (*CA3*) is assessed on existing data (e.g., longitudinal profiles or cross sections) and/or field evidence of bed-level changes that occurred over a time scale of about the last 100 years. Examples of field evidence are differences in elevation between floodplain and recent terraces, or between the higher bars in the channel and the higher gravel layers in floodplains/recent terraces, and erosion of structures within the channel (e.g., bridge piers). As for planimetric adjustments, the indicator of bed-level adjustments aims to give an overall evaluation of vertical changes, and it is not suitable for assessing whether or not different phases of adjustments had taken place (e.g., sedimentation after a phase of incision).

The two indicators of planimetric adjustments (*CA1* and *CA2*) are evaluated only for large channels (width >30 m) because of the errors associated with measurements by aerial photos. This limitation was extended to the third indicator (*CA3*), as we considered it necessary to apply the entire group of indicators of channel adjustments to allow for a complete description of this component. Another reason is that bed-level adjustments are generally more difficult to evaluate in small streams; and, additionally, they are often limited or negligible in the case of confined bedrock streams.

3.5. Classes and scores of the indicators

The classes and corresponding scores of the indicators are briefly illustrated as follows and listed in Tables 4, 5, and 6. As anticipated earlier, the scoring system was developed using the expert judgement of the authors, implying that the scores assigned to each indicator and the limits among classes are arbitrary. Scores and classes were defined and subsequently improved based on the results of the testing phase (see Section 3.7).

Three classes are generally defined for each indicator (except for a limited number with two classes or more than three classes): (A) undisturbed conditions or negligible alterations; (B) intermediate alterations; (C) very altered conditions.

For each indicator, we started by defining reference conditions for that indicator, corresponding to the absence or negligible presence of alterations (class A), and a value of 0 was assigned to this class. For the indicators of functionality, a score of 2 to 3 was assigned to the intermediate class of alteration (class B), and a score of 5 to 6 to class C (highest alteration), depending on the relative importance attributed to each indicator. For indicator *F10* (structure of the channel bed), a forth class (C2) was added to better highlight the different levels of substrate alteration.

A similar approach and scoring was adopted for the indicators of artificiality. For indicators *A2* (upstream alteration of sediment discharges) and *A9* (other bed stabilization structures), more than three classes were defined to account for a large number of cases, and a maximum score of 12 was assigned to class C2 of *A2* (presence of a dam at the upstream boundary of the reach) because this was considered a very strong element of artificiality.

Concerning the first two indicators of channel adjustments (*CA1* and *CA2*, i.e. adjustments in channel pattern and channel width, respectively), a score of 3 for class B and 6 for class C were assigned, whereas bed-level adjustments (*CA3*) were considered being more relevant, and a fourth class (C2) was defined with a score of 12, to account for the case of dramatic bed-level changes (>6 m). In fact, in some Italian rivers, very marked river incision has occurred (up to 10–12 m) in the recent past mostly as a response to gravel mining (Surian and Rinaldi, 2003).

An additional rule was defined for the cases of extremely dense and dominant presence of artificial elements along the reach, such as transversal structures, bank protections, levees, and bed revetments (indicators *A4*, *A6*, *A7*, and *A9*, respectively). This rule was included to adequately rank river reaches with only one or just a few types of artificial elements but at very large extensions and/or density, heavily affecting the overall morphological conditions (e.g., completely embanked reaches in urbanized areas; steep mountain creeks with staircase-like sequences of grade-control structures). Without this

Table 6
Indicators of channel adjustments: description of classes and definition of scores.

Indicator	Classes	Score
CA1	A—absence of changes in channel pattern from 1950s	0
	B—change to a similar channel pattern from 1950s (*PC–U*) or change of channel pattern from 1950s (*C*)	3
	C—change to a different channel pattern from 1950s (only *PC–U*)	6
CA2	A—absent or limited changes (≤15%) from 1950s	0
	B—moderate changes (15 ÷ 35%) from 1950s (*PC–U*) or changes >15% from 1950s (*C*)	3
	C—intense changes (>35%) from 1950s (only *PC–U*)	6
CA3	A—negligible bed-level changes (≤0.5 m)	0
	B—limited or moderate bed-level changes (0.5 ÷ 3 m)	4
	C1—intense bed-level changes (>3 m)	8
	C2—very intense bed-level changes (>6 m)	12

"extra-penalty", the assignation of class C to only a few artificiality indicators would result in an underestimation of artificiality (and thus to the overestimation of morphological quality). To weigh these cases more effectively, rather than defining an additional class, an extra score of 12 was assigned and added only to the numerator of Eq. (1).

3.6. Calculation of the Morphological Quality Index (MQI)

A total score was computed as the sum of scores across all components and aspects. The Morphological Alteration Index (*MAI*) is first defined as follows:

$$MAI = Stot/Smax \tag{1}$$

where *Stot* is the sum of the scores, and *Smax* is the maximum score that could be reached when all appropriate indicators are in class C. Therefore, *MAI* ranges from 0 (no alteration) to 1 (maximum alteration).

The Morphological Quality Index is then defined as

$$MQI = 1 - MAI \tag{2}$$

This index is therefore directly proportional to the quality of the reach and inversely to the alterations, varying from 0 (minimum quality) to 1 (maximum quality).

According to this structure, reference conditions (i.e., class A for each indicator, corresponding to $MQI = 1$) are identified with the following: (i) the full functionality of geomorphic processes along the reach; (ii) the absence or negligible presence of artificial elements along the reach and to some extent (in terms of flow and sediment fluxes) in the catchment; and (iii) the absence of significant channel adjustments (configuration, width, bed elevation) over a temporal frame of about 100 years.

As previously mentioned, the overall assessment procedure is carried out by using two different evaluation forms (reported in Rinaldi et al., 2012): one for confined channels, and one for partly confined and unconfined channels.

The total score (*Smax*) can vary within each category (confined, partly confined and unconfined) depending on river typology and/or physical context. For example, indicator *F6* (bed morphology in single-thread confined channels) is not evaluated for bedrock streams; channel adjustment indicators (*CA1*–*CA3*) are evaluated only for large channels (channel width >30 m, see above); or *F10* (structure of the channel bed) is not applied in deep channels where its evaluation would be impossible.

During the assessment and the compilation of the evaluation forms, some indicators may be affected by a lack of data or information or may require an interpretation that involves a certain degree of subjectivity. To help in indicating how certain the user feels concerning the answer, a degree of confidence (low, medium, high) and a second (alternative) choice in the classes can be expressed. This is calculated by taking the scores associated to the second choice (with low or medium confidence in the answer), and obtaining a range of variability rather than a single final value of the *MQI*.

The three components (geomorphological functionality, artificiality, and channel adjustments) do not have the same weight on the final score of the *MQI*: artificiality has the highest weight on the overall scoring, followed by functionality and channel adjustments. This reflects the authors' opinion that the knowledge of past channel adjustments is important but has a minor weight in the overall score compared to the other two components. In other words, past conditions are important and may affect the morphological quality, but the artificial constraints and the functioning of processes in the present condition are the two major components of the evaluation.

The following classes of morphological quality were defined: (i) high, $0.85 \leq MQI \leq 1$; (ii) good, $0.7 \leq MQI < 0.85$; (iii) moderate, $0.5 \leq MQI < 0.7$; (iv) poor, $0.3 \leq MQI < 0.5$; (v) bad, $0 \leq MQI < 0.3$.

The WFD requires a water body to be in high hydromorphological conditions to confirm the high overall ecological status. Consequently, the main aim of the classification, when applied for the WFD, is the distinction between high state ($MQI > 0.85$) or not ($MQI \leq 0.85$). Other than for the high class, the other four morphological quality classes can be useful to support the classification of the overall ecological conditions and to monitor the efficiency of the measurements, although no specific rules are defined by the WFD. Furthermore, the lower morphological classes can be used in supporting the identification of highly modified water bodies.

3.7. Testing of the indicators and the scoring system

The indicators and the overall scoring system have been tested directly on 102 river reaches (Fig. 2) by the authors and by a group of fluvial geomorphologists. These reaches were selected to represent a sufficiently wide range of conditions, in terms of channel morphology and human intervention of Italian streams, although most of them are localized in Central and Northern Italy. The *MQI* results shown in Fig. 2 are divided into three broad categories, based on a combination of confinement and channel morphology: (1) confined, typical of the mountain areas; (2) partly confined and unconfined braided and wandering, more frequent in the piedmont areas; (3) partly confined and unconfined single-thread (straight, sinuous, and meandering) and sinuous with alternate bars, more frequent in the lowland areas.

Such applications allowed (i) the verification of whether some unexpected result would occur (e.g., river reaches with heavy alterations were expected to fall into the lower categories and vice versa), and (ii) the refining of the indicator scores. This phase of testing was also useful to qualitatively verify that the procedure was comprehensive and suitable for the entire range of geographic conditions and related channel typologies found in Italy.

4. Discussion and final remarks

Limitations, strengths, and applicability of the *MQI* can be appreciated at best if the overall aim of the method is taken into consideration. The *MQI* was designed to define the deviation of present geomorphic reach conditions from reference conditions, and represents just one part of a more comprehensive system under development (IDRAIM) aimed to analyze and monitor stream morphology and processes. It represents the starting point for management or restoration actions, because it gives the quality of a specific reach and the opportunity to start building a sound geomorphological knowledge of the whole fluvial system as well as of the single stream reach. As for any classification scheme or assessment tool, a series of limitations or weaknesses for the *MQI* method can be identified. These limitations, together with possible strengths of the method, are briefly discussed below. Finally, the applicability of the method is analyzed.

Several indicators can appear as extremely simplified, and their evaluation based on limited information. This is related to: (i) the target end-users of the method, i.e., public agencies, and therefore a compromise was required between scientific rigor and practical applicability; (ii) the necessity to be applied to a large number of reaches in a relatively short time, thus the method cannot be too time consuming; (iii) the aim of the method, that is to assess morphological quality, not to get a quantification of processes or an in-depth understanding of channel evolution and future dynamics. A rigorous evaluation of geomorphological processes would imply measurements at different times of process rates (e.g., bank erosion or deposition) or the use of quantitative modelling or analyses (e.g., to assess alterations in sediment transport), which are not feasible for the previous reasons. Therefore, in most cases, indicators of processes are based on a static visual assessment (GIS or field-based) of the occurrence of active processes or associated forms. Similarly, the assessment of channel planimetric adjustments (*CA1* and *CA2*), which is based on a comparison of only

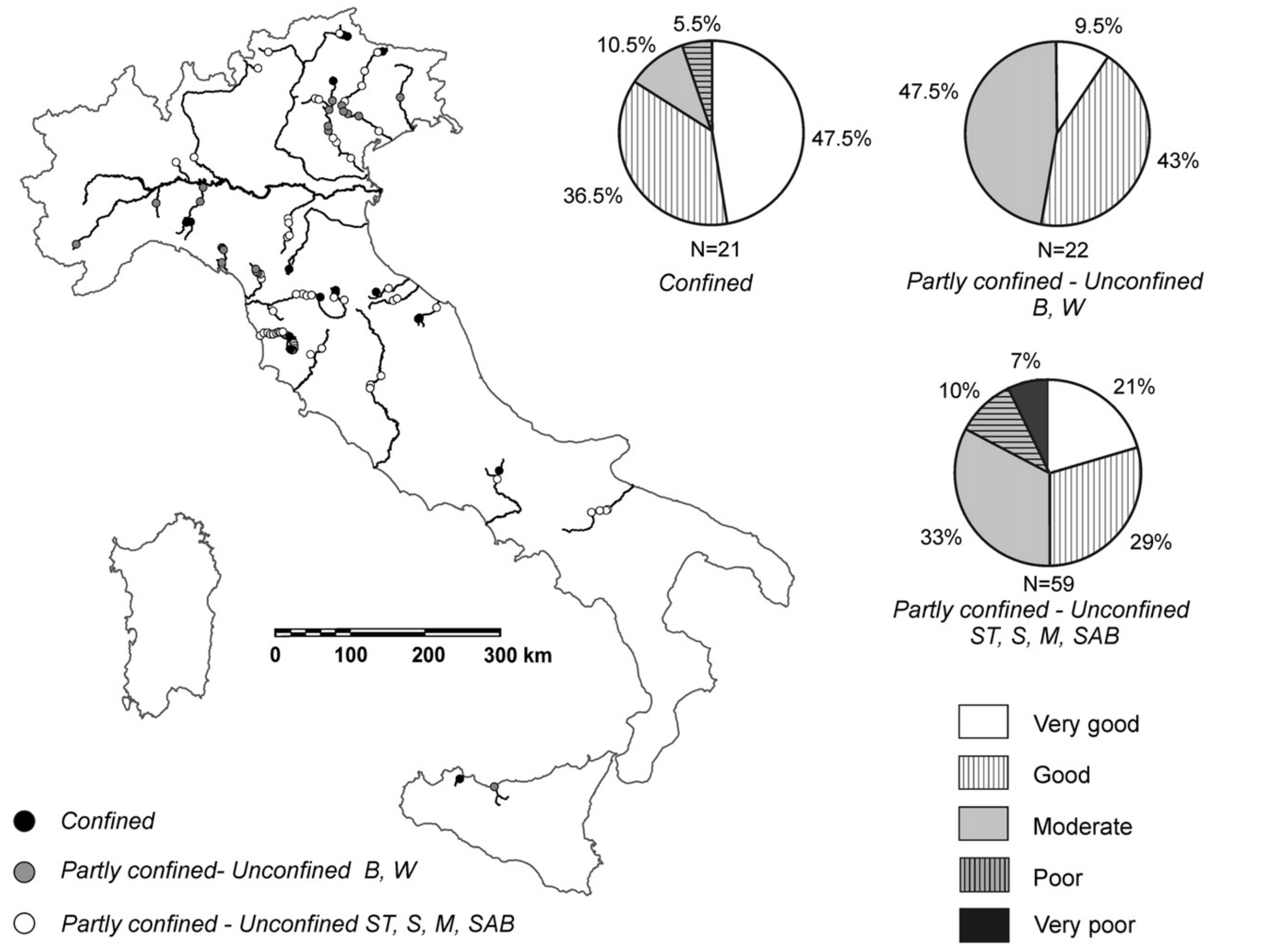

Fig. 2. Application of the *MQI* during the testing phase. On the left, location of river reaches of application. On the right, distribution of classes of *MQI* for different channel typologies. B: braided, W: wandering, ST: straight, S: sinuous, M: meandering, SAB: sinuous with alternate bars.

two sets of aerial photos, could appear to be an extreme simplification in characterizing the trend of channel adjustments that is, in many cases, complex to understand. In such a case, the aim of the indicators is to provide an estimation of the overall change that occurred during the temporal frame of investigation rather than to accurately characterize the evolutionary trajectory.

In contrast to the previous point, some concerns can be raised on the complexity of the method being used by public agencies, e.g., on the high number of indicators and on the relatively long duration of each application. In our opinion, complexity and duration are issues mainly related to the particular background of the operator. In the case of a suitable background in fluvial geomorphology (i.e., geomorphologists, civil/environmental engineers, agro/forest/environmental experts) and sufficient training, difficulties in the application are reduced. Concerning the quantity of indicators, their relatively high number is related to the need for an overall and meaningful assessment of the morphological conditions, which cannot be carried out using a lower number of the former. Possible redundancies among some indicators of functionality and artificiality, as explained earlier, are justified by the advantage of conceptually separating the two components, facilitating the identification of the causes of alteration and encouraging the interpretation of their effects on river processes.

The operator bias is an important issue to address, although rigorous tests have not yet been carried out. The type of professional background is an essential factor in causing operator bias, given that a good knowledge of fluvial geomorphic concepts is required for the application of the *MQI* and that some judgement is also required. In our experience, in the case of trained geomorphologists or other professionals (e.g., engineers, foresters) with a sufficient background in fluvial geomorphology, operator bias should be limited. In order to reduce operator bias, the set of rules is communicated in a clear and consistent manner, with data collection, indicators, and classes clearly documented in the user's guidebook (see Rinaldi et al., 2012), which should facilitate reproducibility by different operators (Kondolf, 1995). In addition, the number of classes for each indicator was kept small, i.e., classes are sufficiently large, generally having two extreme classes and one intermediate. Based on our applications and on the experience gained during the training courses, in most cases the same class is identified by all operators. However, when the answer is close to the limit between two classes, more uncertainty and subjectivity is introduced. As an additional countermeasure, we introduced the possibility to express a degree of confidence in the answers, as explained earlier.

As for the applicability, it is worth stressing again that the main goal of the *MQI* is to assess the present geomorphological conditions of a stream reach and, specifically, the deviation of such conditions from reference conditions. This implies that the *MQI* is not designed for monitoring changes in channel conditions, in particular if such changes refer to a short period of time or if changes occur in small portions of the reach (e.g., due to removal of a bank protection structure). In other words, the *MQI* is not suitable for assessing small changes in morphological quality and, more generally, for monitoring the effects of a specific management or restoration action. In this respect, a different index is under development in the IDRAIM framework to permit the monitoring of morphological quality.

Though the *MQI* does not provide an explicit “target vision” for possible river restoration, the evaluation structure provides a rational framework that is potentially useful for supporting analyses of interventions and impacts and for identifying and prioritizing management strategies, adequate restoration schemes, and measurement programmes. For example, a first obvious prioritization rule consists of preserving present conditions for those indicators which are in class A and considering some possible actions for improving those indicators lying in classes B and C.

The method could potentially be adopted, with the appropriate verification and/or modifications, in other European member states as well as in other non-European countries. However, the potential extension of the Italian classification scheme to other regions should be carried out with caution; in particular, it must be verified that the method actually covers the full range of physical conditions (physiographic units, hydrological, and climatic conditions, etc.) and the morphological types of that region.

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