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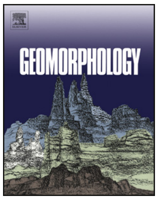

A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management

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ABSTRACT

A methodological framework for hydromorphological assessment, analysis and monitoring (named *IDRAIM*) has been developed with the specific aim of supporting the management of river processes by integrating the objectives of ecological quality and flood risk mitigation. The framework builds on existing and up-to-date geomorphological concepts and approaches and has been tested on several Italian streams.

The framework includes the following four phases: (1) catchment-wide characterization of the fluvial system; (2) evolutionary trajectory reconstruction and assessment of current river conditions; (3) description of future trends of channel evolution; and (4) identification of management options.

The framework provides specific consideration of the temporal context, in terms of reconstructing the trajectory of past channel evolution as a basis for interpreting present river conditions and future trends. A series of specific tools has been developed for the assessment of river conditions, in terms of morphological quality and channel dynamics. These include: the Morphological Quality Index (*MQI*), the Morphological Dynamics Index (*MDI*), the Event Dynamics Classification (*EDC*), and the river morphodynamic corridors (*MC* and *EMC*).

The monitoring of morphological parameters and indicators, alongside the assessment of future scenarios of channel evolution provides knowledge for the identification, planning and prioritization of actions for enhancing morphological quality and risk mitigation.

1. Introduction

During recent decades, increasing effort has been dedicated to the development of conceptual frameworks and methodologies aimed at supporting river management by introducing the use of fluvial geomorphology as a key component, and integrating geomorphological tools in ecological studies and river engineering applications (e.g., Sear et al., 1995; Simon, 1995; Gilvear, 1999; Kondolf et al., 2003a; Downs and Gregory, 2004; Brierley and Fryirs, 2005, 2008; Meitzen et al., 2013). It is widely recognized that innovative geomorphological approaches and methods can provide an essential contribution to many issues in river engineering and planning, and in promoting policies for sustainable environmental management (Brookes, 1995; Thorne, 1995; Downs and Gregory, 2004; Gregory et al., 2008; Sear et al., 2010).

In European countries, this process has been accelerated by the implementation of the EU Water Framework Directive (WFD; European Commission, 2000) and Floods Directive (FD; European Commission, 2007), which have provided a legislative background with an emphasis on the need for integrated approaches for effective river management. However, it is also recognized that EU Directives (WFD, FD, Renewable Energy Directive or RES, Habitat Directive or HD), as well as general environmental and development policies, may have conflicting objectives. This is often the case in relation to the WFD and FD, the former aiming to improve the ecological quality of streams, while the latter aims to identify measures to mitigate flood risk. As a consequence, if such objectives are considered separately, WFD implementation can promote measures to reduce protection structures (e.g., groynes, levées, check-dams) while FD may foster the adoption of structural solutions and therefore a reduction in the natural character of the stream. In light of these conflicting goals, development of integrated approaches for river management is increasingly required by public agencies. During the first decades of the development of stream restoration, many conceptual frameworks were based on defining environmental goals, whereas it is only recently that there has been an increase in the consideration of other social–economic needs and the integration of restoration within wider policy objectives (e.g., Wohl et al., 2005; Kondolf and Yang, 2008; Bennett et al., 2011; Jacobson and Berkley, 2011).

While the contribution of fluvial geomorphology in developing approaches and tools aimed at river restoration has greatly increased over the last years (e.g., Gregory et al., 2008; Simon et al., 2011), relatively few geomorphic methods aim to identify hazards associated

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with channel instability and dynamics (e.g., Sear et al., 1995, 2010; Simon and Downs, 1995; Piégay et al., 1997, 2005; Graf, 2000; Rapp and Abbe, 2003; Chin and Gregory, 2005; Biron et al., 2014). However, river managers are generally beginning to accept the need to assess the most likely channel changes occurring at the event scale. For example, the different flood scenarios along mountain streams are required to appraise reliable hazard maps (Mazzorana et al., 2011, 2013). In addition, channel adjustments (e.g., aggradation vs. incision) over a longer temporal scale (decades) have to be accounted for when planning and designing flood mitigation solutions such as levées or grade-control structures, which otherwise could become ineffective after their implementation. Importantly, these various issues must be considered in relation to flow/sediment flux and historical factors, requiring catchment scale application (Hillman and Brierley, 2005; Brierley and Fryirs, 2009).

Existing frameworks based on a geomorphological approach (e.g., Brierley and Fryirs, 2005) are primarily focussed on river restoration objectives, while there is a lack of integrated methodologies including explicit consideration of both river quality and fluvial hazards (see also Tadaki et al., 2014). In Italy, as well as in other highly populated countries, flood safety is most often the main priority in river management. This implies that river restoration projects and the implementation of the WFD could be successful only if flood risk is properly taken into account.

The methodological framework illustrated in this paper (*IDRAIM*, in Italian: 'sistema di valutazione IDRomorfologica, AnalisI e Monitoraggio dei corsi d'acqua') has been developed over the last six years (Rinaldi et al., 2013, 2014). The development of the framework was promoted and funded by the national Institute for Environmental Protection and Research (ISPRA). The overall aim of the framework is to support the management of geomorphological processes, in order to (i) integrate the objectives of WFD and FD and, more generally, (ii) promote effective river management by considering several aspects and priorities (i.e. flood risk, environmental quality, natural resources, societal needs). A specific goal of *IDRAIM* was the development of tools required for a harmonized implementation of the two Directives, including a method for morphological quality assessment (Rinaldi et al., 2013), and additional tools to assess fluvial dynamics and their related hazards. These latter tools are required for integrating the standard hydraulic analyses used for flood mapping and, therefore, for obtaining an overall more robust and reliable flood risk assessment.

The paper provides first an overview of the methodological framework, focusing on the key concepts that represent the basis of the method (e.g. spatial and temporal contexts, evolutionary trajectory concept), followed by a brief description of the overall structure and of the main tools. Finally, the innovative aspects of *IDRAIM*, its potential as well as its limitations will be considered.

2. General characteristics of the IDRAIM methodological framework

2.1. Key concepts

This section presents some of the key concepts, which constitute the foundation of the overall methodology, including the spatial framework, the temporal component and its implications for reference and target conditions.

In the geomorphic analysis of river systems, various multi-scale hierarchical approaches have been widely adopted to support a better understanding of system functionality (e.g., Frissell et al., 1986; Montgomery and Buffington, 1998; Habersack, 2000; Thomson et al., 2001; Snelder and Biggs, 2002; Brierley and Fryirs, 2005; Thorp et al., 2006; Dollar et al., 2007). Each of these methods was developed for a particular application or set of applications in ecohydraulic, river management and water resources research (Kondolf et al., 2003b; Zavadil and Stewardson, 2013). A multi-scale hierarchical approach is fundamental for many management applications, for example for selecting sampling and monitoring sites, and for interpreting and extrapolating the information gathered at specific sites to other sites of the same typology (Brierley et al., 2013; Zavadil and Stewardson, 2013). This type of approach is also used in the *IDRAIM* framework (see Section 3).

The temporal component of the framework is based on the recognition that fluvial systems are dynamic and follow a complex trajectory through time in response to a series of driving variables acting at various spatial and temporal scales (e.g., Brierley et al., 2008; Dufour and Piégay, 2009). The concept of evolutionary trajectory emphasizes the fact that a river is a complex system which, over time, adjusts its morphology to changes in boundary conditions, such as changes in flow and sediment fluxes. Knowledge of past morphological changes on an appropriate temporal scale (e.g., at least the last 100–150 years, or possibly more) is fundamental for understanding the current morphology and processes and setting them into an evolutionary temporal frame. Each river may have specific characteristics determined by its historical evolution, human pressures, or by a particular sequence of events, so interpretation of the temporal morphological variability is crucial for assessing current morphological conditions and for predicting future scenarios of channel evolution.

Recognition that rivers evolve through time and that current river morphology is one of the possible conditions within an evolutionary trajectory has important implications for the concept of 'reference conditions', which is mostly related to environmental quality issues and river restoration. This concept is crucial in assessing present river conditions and in defining restoration goals (i.e., target conditions). In recent decades, several studies have dealt with the issue of defining the geomorphic reference conditions of streams (e.g., Kern, 1992; Rhoads et al., 1999; Jungwirth et al., 2002; Brierley and Fryirs, 2005; Palmer et al., 2005; Dufour and Piégay, 2009), demonstrating that a common vision of this concept is still lacking. On the other hand, these studies do agree about some key aspects. Many authors have moved away from using the past as a reference condition. In several European countries past conditions are not necessarily natural, e.g. 100–200 years ago sediment supply to river channels was higher than today due to intense deforestation to increase the area of cropping. Besides, reference to past conditions may have limited practical relevance for contemporary management. The awareness that a river follows a complex evolutionary trajectory, reflecting a combination of long-term trends and short-term fluctuations driven by both natural and human controls, implies that in most cases the 'recovery' to an historical or 'pristine' state cannot take place due to completely changed boundary conditions (Dufour and Piégay, 2009). Consequently, the identification of a morphological 'reference state', which is difficult to define in fluvial systems with a long history of human impact, should be avoided when setting restoration goals (Kondolf et al., 2007; Rinaldi et al., 2011). It is more appropriate to define target conditions (e.g. guiding image) 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 (Brierley and Fryirs, 2005; Palmer et al., 2005). In this perspective, knowledge of evolutionary trajectories is not aimed at recreating past conditions but rather at driving the selection of river management actions which would maximize human benefits related to the most likely future river conditions.

2.2. Innovative aspects and main characteristics

The framework partly builds on existing geomorphological approaches developed in other countries (with particular reference to the River Styles Framework, Brierley and Fryirs, 2005) but, as pointed out in the previous sections, it aims to assess both fluvial morphological quality and geomorphological hazard. The framework was developed and tested in several Italian streams but most of the concepts and tools can also be applied in different geographical contexts.

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The main characteristics, including the innovative aspects of the *IDRAIM* framework, can be summarized as follows.

(i) The method embraces a catchment-wide perspective by using a multi-scale, process-based hierarchical approach that is widely recognized as a key component for a better understanding of the functioning of river systems.
(ii) The temporal component of analysis is explicitly accounted for. The framework is based on the recognition that rivers are dynamic and follow complex evolutionary trajectories over time.
(iii) The overall framework is based on an open-ended approach, rather than on a prescriptive application of rule-based procedures, allowing for the optimum use of locally available data sets. At the same time, the methodology contains a clear statement of the procedures, and the application of assessment and monitoring tools (e.g., indices of morphological quality and channel dynamics) is supported by detailed documentation (Rinaldi et al., 2014). These are important requisites to facilitate the communication and interpretation of the results (Brierley et al., 2013).
(iv) The method is based on an integration of GIS/remote sensing analysis and field techniques.
(v) Because the assessment tools are to be used for practical application by environmental or water agencies, they have been designed to be relatively simple and not excessively time consuming. However, for the application of the overall methodology, increasing levels of experience may be required by trained personnel with an appropriate background and sufficient skills in fluvial geomorphology.
(vi) Channel dynamic implications for fluvial hazards are key components of the overall analysis. Standard methods for flood hazard mapping typically neglect channel changes.
(vii) The method is specifically designed to comply with the requirements of the WFD and, most important, to integrate the goals of WFD and FD. In addition, the framework could be used for other purposes in river management (e.g., sediment management plans and environmental assessment of the impact of engineering projects).

The main innovations of *IDRAIM* are those summarized in the last two points (i.e., vi and vii), which also represent the main differences compared to previous procedures of fluvial auditing used in other countries (e.g., Sear et al., 1995, 2010).

2.3. Framework structure

According to the spatio-temporal frame delineated above, the general structure of *IDRAIM* is organized in the following four phases, with the main tasks of each phase summarized in Table 1.

Phase 1 Characterization of the fluvial system. This phase provides a catchment-wide delineation, characterization and analysis of the river system in its current conditions, with a particular focus on reach morphology and sediment transfer processes.
Phase 2 Past evolution and current river conditions. Reconstruction of evolutionary trajectories is used as fundamental knowledge for interpreting and assessing the present river conditions, both in terms of morphological quality and channel dynamics.
Phase 3 Future trends. This phase is aimed at monitoring and predicting possible future scenarios of river conditions.
Phase 4 Management. This phase aims to identify the best river management options taking into account the results stemming from the previous phases.

3. Phase 1: characterization of the fluvial system

This phase is aimed at subdividing the fluvial network into homogeneous spatial units, describing the characteristics of the spatial units, and characterizing the physical conditions and factors controlling these spatial units at different scales. This is based on a catchment-wide, spatially hierarchical framework following the scheme proposed by Brierley and Fryirs (2005), and the adaptation described by Rinaldi et al. (2012, 2013), and is consistent with the recent delineation and characterization procedure developed for European streams (Gurnell et al., 2015).

The procedure is composed of four steps synthetically described as follows (more details are reported in Rinaldi et al., 2012, 2013): (i) in step 1, the catchment is divided into physiographic units (or 'landscape units': Brierley and Fryirs, 2005) and the river network into segments, i.e., macro-reaches reflecting the boundaries of the physiographic units and other possible major differences in valley setting; (ii) in step 2, streams are categorized based on lateral confinement; (iii) step 3 consists of the identification and classification of morphological typologies based on the stream planimetric characteristics; and (iv) in step 4, further discontinuities are taken into account (e.g., in hydrology, bed slope, bed sediment, assemblage of geomorphic units) to subdivide the river

Table 1
Summary of the phases and the main tasks for each phase of the *IDRAIM* framework.

Phases	Tasks
1. Characterization of the fluvial system	Catchment-wide general setting (geology, topography, climate, hydrology, land cover, land use) Multi-scale delineation and classification of spatial units (catchment/sub-catchments, physiographic units, segments, reaches, geomorphic units) Description of characteristics at different spatial scales Analysis of factors and processes controlling the spatial pattern of channel morphologies: sediment sources and delivery, sediment budget, controlling factors (e.g., bed slope and stream power)
2. Analysis of past evolution and assessment of current river conditions	Analysis of past evolution of the fluvial system: reconstruction of evolutionary trajectories of channel change and classification of channel adjustments Analysis of causes (human impacts, chronology or time chart to visualize changes, etc.) Assessment of hydromorphological quality (Morphological Quality Index) Assessment of morphological dynamics associated to progressive changes (Morphological Dynamics Index) Assessment of morphological dynamics associated to extreme events (Event Dynamics Classification) Delineation of morphodynamic corridors (morphodynamic corridor and event morphodynamic corridor)
3. Future trends	Protocols for monitoring of morphological conditions (indicators, parameters, etc.) Morphological Quality Index for monitoring Evaluation of impacts of projects Prediction and modeling of future channel changes for different scenarios (present conditions or following management actions or interventions)
4. Management	Identification of actions for hydromorphological improvement Identification of actions for risk mitigation Identification of priorities

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into homogeneous reaches, which are defined as river stretches along which the present boundary conditions are sufficiently uniform (i.e., with no significant changes in valley setting, channel slope, imposed flow and sediment load). Although the reach is the main scale used in *IDRAIM*, the framework also considers smaller spatial scales, specifically, geomorphic units determining the channel pattern at the reach scale are identified and classified.

After the segmentation of the river network, a more detailed catchment-wide characterization and analysis of the processes and controlling factors must be carried out, thus providing a better understanding of the observed spatial patterns of the morphological features. Particular emphasis is directed to the sediment dynamics at the catchment scale, including identification of the main sediment sources, mechanisms of sediment delivery, connectivity and transport in the fluvial system. Various approaches for the characterization and analysis of sediment dynamics on hillslopes and in low-order stream channels are suggested in *IDRAIM*, including (i) the analysis of thematic maps and landslide inventories (e.g., Galli et al., 2008); (ii) multitemporal analysis of sediment sources (e.g., Brardinoni et al., 2013); (iii) geomorphometric connectivity analysis (e.g., Borselli et al., 2008; Cavalli et al., 2013); (iv) modeling hillslope stability (e.g., Borga et al., 1998; Lanni et al., 2012); and (v) semi-quantitative approaches for evaluating potential sediment recharge (e.g., Liébault et al., 2008; Rinaldi et al., 2009).

The spatial distribution of stream power is then analyzed, as it is widely recognized as one of the main factors influencing channel morphologies and their spatial distribution within the catchment (e.g., Lawler, 1992; Knighton, 1999; Fonstad, 2003). Notable efforts have recently been made to define methodologies for a systematic analysis of the spatial pattern of this parameter (e.g., Barker et al., 2009; Alber and Piégay, 2011; Vocal Ferencevic and Ashmore, 2012).

At a further level of detail, the reconstruction of sediment budgets is also recommended to quantitatively define the tendencies of a given reach or portion of river towards incision or aggradation. A sediment budget can be attempted by various approaches, including the morphological method (e.g., Ashmore and Church, 1998; McLean and Church, 1999; Ham and Church, 2000; Brewer and Passmore, 2002) or by estimating sediment transport capacity (e.g., Rinaldi et al., 2009, 2011).

4. Phase 2: analysis of past evolution and assessment of current river conditions

The second phase analyzes temporal changes to provide an assessment of current river conditions. Two specific tools have been developed to assess river morphological quality and channel dynamics, respectively. Collectively, these tools generate geomorphically-framed actions to support integrated management.

4.1. Reconstruction of trajectories of channel evolution

Reconstruction of the trajectories of morphological channel change and their relation to the potential causes is fundamental information required for correctly interpreting current stream conditions. It is important to identify the types of adjustments that have generated present channel morphology in order to understand the present process-form interactions and the response of the river system to human pressures (e.g., land use changes, dams, sediment mining) or other natural factors (e.g., past climate changes, large floods) (Fig. 1).

Analysis of channel change is highly recommended for alluvial, relatively large, dynamic rivers and smaller, highly mobile ones, whereas in the case of small confined streams, as well as substantially channelized rivers, morphological changes are likely to be limited and more difficult to investigate. The reconstruction of evolutionary trajectories is based on a series of key parameters, including channel pattern (i.e., sinuosity, braiding or anabranching indices), channel width, and bed elevation. Planimetric changes are investigated through a multi-temporal series of aerial photos and maps, while bed-level adjustments are based on the comparison of cross-sections or longitudinal profiles, when available, and field evidence.

The temporal scale of investigation generally corresponds to the past 100–150 years. This scale is considered relevant for the interpretation of the current conditions. Also, reliable data on channel morphology are usually unavailable on longer time scales. Bed level adjustments (i.e., incision or aggradation) that occurred within this timescale are fundamental for evaluating the correct functioning of some ecologically relevant processes (e.g., lateral continuity of flows is impeded if a modern floodplain is absent due to incision). This is the case of several Italian alluvial rivers, which underwent remarkable changes (i.e., bed incision and channel narrowing) during the last century mainly in response to a series of human interventions and activities (e.g., Comiti, 2012; Rinaldi, 2003; Rinaldi and Simon, 1998; Surian and Rinaldi, 2003; Surian et al., 2009a,b; Ziliani and Surian, 2012).

While a time interval of 100–150 years is necessary to set the present channel morphology within an evolutionary time frame, it is also important to refer to a shorter time scale (of about 10–15 years) to identify geomorphological stability (dynamic equilibrium) or current unstable conditions (Shields et al., 2003). For example, a recent phase of partial inversion of trends (i.e., bed aggradation and channel widening) has been observed in many Italian rivers (e.g., Rinaldi et al., 2009; Surian et al., 2009a,b; Ziliani and Surian, 2012). This is interpreted in most cases as a lagged response to the end of industrial sediment mining, combined with a renewed high sediment delivery from bank erosion and hillslopes related to intense flood events. These ongoing processes of aggradation and widening have further increased the impacts of recent flood events and the perception of risk related to river processes. Therefore, interpretation of the present trends of adjustments is particularly relevant for the assessment of channel dynamic hazards (see Section 4.3).

4.2. Assessment of hydromorphological quality

Many current hydromorphological assessment methods coincide with physical habitat assessment procedures, which may provide useful site information characterizing the river at the time of survey, but their use for understanding physical processes and causes of river alteration is affected by a series of weaknesses (Fryirs et al., 2008; Rinaldi et al., 2013; Gurnell et al., 2015). As a consequence of these limitations, an increasing effort has recently been made to develop methods based on a more robust geomorphological approach, with a stronger consideration of physical processes at appropriate spatial and temporal scales (e.g., Montgomery and MacDonald, 2002; Brierley and Fryirs, 2005). Among these methods, the Morphological Quality Index (*MQI*) has recently been developed (Rinaldi et al., 2013).

The *MQI* is applied at the reach-scale, as defined in Section 3, by an integration of remote sensing-GIS analysis and field survey. It includes a set of twenty-eight indicators assessing longitudinal and lateral continuity, channel pattern, cross-section configuration, bed structure and substrate, and vegetation in the riparian corridor (Table 2). These characteristics are evaluated in terms of three components: geomorphological functionality, artificiality, and channel adjustments. The evaluation is based on a scoring system, considering that reference conditions are identified with a river reach in dynamic equilibrium, performing those morphological functions that are expected for a specific morphological typology, and where artificial elements and pressures are absent or do not significantly affect the river forms and processes.

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; and (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, whereas scores ranging from 5 to 12 were assigned to class C (highest alteration), depending on the

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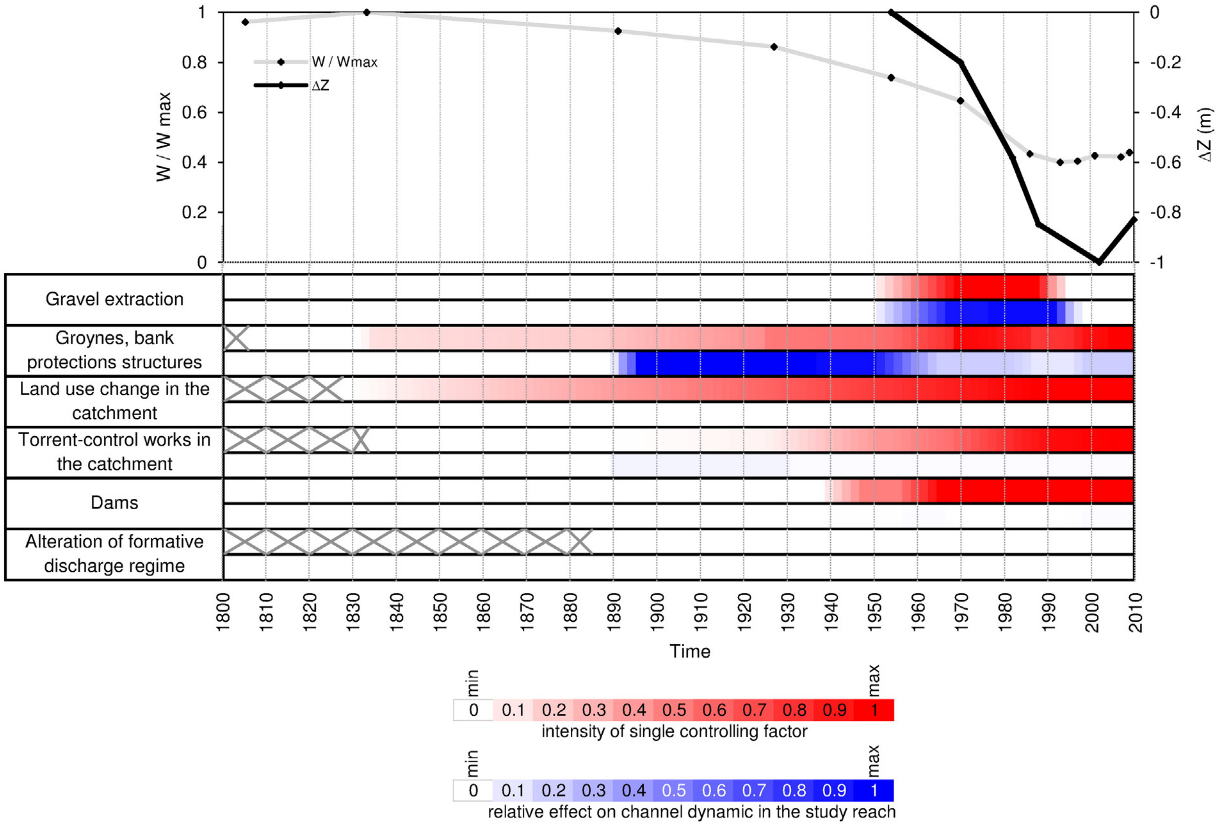

Fig. 1. Evolutionary trajectory of channel morphology and controlling factors in the Tagliamento River (Italy) over the last 200 years (from Ziliani and Surian, 2012). W/Wmax and ΔZ represent, respectively, a dimensionless width and bed elevation change referring to elevation in the 1950s. Different colors are used to show the intensity of single controlling factors and the relative effect of each factor on channel dynamics in the study reach (49 km in length). Periods with no data are shown with a cross. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

relative importance attributed to each indicator (see Rinaldi et al., 2013). A total score is then calculated as the sum of the scores of all the indicators. The Morphological Quality Index (*MQI*) is first defined as follows:

$$MQI = 1 - Stot/Smax \tag{1}$$

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, *MQI* ranges from 0 (minimum quality) to 1 (maximum quality). The following five classes were defined: (i) high, $0.85 \le MQI \le 1$; (ii) good, $0.7 \le MQI < 0.85$; (iii) moderate, $0.5 \le MQI < 0.7$; (iv) poor, $0.3 \le MQI < 0.5$; and (v) very poor, $0 \le MQI < 0.3$.

The assessment of morphological quality is integrated by an analysis of the hydrological regime which is assessed separately by a specific index of hydrological alteration (*IARI*; ISPRA, 2009) based on the thirty-three Indicators of Hydrologic Alteration (IHA; Richter et al., 1996; Poff et al., 1997). This hydrological index is used to obtain an overall classification of the hydromorphological state of a river reach.

4.3. Assessment of morphological channel dynamics

Flood hazard mapping by water agencies is in most cases identified with the spatial analysis of the probability and magnitude (i.e., depth, velocity) of inundation, whereas hazards related to channel dynamics are commonly neglected. In the case of low-energy or highly-controlled rivers this approach could potentially be sufficient, although the modeling of the consequences of levée failures is receiving increasing attention (e.g., Domeneghetti et al., 2013; Viero et al., 2013). Conversely, hazards in more dynamic gravel-bed and mountain rivers are not reliably assessed by adopting a static channel geometry scenario (Mazzorana et al., 2013). Poor consideration of hazard related to morphological channel changes also reflects the fact that few geomorphological approaches and methods aimed to specifically assess channel dynamics or instability have been developed (e.g., Graf, 1984, 2000; Simon and Downs, 1995; Chin and Gregory, 2005). This part of the *IDRAIM* framework is intended to provide a series of geomorphological tools in order to account for channel dynamics within the overall analysis of flood hazard. Three different tools have been developed to be applied at the reach scale: the Morphological Dynamics Index (*MDI*), the Event Dynamics Classification (*EDC*), and the river morphodynamic corridors.

The *MDI* classifies the degree of channel dynamics related to progressive changes occurring over a relatively long time scale, not including the possible responses to extreme flood events (which are addressed in the *EDC*). *MDI* is highly recommended for alluvial unconfined or partly confined river reaches, but could also be applied to confined reaches if the necessary information is available.

For the *MDI*, a set of eleven indicators has been defined (Table 3). These are structured into three main components (similar to the structure of the *MQI*): (i) morphology and processes; (ii) artificiality; and (iii) channel adjustments. Indicators of morphology and processes assess the characteristics of channel pattern, bed, banks, and current processes, i.e. rates of bank retreat and trends of adjustment on a time scale of the last 10–15 years. Indicators of artificiality evaluate the presence and longitudinal extent of bank and bed protection structures which can prevent or reduce channel dynamics. Lastly, indicators of channel adjustments focus on morphological changes occurring over a relatively long time period (i.e., about the last 100 years) that are indicative of a systemic instability related to some imbalance between the flow regime and the sediment load. They are considered in this evaluation because river reaches experiencing long term instability are likely to remain

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Table 2

Morphological Quality Index (*MQI*): synthesis of indicators and assessed parameters (for more details see Rinaldi et al., 2013).

Indicators	Assessed parameters
Geomorphological functionality	
F1 — longitudinal continuity in sediment and wood flux	Presence of crossing structures altering sediment and wood continuity
F2 — presence of a modern floodplain	Width and longitudinal length of a modern floodplain
F3 — hillslope–river corridor connectivity	Presence and length of elements of disconnection on river sides
F4 — processes of bank retreat	Presence/absence of retreating banks
F5 — presence of a potentially erodible corridor	Width and longitudinal length of an erodible corridor
F6 — bed configuration–valley slope	Identification of bed configuration and comparison with expected bed configuration based on valley slope
F7 — forms and processes typical of the channel pattern	Percentage of the reach length with alteration of forms
F8 — presence of typical fluvial forms in the alluvial plain	Presence/absence of fluvial forms in the alluvial plain
F9 — variability of the cross-section	Percentage of the reach length with alteration of the natural heterogeneity of cross-section
F10 — structure of the channel bed	Presence/absence of alterations of bed sediment
F11 — presence of in-channel large wood	Presence/absence of large wood
F12 — width of functional vegetation	Mean width of functional vegetation in the fluvial corridor
F13 — linear extension of functional vegetation	Longitudinal length of functional vegetation along the banks
Artificiality	
A1 — upstream alteration of flows	Amount of changes in discharge caused by interventions upstream
A2 — upstream alteration of sediment discharges	Presence, type, and position (drainage area) of relevant structures responsible for bedload interception (dams, check-dams, weirs)
A3 — alteration of flows in the reach	Amount of changes in discharge within the reach
A4 — alteration of sediment discharge in the reach	Type and density of structures intercepting bedload along the reach
A5 — crossing structures	Spatial density of crossing structures
A6 — bank protections	Length of protected banks
A7 — artificial levées	Length and distance from the channel of artificial levées
A8 — artificial changes of river course	Percentage of the reach length with artificial modifications of the river course
A9 — other bed stabilization structures	Presence, spatial density and typology of other bed-stabilizing structures and revetments
A10 — sediment removal	Existence and relative intensity of past sediment mining activity
A11 — wood removal	Existence and relative intensity of in-channel wood removal
A12 — vegetation management	Existence and relative intensity of riparian vegetation cuts
Channel adjustments	
CA1 — adjustments in channel pattern	Changes in channel pattern from 1950s based on changes in sinuosity, braiding, and anastomosing indices
CA2 — adjustments in channel width	Changes in channel width from 1950s
CA3 — bed-level adjustments	Bed-level changes over the last 100 years

unstable, and they may tend to partially recover their previous morphology (for example, reaches where an intense channel narrowing occurred in the past may tend to recover part of their original width).

The evaluation, as for other components of the framework, is carried out by making a synergistic 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.

A scoring system is used for this index, similar to the *MQI*. For most of the indicators, five classes are defined (except for three indicators with three, four or seven classes, respectively), ranging from class A indicating negligible dynamics, to class E associated with a maximum degree of morphological dynamics. Accordingly, the scores associated to each class are progressively higher from A to E, so that the final index (ranging from 0 to 1) increases with increasing dynamics (Table 4; details on classes and scores are reported in Rinaldi et al., 2014). A total score is then calculated as the sum of the scores of all the indicators. The Morphological Dynamics Index (*MDI*) is defined as follows:

$$MDI = Stot/Smax \tag{2}$$

where *Stot* is the sum of the scores, and *Smax* is the maximum score that could be reached when all appropriate indicators are in the highest class. Therefore, *MDI* ranges from 0 (minimum morphological dynamics) to 1 (maximum morphological dynamics). The following five classes were defined: (i) very low, $0.0 \leq MDI < 0.2$; (ii) low, $0.2 \leq MDI < 0.4$; (iii) medium, $0.4 \leq MDI < 0.6$; (iv) high, $0.6 \leq MDI < 0.8$; and (v) very high, $0.8 \leq MDI \leq 1.0$.

High values of *MDI* can be associated with relatively high-energy rivers (e.g., braided or wandering) with limited artificial control and with relevant tendency to channel instability during the last 10–15 years

Table 3

Morphological Dynamics Index (*MDI*): synthesis of indicators and assessed parameters.

Indicators	Assessed parameters
Morphology and processes	
M1 — channel typology	Definition of channel pattern based on sinuosity, braiding, and anastomosing indices
M2 — bank erodibility	Type of banks (cohesive, non-cohesive), percentage of protected banks and vegetation cover
M3 — bed erodibility	Type of bed (alluvial, bedrock outcrops), percentage of bed revetments
M4 — bank erosion processes	Length of retreating banks and rate of retreat
M5 — channel width trend	Changes in channel width during the last 10–15 years
M6 — bed-level trend	Bed-level changes during the last 10–15 years
Artificiality	
A1 — bank protection	Length of protected banks
A2 — bed protection	Length of bed protected by revetments or ramps
Channel adjustments	
CA1 — adjustments in channel pattern	Changes in channel pattern from 1950s based on changes in sinuosity, braiding, and anastomosing indices
CA2 — adjustments in channel width	Changes in channel width from 1950s
CA3 — bed-level adjustments	Bed-level changes over the last 100 years

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Table 4
Indicators of the Morphological Dynamics Index (*MDI*): description of classes and definition of scores (more detail on the definition of the classes is reported in Rinaldi et al., 2014).

Indicator	Classes	Score
M1	A — very low energy channel morphologies (lowland straight or sinuous with no bars)	0
	B — low energy channel morphologies (sinuous or meandering, anastomosing)	3
	C — medium energy channel morphologies (sinuous or meandering with bars)	6
	D — high energy channel morphologies (wandering, braided)	10
M2	A — erodible non-cohesive alluvial banks ≤10% of total bank length, or cohesive ≤33%	0
	B — erodible non-cohesive alluvial banks ≤33% of total bank length, or cohesive ≤66%	2
	C — erodible non-cohesive alluvial banks ≤66% of total bank length, or cohesive ≤90%	4
	D — erodible non-cohesive alluvial banks ≤90% of total bank length, or cohesive >90%	6
	E — erodible non-cohesive alluvial banks >90% of total bank length	8
M3	A — erodible alluvial bed, with the absence of bed protection or bedrock outcrops, ≤10% of reach length	0
	B — erodible alluvial bed ≤33% of reach length	2
	C — erodible alluvial bed ≤66% of reach length	4
	D — erodible alluvial bed ≤90% of reach length	6
	E — erodible alluvial bed >90% of reach length	8
M4	A — complete absence of retreating banks	0
	B — retreating banks ≤5% of total bank length	2
	C — retreating banks ≤33% of total bank length with rate of retreat ≤3 m/year	4
	D — retreating banks ≤33% of total bank length with rate of retreat >3 m/year, or >33% of total bank length but with rate of retreat ≤3 m/year	6
	E — retreating banks >33% of total bank length with rate of retreat >3 m/year	8
M5	A — change in channel width ≤10% (single-thread) or ≤5% (wandering or braided) during the last 10–15 years	0
	B — change in channel width ≤25% (single-thread) or ≤10% (wandering or braided) during the last 10–15 years	4
	C — change in channel width >25% (single-thread) or >10% (wandering or braided) during the last 10–15 years	8
M6	A — prevailing stable conditions of bed elevation during the last 10–15 years	0
	B — evidence of local incision or aggradation during the last 10–15 years along the reach	4
	C — evidence of widespread incision or aggradation during the last 10–15 years along the reach	8
A1	A — presence of bank protections for most of the reach, i.e. >80% of total length of alluvial banks	0
	B — bank protections >66% of total length of alluvial banks	4
	C — bank protections >33% of total length of alluvial banks	8
	D — bank protections ≤33% of total length of alluvial banks	12
	E — localized bank protections, i.e. ≤5% of total length of alluvial banks	15
A2	A — presence of bed revetments for most of the reach, i.e. >80% of reach length	0
	B — bed revetments >66% of reach length	4
	C — bed revetments >33% of reach length and/or widespread presence of transversal structures	8
	D — bed revetments ≤33% of reach length and/or localized presence of transversal structures	12
	E — localized bed revetments, i.e. ≤5% of reach length, and complete absence of other transversal structures	15
CA1	A — absence of changes in channel pattern from 1950s	0
	B — change to a similar channel pattern from 1950s	3
	C — change to a different channel pattern from 1950s	5
CA2	A — absent or limited change (≤15%) from 1950s	0
	B — moderate change (15 ÷ 35%) from 1950s	3
	C — intense change (>35%) from 1950s	5
CA3	A — negligible bed-level change (≤0.5 m)	0
	B — limited or moderate bed-level change (0.5 ÷ 3 m)	3
	C — intense bed-level change (>3 m)	6
	D — very intense bed-level change (>6 m)	10

and/or in the past (last 100 years) (Fig. 2A, B). Conversely, low values of *MDI* are associated with stable reaches (e.g., lowland rivers with very gentle slopes and cohesive, stable banks) and/or reaches characterized by strong planimetric and altimetric artificial control (Fig. 2C).

The *EDC* is used to assess the most likely channel responses to extreme flood events (>100 yr return period, i.e. the most severe scenarios used in flood risk analysis according to the Floods Directive). The classification aims to assess the degree of expected change to channel boundaries that a given reach is likely to experience in response to geomorphological processes (i.e., sediment and wood transport, mass failures) during an extreme event. The output of the classification can then be used to rank reaches based on the expected magnitude of morphological changes during extreme flood events, and to define consistent scenarios that should be analyzed further by hydrodynamic and/or morphodynamic modeling to predict more reliable flooding patterns (e.g., bridge clogging by wood transport, channel avulsion by sudden bed aggradation; Mazzorana et al., 2011, 2012). *EDC* leads to the classification of each reach into one of four classes of expected event dynamics (I: very high, II: high, III: medium, IV: low). A guided logical procedure based on flow charts is applied, where the occurrence of a condition for a given indicator can lead directly to the final classification.

The assessment is carried out by combining two aspects: (1) assessment of the expected magnitude of morphological changes taking place during the event and (2) assessment of the clogging conditions at critical cross-sections (e.g., typically bridges). The former is analyzed differently for confined/partly-confined and for unconfined reaches, whereas the latter is the same for all reach types.

The flow charts used to assess morphological changes (in the case of confined and partly confined reaches) and clogging conditions are reported in Figs. 3 and 4, respectively (a similar flow chart is defined for unconfined reaches, see Rinaldi et al., 2014). The final class of expected event dynamics is obtained by combining the results of the two flow charts (Table 5). Two examples of application of the *EDC* are reported in Fig. 5.

As presented, *MDI* and *EDC* provide information on the expected magnitude of channel dynamics in a given reach on a one-dimensional scale. This information has to be integrated with a 2-D analysis to define the areas of the fluvial corridor that will be affected by such dynamics. Methodologies for defining and mapping zones of possible channel mobility have been developed over recent years either for application to river management (e.g., the ‘Erodible Corridor Concept’ by Piégay et al., 2005; the 'Freedom Space for Rivers' by Biron et al., 2014) or for mapping fluvial hazards (the ‘Channel Migration Zone’ by Rapp and Abbe, 2003). Two river morphodynamic corridors are defined in IDRAIM, the Morphodynamic Corridor (*MC*) being the narrowest, wherein the probability that channel dynamics will take place is very high even without extreme events, and the Event Morphodynamic Corridor (*EMC*) the largest, including the portion of the alluvial plain that is likely to be affected by channel dynamics less frequently or just during extreme events.

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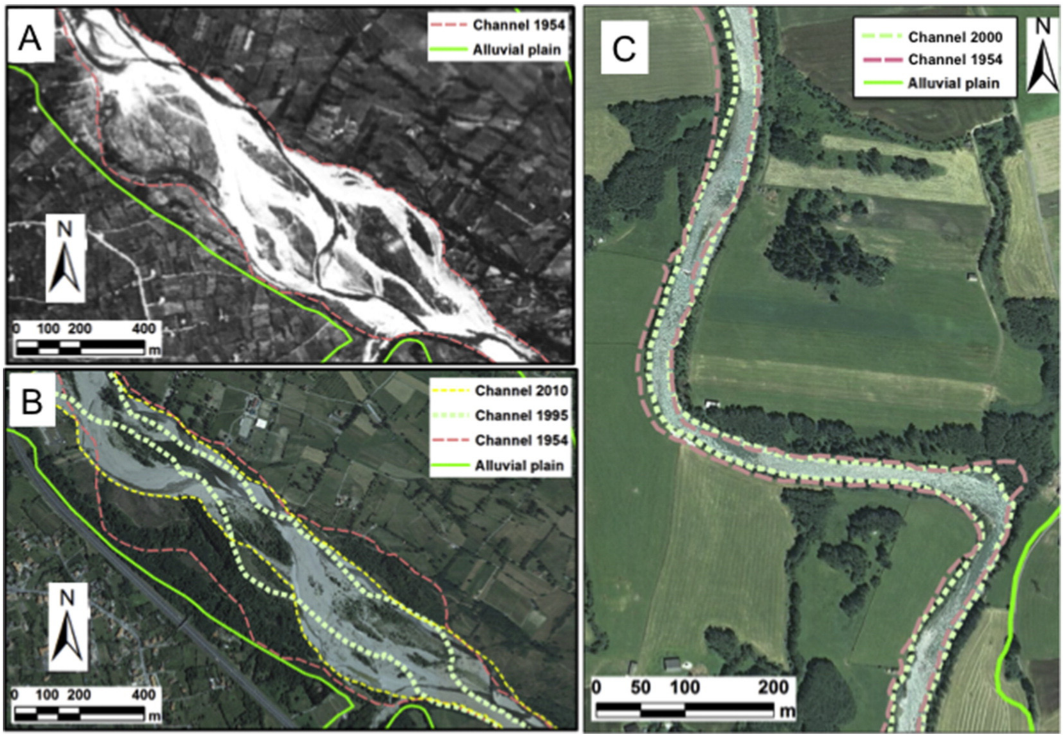

Fig. 2. Examples of the application of the Morphological Dynamics Index (*MDI*). (A) and (B) refer to the Magra River (Apennines, Italy). The reach consists of an unconfined, braided channel, with bed sediment predominantly composed of cobbles and gravel, and a mean bed slope of 0.0086. The analysis of aerial photos has shown significant channel dynamics during the past decades and during the last 10–15 years. The *MDI* of this reach is 0.77 (class "high") mainly as a result of high energy channel morphology, erodible non-cohesive banks, current trends of widening and aggradation, and limited presence of artificial elements preventing channel mobility. (C) Ahr/Aurino River (Alps, Italy). The analyzed reach is a partly confined, sinuous channel with an average slope of 0.3% and bed sediment composed of gravel and cobbles. Channel changes (both in planform and in elevation) over the last 10–15 years are virtually absent, and those which have occurred since the 1950s are quite minor. The resulting *MDI* of this reach is 0.46 (class "intermediate").

The procedure for the delineation of the river morphodynamic corridors builds upon similar approaches (e.g. Malavoi et al., 1998; Rapp and Abbe, 2003; Lagasse et al., 2004), and is implemented mainly by GIS analysis. The procedure includes (Table 6): (i) reconstruction of historical river courses; (ii) definition of possible future erosion by extrapolating the mean rate of bank retreat for a given reach; (iii) identification of natural elements of confinement (e.g., hillslopes, cemented ancient terraces); and (iv) identification of structures preventing lateral channel mobility. While the *MC* is associated with progressive channel changes without the occurrence of extreme floods (similar to the *MDI*), the *EMC* is linked to extreme events comparable to the reference events used in the EDC.

5. Phase 3: future trends

This phase considers the potential future trajectories of channel morphological evolution. It entails assessment of potential responses to existing factors or to different scenarios of management, and appraisal of their implications in terms of morphological quality and dynamics. The phase is divided into two steps: (1) monitoring, consisting of periodic measurement of morphological indicators and parameters and analysis of change and trends of adjustment and (2) modeling, entailing the prediction of future trends of channel evolution.

5.1. Monitoring

Monitoring is intended as a periodic evaluation or measurement of change of a series of parameters and indicators relative to an initial condition and, as such, is the logical tool to use for testing the veracity of previous predictions (Montgomery and MacDonald, 2002). Parameters and indicators selected for periodic measurement in the context of the *IDRAIM* framework are consistent with the previous phase of assessment and analysis (Tables 2 and 3). Furthermore, a specific tool named Morphological Quality Index for monitoring (*MQIm*) has been developed (Rinaldi et al., 2014). In fact, the *MQI* was designed to assess current morphological conditions reflecting alterations over a long time scale (i.e., last 50 years or longer periods), and may not be suitable for monitoring short-term changes in channel conditions. In contrast, the *MQIm* was specifically designed to take into account small changes (e.g. relative to small portions of a reach) and short time scales (i.e., a few years), because the score of many indicators is based on continuous interpolating functions rather than on discrete classes as for the *MQI*. Therefore, *MQIm* is particularly suitable for the environmental impact assessment of interventions, including both flood mitigation and restoration actions.

Another approach consists of analyzing temporal trends of one or more selected parameters (e.g., bed elevation, channel width, sediment size). This approach is particularly appropriate when a detailed understanding of the evolution of some specific aspect and its relative causes is required (e.g., the operative monitoring of the WFD in response to some specific pressure). The interpretation of an observed trend, or the lack of a trend, along representative sites, can then be used to verify the predicted adjustments of some aspects of the system. The parameters to be monitored are case-specific, depending on the monitoring aims and the type of influencing factors involved (i.e., those parameters more relevant to a given pressure need to be identified; see Rinaldi et al., 2014).

5.2. Prediction of future trends

Having reached an understanding of how the river has changed over time in response to different influencing factors, prediction of future

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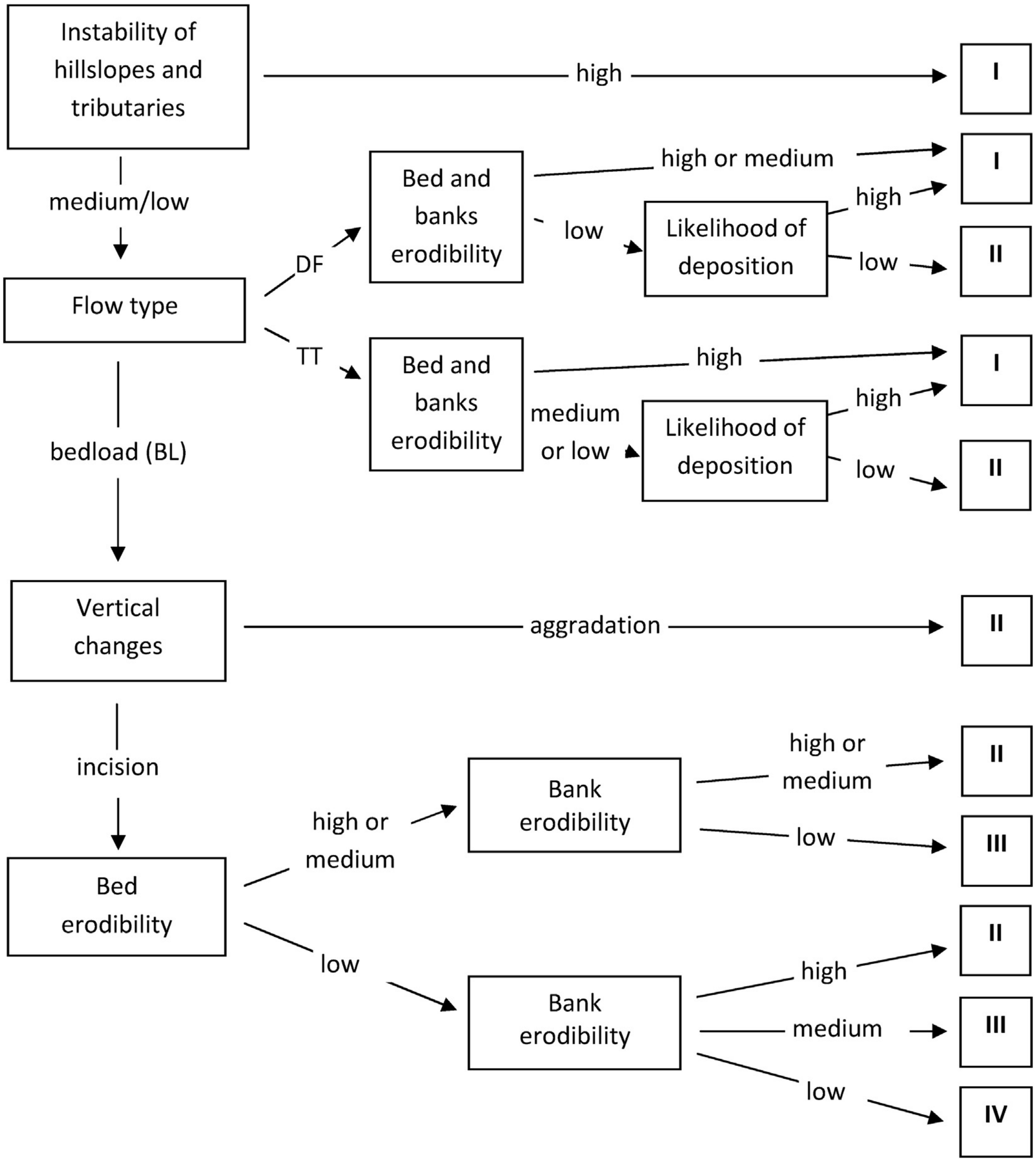

Fig. 3. Event Dynamics Classification (*EDC*): flow chart for the assessment of expected morphological changes during the "reference" extreme event. DF: debris flows; TT: transitional transport (debris floods and hyperconcentrated flows); BL: bedload; I: very relevant, II: relevant, III: intermediate, IV: small.

channel and floodplain evolution under a range of possible management scenarios can be attempted. The outputs of the analyses carried out during the previous phases can be synthesized in a cause–effect diagram, where the causes and relative weights on the morphological responses are summarized (Fig. 1).

Although the use of numerical models is progressively gaining an important role in fluvial geomorphology and in its application to river management, the prediction of morphological evolution is still difficult, given the inherent significant complexity of the processes involved and of the cause–effect relations, which are highly non-linear, and much debate still exists concerning the problems, uncertainties and limitations of the models (e.g., Darby and Van De Wiel, 2003; Wilcock and Iverson, 2003; Coulthard and Van De Wiel, 2012). Consequently, prediction of future changes within the *IDRAIM* framework is open-ended, and various types of modeling approaches could be used, including conceptual, empirical/statistical, analytical and numerical models (Darby and Van de Wiel, 2003). Selection of the type of modeling approach depends on various factors, such as the objectives of the modeling, the spatial and temporal scales, and the available data and resources.

In the *IDRAIM* framework, the following guidelines are provided for the prediction of future trends: (1) the temporal scale is the management scale, i.e., of the order of the next 50–100 years; (2) an empirical–conceptual approach at the segment or reach scale is often preferred, based on the reconstruction of the past trajectory of changes and the use of qualitative, conceptual models (e.g., Surian et al., 2009b); (3) the use of models should be aimed at evaluating possible trends of channel morphology rather than at predicting the exact channel geometry; and (4) numerical morphodynamic models could be included in this framework at a more detailed level, for example at the reach or sub-reach scale, depending on the specific problem and aims of the project.

6. Phase 4: management

Over recent years, several conceptual frameworks have been developed where restoration objectives have been integrated with

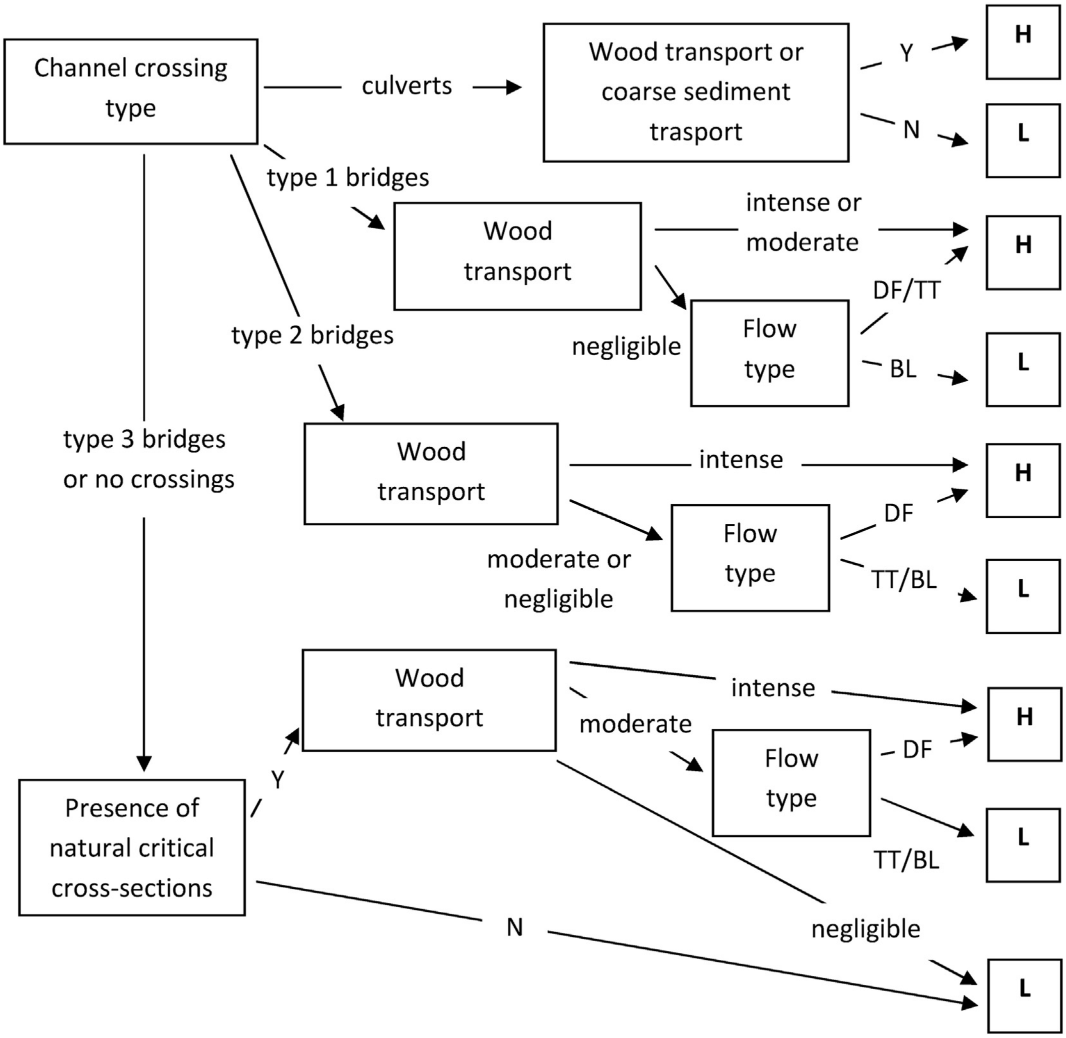

Fig. 4. Event Dynamics Classification (*EDC*): flow chart for the assessment of clogging probability at critical cross-sections during an extreme event. DF: debris flows; TT: transitional transport; BL: bedload; H: high, L: low.

consideration of other socio-economic aspects (e.g., Wohl et al., 2005; Kondolf and Yang, 2008; Bennett et al., 2011; Jacobson and Berkley, 2011). It is worth recalling that the *IDRAIM* framework focuses on geomorphological aspects and processes alone. This means that other types of analyses have to integrate the outputs provided by *IDRAIM*. Specifically, for the objectives of quality enhancement and risk mitigation, ecological assessments and hydraulic modeling, respectively, are necessary. Then, selection of the final management options needs to account for other types of evaluations and factors (e.g., socio-economic, cultural, landscape aspects) reflecting a wider range of human expectations and services.

Table 5
Event Dynamics Classification (EDC): final classes (from very high to low) deriving from the combination of expected morphological changes and clogging probability.

		Clogging probability	
		High (H)	Low (L)
Expected morphological changes	Very relevant (I)	Very high	Very high
	Relevant (II)	Very high	High
	Intermediate (III)	High	Medium
	Small (IV)	Medium	Low

6.1. General decision-making framework

Bearing in mind the specific focus of *IDRAIM*, in this final phase a simple conceptual framework is provided on how to use the assessment tools described in the previous sections in order to select actions and set priorities aimed at morphological quality enhancement and/or the mitigation of hazards related to channel dynamics.

A general decision-making framework is shown in Fig. 6. Once the problems and critical reaches have been identified by using the set of assessment tools (*MQI*, *MDI*, *EDC*, *MC*, *EMC*), a series of possible intervention scenarios can be formulated.

The first attempt is to identify possible scenarios that would both increase morphological quality as well as mitigating risk. In the case where these scenarios are neither possible nor achievable, then alternative scenarios specifically aimed at the primary goal of the reach (improving the quality or risk mitigation) need to be defined. In the following step, the effects of these scenarios are evaluated. For example, if some management or restoration actions are identified for improving hydromorphological quality, the possible consequences in reducing flood safety are then evaluated. Similarly, an evaluation of environmental impacts is carried out for possible interventions aimed at mitigating flood risk. Based on these evaluations, actions which minimize adverse effects should be identified, leading to the definition of a best scenario at the reach scale. This should be followed by additional consideration of

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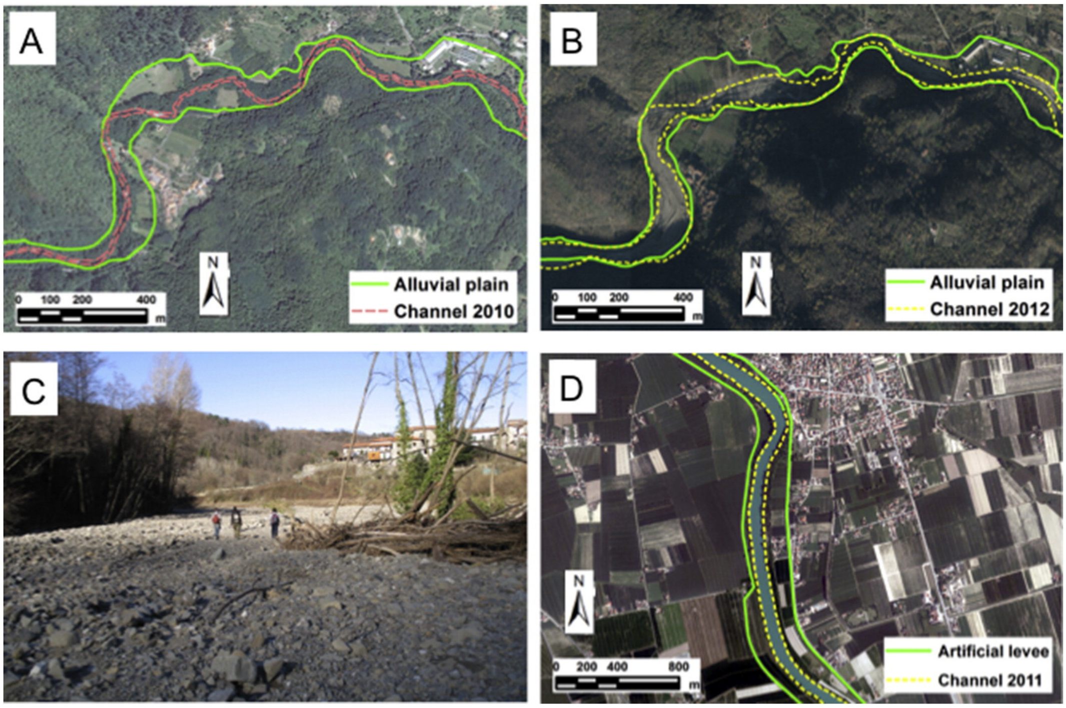

Fig. 5. Examples of application of the Event Dynamics Classification (*EDC*). (A), (B) and (C) refer to the Teglia River (Apennines, Italy) along a partly confined reach, with bed sediment mainly composed of cobbles and has a mean slope of 0.023. The event dynamics is classified as "very high" primarily as a result of the high instability of adjacent hillslopes. The two aerial photos (B) and (C) show the remarkable channel widening that took place during an extreme event (25th October 2011). (D) The Tagliamento River (Alps, Italy): the event dynamics is "medium" in this lowland reach where banks are cohesive and characterized by low erosion rates; the dynamics is "medium" because moderate bed-level changes may take place during an extreme event.

the effects on a wider spatial scale (e.g., effects on upstream and downstream reaches), leading to the identification of the best scenario at a wider spatial scale (e.g., segment scale or ideally the whole river).

6.2. Examples of application of the general decision-making framework

Two examples are provided in this section, reporting the results of some tools (e.g., *MQI*, *MDI*, *EDC*) and an application of the general decision-making framework previously described.

The first example refers to the reach reported in Fig. 2A and B, which is representative of the general conditions of a whole segment of the Magra River crossing an intermountain plain (total length of about 23 km, Nardi and Rinaldi, 2015). The segment includes an alternation of partly confined and unconfined reaches, with wandering and braided channel morphologies, bed sediment predominantly composed of cobbles and gravel, and bed slope ranging from 0.37 to 1.58 %.

The *MQI* of the reach is 0.78 (class "good"), with only some alterations related to the presence of small dams in some tributaries, sediment and large wood removal within the reach, and moderate channel adjustments during recent decades (narrowing and incision). The *MDI* is 0.77 (class "high"), as a result of the high-energy morphology, presence of non-cohesive banks, current trends in channel widening and bed aggradation, and a limited extent of artificial elements preventing vertical and lateral channel mobility (Fig. 2). The *EDC* results in class "high", deriving from the combination of "relevant" expected morphological changes due to a high possibility of avulsion, and a "low" clogging probability, due to the absence of crossing infrastructures within the reach (Table 5). The reach is therefore an example of high morphological quality combined with high channel dynamics and associated hazards. The latter represent the main issue of this reach and of the whole segment, as demonstrated by a recent major flood event which produced notable morphological changes (Nardi and Rinaldi, 2015). A high potential for damage exists in some portions of the alluvial plain, whereas in other parts of the reach (e.g. see Fig. 2) the density of exposed elements is lower and a certain degree of channel mobility is possible.

In order to improve the overall conditions of the reach, it is possible to identify one or more scenarios of possible management actions, and the relative effects in terms of morphological quality and dynamics at reach-scale and on a wider spatial scale can be evaluated (Table 7). Scenarios 2 and 3 result in a reduction of channel dynamics but produce adverse effects in terms of morphological quality, whereas the first option (delimitation of morphodynamic corridors and definition of policy and planning regulations) would provide the most favorable impact in the long term both in terms of risk mitigation and morphological quality.

The second example refers to the Ahr/Aurino River, in a reach (near the town of Gais) a few kilometers downstream but with similar characteristics to that reported in Fig. 2C, where a series of restoration interventions was carried out in the period 2003–2011 (described in detail

Table 6
Definition of the two river morphodynamic corridors. Priority indicates those elements that are essential for the identification of the corridor, whereas no priority indicates those elements that need to be considered but do not determine the final delimitation of the corridor which depends on other elements.

	Historical evolution	Potential future erosion	Natural elements of confinement	Bank protection and other artificial elements
MC	Since 1950s of XX century	50 years	No priority	Priority
EMC	Since end XIX century/beginning XX century	50 or 100 years (depending on the probability of avulsion)	Priority	No priority

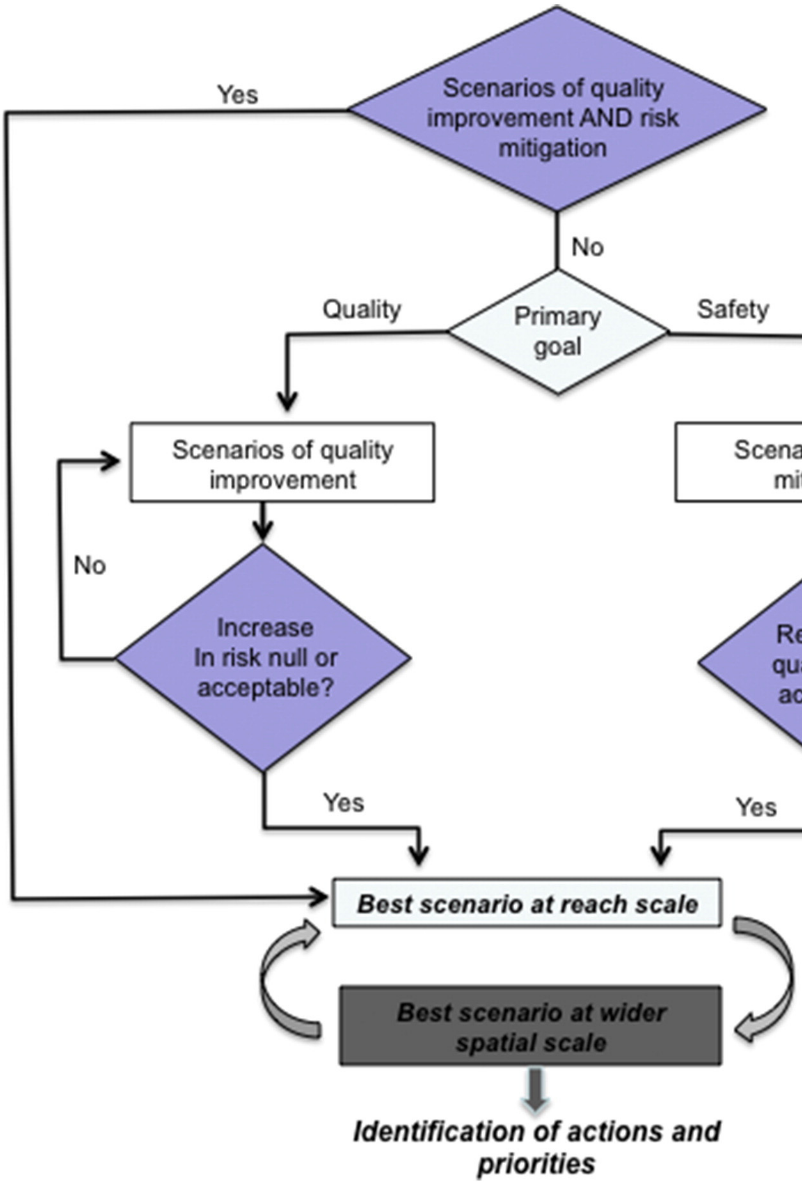

Fig. 6. General decision-making framework.

in Campana et al., 2014). Hence, this provides an opportunity for an ex-post application of the decision making framework. In this case, the improvement of morphological quality was initially sought to combine with relevant benefits also in terms of risk mitigation on a wider spatial scale. In fact, in the restored reach – the most incised by previous gravel mining activities – the local river managers originally intended to considerably raise the riverbed and use a large part of the valley bottom as a flood retention basin to reduce flood hazards in the downstream city of Bruneck/Brunico. However, due to the opposition of local inhabitants and farmers, eventually the flood retention basins were not implemented and the bed was only slightly elevated, leaving the former floodplain still disconnected from the channel.

Nonetheless, the *MQI* for this reach has increased from 0.52 (class “moderate”, in year 2000) to 0.73 (class “good”, in 2013), mostly due to improvements in the morphological and substrate diversity (i.e. increased functionality) and to the removal of some bank protections and crossings (i.e. reduced artificiality). The change in *MDI* before and after the restoration is small (in both cases the reach lies within the “intermediate” class) due to the marked planform stability exhibited by this reach during the whole second half of the 20th century. This makes the increased portion of unprotected banks associated with the restoration works of limited relevance for the final *MDI* assessment. As to *EDC*, the restoration works are believed to have not modified the morphological response of this river reach during extreme events, such that both pre- and post-restoration conditions are classified as ‘high’. This is due to the likely depositional tendency expected during large floods, in the absence of probable wood-related obstructions.

Overall, the restoration interventions in the Ahr River at Gais led to an increased morphological quality at the reach scale (Campana et al., 2014), with almost negligible adverse effects in terms of increased morphological dynamics and related hazards. On the other hand, on a wider scale (i.e. for the downstream reaches), the interventions probably have very limited effects in terms of morphological quality, and flooding conditions are not substantially modified due to the negligible increase in storage volumes.

7. Discussion

7.1. Applications of IDRAIM

Concerning the application of *IDRAIM*, some of the methodological tools (i.e., *MQI*) have already been tested and applied to a large number

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Table 7
Example of application of the general decision-making framework to a reach of the Magra River: management scenarios and potential impacts.

Management scenarios	Description	Possible reach-scale effect	Possible effects at wider scale
1. Morphodynamic corridors	No direct interventions, delimitation of morphodynamic corridors, definition of policy and planning regulations, possible relocation of some exposed elements, no need to maintain existing bank protections	*Morphological dynamics and risk*: no measurable impact on *MDI* and *EDC*, but mitigation of risk in the long term by reducing exposed elements *Morphological quality*: channel mobility would enhance morphological functionality, thus an overall increase of morphological quality is expected	Morphodynamic corridors may reduce flood peak within the reach and downstream by increasing retention of flood volumes
2. Bank protection	Increase of bank protections from 33% to 60% of total bank length	*Morphological dynamics and risk*: significant reduction of channel dynamics (*MDI* from 0.77 to 0.71 and reduction of *EDC* to class "medium") and consequent mitigation of risk related to bank erosion *Morphological quality*: deterioration (*MQI* from 0.78 to 0.71)	Increased bank protection may reduce sediment supply for downstream reaches, with potential positive effects for risk mitigation and adverse impact on morphological quality
3. Reduction of sediment supply to the reach and channel maintenance	Construction of check dams along most relevant tributaries; partial sediment and vegetation removal within the reach	*Morphological dynamics and risk*: reduction of channel dynamics (*MDI* from 0.77 to 0.73 but no effects on *EDC*) because of reduced aggradation, and possible mitigation of inundation hazard *Morphological quality*: significant deterioration (*MQI* from 0.78 to 0.71)	Reduced sediment supply to downstream reaches, with potential positive effects for risk mitigation and adverse impact on morphological quality

of river reaches in Italy (Rinaldi et al., 2013), whereas other tools (e.g., *MDI* and *EDC*) and the overall framework have so far been tested on a limited number of case studies in Central and Northern Italy (i.e., Magra, Tagliamento and Rienz/Rienza catchments). These latter tests have been used to refine and test the overall framework and were carried out to cover a wide range of conditions in terms of channel morphologies, confinement, and artificiality. That said, more tests would certainly be useful in further improving some tools or some specific parts of the framework.

Although *IDRAIM* was developed for and applied to Italian streams, we believe that it could be applied in several different contexts. Because *IDRAIM* relies on up-to-date geomorphic concepts and approaches, and the method was designed to be applied to a wide range of river typologies (i.e. from steep mountain streams to lowland rivers), its applicability should be relatively wide. Of course some tests and, eventually, some changes could be required to account for different environmental conditions or river typologies.

7.2. Strengths and limitations of the methodological framework

IDRAIM represents an overall geomorphological assessment framework aimed at supporting decisions and strategies for river management. The main strengths of the framework can be summarized as follows: (i) the methodology builds on a catchment-wide analysis of the fluvial system, by using a hierarchical, multi-scale approach within which the river reach is the key spatial unit of analysis; (ii) a temporal context is explicitly provided and knowledge of past channel morphology and evolution is required to assess the present and future conditions; (iii) the framework is strongly based on the consideration and, in many cases, on the quantification of geomorphic processes; these are fundamental to the assessment of morphological quality and fluvial hazard due to channel dynamics; and (iv) the methodology provides a general framework for integrating geomorphological analysis into potentially conflicting goals (e.g. improving ecological quality and reducing flood risk) and for assessing different scenarios and the best options for river management.

On the other hand, *IDRAIM* does present a series of limitations/weaknesses. These can be identified in the relatively simple approach used in some parts of the framework. For example, several indicators used in the various tools are simplified, and/or their assessment is typically based on limited available data. In contrast, other indicators require a rigorous evaluation of various geomorphological processes (e.g., estimation of bank erosion rates by remote sensing) or some quantitative modeling or analyses (e.g., expected magnitude of bedload variations to assess bed-level trend).

Overall, we believe that the framework and the single tools have been made as simple as possible, considering that they were designed (i) to be used by personnel trained in fluvial geomorphology and not limited solely to scientists and (ii) to be applied on a regional/national scale, i.e. on a large number of reaches. The latter aspect implies that the tools should not be too time consuming.

The *IDRAIM* framework can be used in different ways. The application of the entire procedure itself is without doubt to be recommended, but the application of just some of its parts (e.g., one or more tools) for specific purposes is also possible. Furthermore, according to data availability and to the background/skills of the user, relatively simple or more sophisticated approaches can be adopted. In fact, the methodology is an open-ended framework that can be structured in increasing levels of detail. A basic assessment of morphological conditions can be followed by the application of quantitative analyses, modeling approaches, or repeated measurements. For instance, the application of *MQI* provides an assessment of the overall morphological condition of a river reach, whereas the analysis of sediment sources, sediment budgets, and a detailed reconstruction of the trajectories of channel evolution can provide a better understanding of the controlling factors and supports generation of inferences about future evolution. Both for the whole application of *IDRAIM* and for the application of single tools, increasing levels of experience and training are required to ensure quality in data collection and final results.

8. Final remarks

Integrated approaches for river management are increasingly required by public agencies as they are challenged to support the achievement of many demanding policy objectives (ecological quality, flood risk management, renewable energy production, agricultural etc.). In order to achieve them synergistically, the prioritization of measures and the choice of the most possible multipurpose (win–win) options are therefore crucial and a comprehensive evaluation of the different scenarios is required. The analysis of the impacts of the different scenarios of measures requires a sound knowledge of river geomorphology and the development of relevant geomorphological methodologies. These should be able to address, in a clearer and simpler way, the different aspects of river processes, including sediment dynamics. All too often, these understandings are neglected in many approaches to river restoration and to river management in general.

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Geomorphological methodologies aimed at supporting integrated river management need to include tools to assess the various components of the fluvial system and need to address different objectives.

The *IDRAIM* framework comprises specific tools to address issues related to hydromorphological quality and fluvial hazard. A multi-scale spatial hierarchical approach provides the basis for a meaningful delineation and characterization of the river network. Recognition that fluvial systems are dynamic and follow complex evolutionary trajectories through time is a second key component of the methodological framework. Basic knowledge of past morphological changes is required to assess current river conditions whereas a detailed reconstruction of evolutionary trajectories is needed for a better understanding of current forms and processes and prediction of future channel evolution.

The tools developed within *IDRAIM* can provide an integrated assessment of morphological quality and channel dynamics. The Morphological Quality Index (*MQI*) can effectively provide an assessment of the overall conditions in terms of the morphological quality of each investigated river reach. The Morphological Dynamics Index (*MDI*) and the Event Dynamics Classification (*EDC*) provide information on the expected magnitude of channel dynamics in a given reach on a one-dimensional scale, and can be integrated with the river morphodynamic corridors (*MC* and *EMC*) to define the areas of the fluvial corridor that will be affected by such dynamics.

Monitoring of morphological changes and prediction of potential future trajectories of channel morphological evolution, in response to existing factors or to different scenarios of management, are essential steps for evaluating possible future geomorphic conditions. This knowledge represents the starting point for the identification and classification of critical conditions, providing the geomorphological basis for selecting suitable actions aimed at supporting integrated management.

Due to its open-ended structure, the *IDRAIM* framework and the new tools that have been developed should allow a wider application of fluvial geomorphology in river management. Furthermore, the framework represents an example of how concepts and tools developed within the scientific community can be put into practice and can be used in applied studies. Finally, concerning further development, the framework could be updated continuously by new findings and tools developed by basic research. Use of emerging technologies will provide the opportunity to enhance the application of this approach.

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