UNIVERSITÀ DEGLI STUDI FIRENZE

DOTTORATO DI RICERCA IN SCIENZE DELLA TERRA

CICLO XXXI

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Hydromorphological assessment to support river management and restoration

Settore Scientifico Disciplinare GEO/05

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ABSTRACT

This study explores the role and skills of hydromorphological assessment methods in supporting river management and restoration, with a major focus on the Italian process-based method MQI (Morphological Quality Index; Rinaldi et al., 2011), and its applicability to European rivers, in order to fulfil the requirements of the Water Framework Directive (WFD; European Commission, 2000).

Three major objectives directed the lines of analysis: i) to critically review the European methods and their capacity in supporting WFD river management stages; ii) to analyse the diagnostic capacity, robustness and objectivity of MQI and verify its potential to inform river management and restoration; iii) to test and enable the applicability of MQI to European rivers through appropriate modifications and finally propose an enhanced version to support management and restoration of Italian and European rivers compliantly with WFD.

Fifty-five European hydromorphological methods were reviewed, based on a comprehensive survey encompassing their characteristics and skills. Only few methods result in having diagnostic capacities (among which MQI), necessary for a correct assessment of river conditions and for the design and monitoring of efficient measures. The implications on river management and WFD implementation are discussed.

Data deriving from MQI assessment on almost five thousand river reaches in Italy were analysed with different statistical techniques and demonstrated that MQI responds consistently to pressures along the entire gradient and across river types, coherently with several studies on the evolution of Italian rivers, in response to the pressures exerted on them in the last centuries. Besides, MQI analysis allowed for having a general picture of Italian river conditions and critical aspects, and for formulating a general strategy to improve the conditions of Italian rivers, focused on enhancing longitudinal and lateral connectivity and preserving headwaters. A multivariate analysis attested the robustness of MQI, since each indicator results statistically independent at capturing a peculiar aspect of hydromorphological processes to compose the MQI. The analysis of uncertainty established that only in 6% of the cases the value of MQI lies in a confidence interval, resulting in upper or lower classes, due to insufficient information and/or the operator bias, reducible through some enhancements in the method.

Finally, the applicability of MQI across countries and river types was tested in different European river settings, and MQI underwent some modifications to better account for river types infrequent in Italy, such as low-energy streams. Although not yet largely applied, the modifications have proven to contribute to a more extensive application of MQI also outside Italy, while reducing the uncertainty in some indicators. The new version of MQI (MQI_{EU}) can now be used across Europe and support river management and restoration as envisaged by the European Water Framework Directive.

ACKNOWLEDGMENTS

I wish to thank Massimo Rinaldi for instilling me the rigor of scientific thinking and for promoting a quantum leap in my knowledge of river systems. My life has changed since then.

Franz, thanks for sharing your sharp and bright scientific knowledge with me, thanks for your continuous encouragement.

Wouter, Walter, Guido, Simone, and Paolo: your priceless support has accompanied this journey. I am honoured to work with you.

Atle, I appreciated your sharp and stimulating criticism, our endless discussions, and your growing interest. Thanks so much.

Joanna, Rafaela, Vittoria, Barbara B.; thanks for your esteem and encouragement.

Barbara L., no words are enough to thank you.

To all the regional river practitioners who enthusiastically welcomed and applied MQI: thanks, guys, this work is also for you.

To my team at ISPRA: we are a great team, thanks for your faithfulness and devotion.

To my parents, to Maria and Gianni: thanks for your unconditional support.

“This is the only thing they can’t take away from you”, you said. Thanks, Nikolai.

Life is cruel at times, but very beautiful.

My eternal gratitude to all river scientists I had the fortune to meet along my way.

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LIST OF ABBREVIATIONS

CIS	Common Implementation Strategy
COM	European Commission
EC	European Parliament and Council
EDC	Event Dinamycs Classification
EEA	European Environmental Agency
FD	Directive 2007/60/EC or Floods Directive
GUS	Geomorphic Unit Survey and Classification System
GWD	Dir 2006/119/EC or Groundwater Directive
HMQI	Hydro-Morphological Quality Index
IARI	Indice di alterazione idrologica
MesoHABSIM	Mesohabitat Simulation Model
MDC	Morphological Dynamics Corridors
MDI	Morphological Dynamics Index
MH_C	Mountainous/Hilly; Confined
MH_PC/U	Mountainous/Hilly; Partly-Confined/Unconfined
MQI	Morphological Quality Index
MQI_{EU}	Morphological Quality Index - European version (developed hereby)
MQI_{IT}	Morphological Quality Index - Italian version
MQIm	Morphological Quality Index for monitoring
MQI_{REFORM}	Morphological Quality Index – first extended version developed inside the REFORM project
P_U	Alluvial Plains; Unconfined reaches
REFORM	REstoring rivers FOR effective catchment Management - FP7 European Project
RBMP	River Basin Management Plans
VAF	Variance Accounted For
WFD	Dir 2000/60/EC or Water Framework Directive

1 Introduction

Socio-economic development inevitably entails anthropic pressures on catchments, which impair the status of river systems and undermine the achievement of environmental protection policies.
Indeed, according to the information reported in the European River Basin Management Plans (RBMP), hydromorphological alterations are a major obstacle for European rivers to achieve good ecological conditions (European Environmental Agency- EEA, 2018), as envisaged by the European Water Framework Directive (Dir.2000/60/EC or WFD; European Commission, 2000).

The history of river management is characterized by the perception of rivers as canals, to be fixed and controlled through engineering works, and its cumulative effects are increasingly evident, from loss of flood attenuation to severe declines in biodiversity (Vorosmarty et al., 2010; Jongman et al., 2012, Williams et al., 2014). Centuries of river engineering have dramatically changed the configuration of river corridors and disrupted hydromorphological processes, gradually reducing their ability to promote biodiversity and provide ecosystem services (e.g. Poff et al., 2007; Moyle & Mount, 2007; Nilsson et al., 2007; Pasternak, 2013).

River hydrological and geomorphological (i.e. hydromorphological) processes create the boundary conditions for aquatic ecosystems to thrive in, both directly, via the formation of habitats (e.g. Southwood, 1977; Boon et al., 1992; Wohl. et al., 2015a), and indirectly, constraining the hydrodynamics, like stream conveyance, dispersion and diffusion capacity (e.g. Nilsson & Malm Renöfält, 2008).
Understanding fluvial hydromorphological processes, and their dynamics in space and time, is therefore fundamental for river management and restoration to correct the anthropogenic disruption to such processes adopting a more holistic and "process-based" approach, as called for by river scientists and practitioners after decades of "form-based restoration" failures (e.g. Kondolf et al., 2006; Beechie et al., 2010).
Whereas "process –based" restoration aims "*to re-establish normative rates and magnitudes of physical, chemical, and biological processes that create and sustain river and floodplain ecosystems*" (Beechie et al., 2010),"form-based" restoration focuses on creating specific habitat features according to some perceived "good" conditions (e.g. Newson & Large, 2006), and somehow to "control" processes instead of restoring them (Beechie & Bolton, 1999). The failure of the form-based actions, mainly imputable to not targeting the causes of river degradation, has been widely proven and discussed (e.g. Beechie & Bolton, 1999; Kondolf et al., 2001; Kondolf et al., 2006; Palmer et al., 2005) and the effectiveness and success of process-based restoration is now widely recognized.

The success of restoration actions is equally dependant on the definition of appropriate objectives and the capacity to quantitatively monitor and evaluate the achievement of those objectives.

Yet, many projects still include scarce or no strategies to evaluate their success (e.g. Palmer et al., 2007; Morandi et al, 2014; Nilsson et al., 2016). When they do, they reveal an inconsistency between the large scales of channel dynamics and processes and the small scales of the adopted evaluation approach (e.g. Kail & Hering, 2005; Poppe et al. 2016). Thus, unproductively, success is still measured by means of biological metrics inapt to discriminate the effect of hydromorphological pressures (e.g. Friberg, 2009, 2014; Muhar et al., 2016) and habitat metrics by nature incapable to distinguish the levels of complexity naturally inherent in a particular river context.

A major reason is that process-based approaches are still very few (e.g. Belletti et al., 2015) and have only recently been applied to evaluate restoration success (e.g. Habersack & Piégay, 2007; Campana et al., 2014)

The relevance of hydromorphology in ecological assessment and restoration of aquatic ecosystems has thus increased considerably in the last decades, not only at the scientific level, triggering scientific discussions and a copious academic production (e.g. Poff, 1997; Wohl et al., 2005; Newson & Large, 2006; Vaughan et al., 2009; Rinaldi et al., 2013; 2015d; 2016c; 2016a; Gurnell et al., 2016; Friberg, 2009, 2010, 2014) but also at the policy-making level, through the emanation of relevant legislation, such as the current European legislation on river management, namely the Water Framework Directive.

The WFD ennobled hydromorphology as an aspect to be considered in all the stages of river management (characterization, diagnosis, design and implementation of measures). Nevertheless, the approaches to river monitoring and assessment are yet mostly focussed only on how biota directly responds to the relevant alterations, with no or scarce consideration on the cascade of effects going from habitat conditions to ecosystem functioning (e.g. Von Schiller et al., 2017).

The WFD identifies the objectives of river management and restoration with the good status of specific biological quality elements, currently estimated through specific indicators and metrics not often sensitive to hydromorphological pressures, as they were mainly designed for detecting organic pollution (e.g. Friberg, 2010; Friberg et al, 2011; Friberg, 2014; EC, 2015; Muhar et al., 2016). This makes them insufficient to indicate the status of rivers and inform restoration strategies, and inconsistent with stream ecology paradigm, according to which good hydromorphological processes promote good ecological processes via the formation and sustenance of aquatic physical environment (e.g. Boon et al., 1992; Kondolf et al., 2003; Wohl et al., 2005; Elosegi et al., 2010)

Whereas the nexus among hydromorphology and habitat, and consequently biota, is scientifically consolidated, the quantitative correlations between hydromorphology and biological response are still scarcely known, and mostly focused on the response of few species, mainly fish (European Commission, 2003c; 2003d; Friberg et al., 2011; Poff & Zimmerman, 2010; Friberg, 2014).

The main reason resides in the number and complexity of the processes involved, including the necessity to consider all the different spatial and time scales that characterize river dynamics (Frissell et al., 1986; Allan, 1996; Poff et al., 1997; Vaughan et al., 2009).

In absence of responsive biotic metrics, indicating the effect of pressures on habitats (and consequently on biota) in terms of river hydrological, hydraulic and geomorphological characteristics (i.e. hydromorphological characteristics) appears to be a more reliable way for assessing river status and for supporting the biological evaluations. In this way, errors in ecological assessment can be avoided as well as harmful consequences on river protection and management. More responsive biological methods can be developed in parallel (e.g. ecological networks, food webs – Friberg, 2014 Woodward et al., 2010, Von Schiller et al., 2017) for their future standardization and intercalibration. For the same aforementioned reasons, where hydromorphology is the prevailing pressure affecting the status of water bodies, it seems logical to define the ecological objectives in terms of functionality of hydromorphological processes, and measure the efficiency of restoration measures through hydrological and morphological parameters in the short and in the long term, while continuing monitoring the biotic conditions.

In the recent decades, a wide range of hydromorphological assessment methods has been developed worldwide, differing in aims, scales and approaches. Historically, hydromorphological assessment has been equalized to habitat survey, although this latter approach only sees a part of hydromorphological conditions (i.e. the forms). Consequently, the majority of the methods records small-scale physical habitat features (e.g. riffle, pools) and statistically determine the hydromorphological conditions of a reach, attributing the highest score to the higher diversity in habitats (e.g. Raven et al., 1998), unconnectedly from what occurs at the upper scales or in time. These methods have therefore scarce diagnostic skills, which makes them unfit for management purposes.

Several reviews of hydromorphological methods have been published up to now.

The majority of them examined only a limited group of methods or aimed to specific purposes (e.g. Parsons et al, 2002. Fernandez et al., 2011; Tadaki et al., 2014).

The most extensive review (Belletti et al., 2015) analysed in details 121 methods. Information on general characteristics, recorded features and river processes were screened out, allowing a comparative analysis. The main gap the review highlighted was the insufficient consideration of physical processes, whose knowledge is necessary to comprehend, diagnose and possibly maintain or enhance river status and thus to support river management.

The need of describing and assessing hydromorphological conditions of a water body, demands approaches capable of understanding the multi-scalar nature of hydromorphological processes; and to contextualize the characteristics of a water body in the frame of that multi-scalar nature, in time and space, in order to have a sound diagnosis and cure (e.g. Petts, 2000; Brierley and Fryirs, 2005; Rinaldi et. al., 2013; Gurnell et al., 2016; Elosegi et al., 2010). Such approaches are referred to as *process-based* approaches.

In the recent past, some process-based approaches were developed (Brierley and Fryirs, 2005; Ollero et al., 2011, Rinaldi et al., 2013; 2015d; Gurnell et al., 2016) and used for different purposes, from scientific application to policy implementation, at local or country-wide scale.
Nevertheless, the potential of such methods in terms of characterization, diagnosis and applicability needs to be better analysed – and extensively implemented - in order to understand to which extent such methods can effectively support all stages of river management (Fryirs, 2015).
In other terms, there are some relevant aspects, which are crucial for a method to be applied extensively and effectively, that should be investigated: the responsiveness to pressures, the applicability across countries and river contexts and the degree of objectivity/standardization, which also denotes the minima professional profiles of the implementers.
Up to now, no in depth analysis of a nationwide implemented method has been carried out in order to assess, enhance the method itself, and verify its capacity to support river management.

In response to that research and policy need, such an analysis constitutes a central part of this doctoral work and regards a specific method, the Morphological Quality Index, developed in Italy in 2010 compliantly with WFD obligations (MQI - Rinaldi et al., 2011; 2016).

1.1 *Objectives*

This research focuses on how hydromorphological analysis can support river management and, in particular, how a process-based method, namely the MQI, can be better used in river management, inside the European legislative context dictated by the WFD.

Consequently, the objectives of my doctoral work are identified as follow:

1. To carry out a review of the European hydromorphological methods used in Europe for the implementation of WFD, evaluating their skills and degree of maturity to support the management actions required by the WFD.
2. To perform a critical analysis of the Italian process based hydromorphological method MQI and verify its diagnostic skill and objectivity, investigating the results of eight-year nationwide implementation of MQI countrywide.
3. To evaluate the applicability of MQI outside Italy and eventually propose and implement modifications in order to make it suitable to its extensive application in Europe, to support river management and restoration.

The study is structured as follows.

After the introduction on the concept of hydromorphology and the role of hydromorphological assessment in river science and management, effected in Chapter 1, Chapter 2 carries out a state of the art on hydromorphology and its assessment, both in the legislative context and in science, with an excursus on its implications for river management and restoration.

Chapter 3 deals with the first objective of this doctoral work, resulting in a critical review of all European hydromorphological methods used for WFD and their suitability for implementing the different stages of river management envisaged by the legislation.

Chapter 4 investigates the process-based method MQI in terms of diagnostic capacity and operator bias, through several statistical techniques. It moreover characterizes the conditions of Italian streams and proposes management action to improve them.

Chapter 5 verifies the possibility to apply MQI to European rivers and proposes modifications to the method to also account for those river types that are infrequent in Italy. Conclusions on the new method MQI_{EU} are then drawn

Chapter 6 draws the conclusions of the entire work and provides suggestions on a more effective use of hydromorphological analysis to support river management and its possible introduction in the relevant European legislation.

This doctoral work was been carried out while working as a researcher in the field of river sciences. It allowed the development of specific research on hydromorphological methods to support river management in Europe and the publication of several papers and technical reports, since the end of 2015 up to now, which are reported in the References.

2 State of the art

2.1 Legislative context

Impacts of human activities on river hydrological and geomorphological processes have caused in time severe and often irreversible alterations in river structures and functions at the different scales, changing the quality and availability of natural resources (e.g. water, sediments, habitats) to sustain ecosystems.

The knowledge, assessment and rehabilitation of hydromorphological processes is therefore fundamental to support the provision of ecosystem services and more in general to achieve predefined environmental and/or societal objectives (e.g. Newson & Large, 2006).

This is the reason why, in the most recent body of legislation, the role of hydromorphology has been more and more recognized and valorised.

The term "hydromorphology" is indeed a neologism introduced for the first time through the European Directive 2000/60/EC or Water Framework Directive (WFD) to take into account hydrological and geomorphological processes and their close interrelation in shaping and sustaining the ecosystems.

2.1.1 The Water Framework Directive

The Water Framework Directive is the most comprehensive body of law regarding river systems management, from water protection to the mitigation of the effects of hydrological extremes. Because of this wide-ranging scope, several "daughter directives" stemmed from WFD, aimed to better govern some specific issues, such as groundwater protection (Directive 118/2006/CE) and flood risk mitigation (Directive 2007/60/CE).

The environmental objective of WFD is the achievement of good ecological status for all water bodies within 2015 and each successive 6 years, according to a sexennial planning cycle (Figure 2.1).

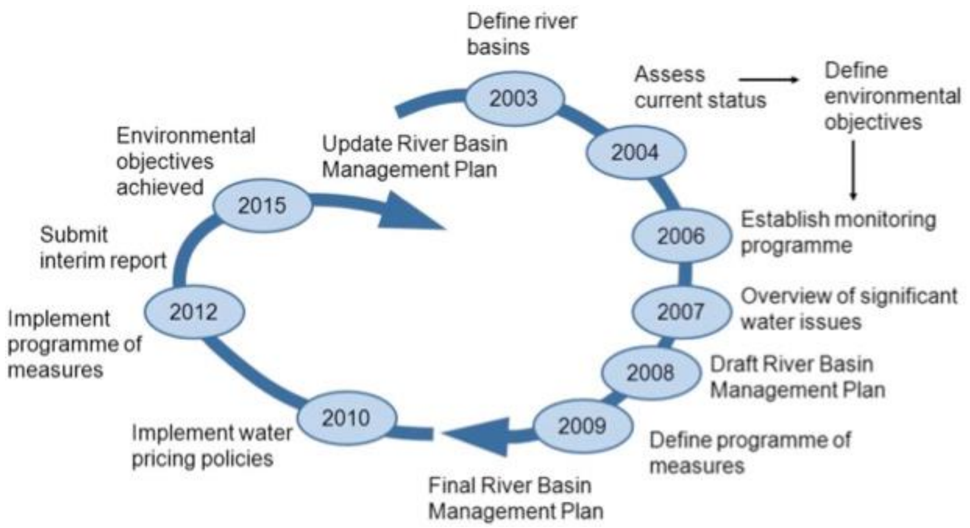


Figure 2.1 The WFD river basin planning cycle.

In order to reach the environmental objectives, a river basin management plan, articulated in different stages, is issued each six years envisaging a monitoring strategy and a programme of measures.

The WFD requires a profound knowledge of catchment processes, seen as interactions between ecosystems and human pressures at the different scales. The status of water bodies results from such interrelations, in a systemic view of causes and effects.

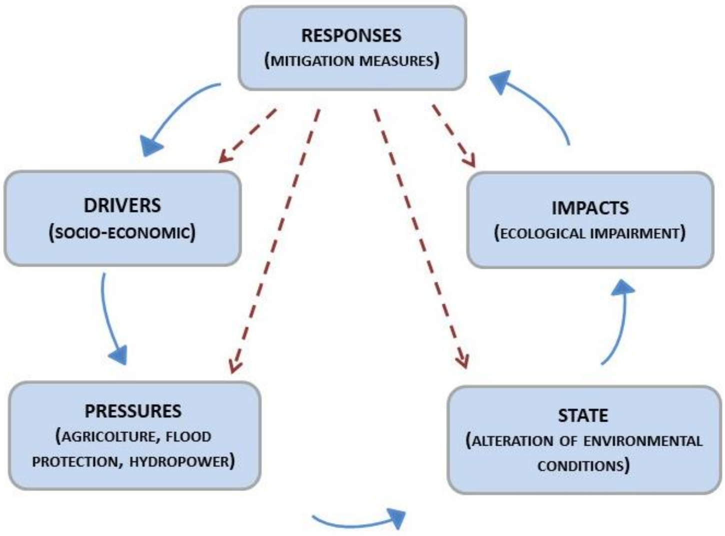


Figure 2.2 The DPSIR approach

This view reflects a DPSIR approach (EEA, 1999) where the drivers of socio-economic development (D) elicit pressures on environment (P), altering environmental conditions (state - S) and determining the significance of impacts (I) on ecosystems (where "impact" corresponds to the "status" of WFD). In response, adequate mitigation measures aimed to determine ecosystems enhancements (responses, R) have to be put in place (Figure 2.2)

For each stage of its implementation process, the WFD recognizes the crucial role of hydromorphological processes and specifies how to consider them (table 2.1).
Technical indications for implementing such a consideration of hydromorphology can be found in the relevant technical guideline developed in the frame of the WFD Common Implementation Strategy (CIS) (COM, 2018a).

Table 2.1 Role of hydromorphology in the different stages of WFD implementation

WFD stage	***Consideration of hydromorphology***	***Articles***	***CIS Guidance***
Characterization	Definition of types; segmentation in water bodies	Art. 5; Annex II	1,2,10
Risk analysis	Analysis of pressures and impacts	Art. 5 Annex II	3
Reference Conditions	Unaltered Hydromorphology	Art. 4 Annex II	10
Monitoring strategies	Programme of monitoring	Art. 8; Annex II	7
Status/Potential assessment	Hydromorphological status; ecological potential	Art. 4; Annex V	4,13

WFD stage	*Consideration of hydromorphology*	*Articles*	*CIS Guidance*
Programme of measures	Total	Art. 11; Annex VI	31
HMWB designation	Identification, evaluation of environmental better alternatives	Art. 4.3.c	4
Exemptions	Evaluation of unavoidable hydromorphological impacts	Art. 4.	20,36

In the *characterization* stage, changes in main controls on the river systems, from catchment to reach scale, should be considered in order to identify different classes (or types) of rivers, which share the same type of behaviour in terms of functions and features (energy, channel morphology, erosional/depositional characters, assemblages of geomorphic units etc.).

According to Annex II, EU member states should differentiate the "relevant surface water bodies" within each river basin district according to types derived either from system A or B (Figure 2.3). These two systems, which require different types of information, are supposed to be equivalent in their results.

Figure 2.3 Systems to characterize river types according to WFD. Left: System A; Right: System B.

SYSTEM A

Fixed typology	**Descriptors**
Ecoregion	*Ecoregions shown on map A in Annex XI*
Type	*Altitude typology* high: 800 m mid-altitude: 200 to 800 m lowland: <200 m *Size typology based on catchment area* small: 10 to 100 km2 medium: >100 to 1 000 km2 large: >1 000 to 10 000 km2 very large: >10 000 km2 *Geology* Calcareous siliceous organic

SYSTEM B

Alternative characterisation	**Physical and chemical factors that determine the characteristics of the river or part of the river and hence the biological population structure and composition**
Obligatory factors	altitude latitude longitude geology size
Optional factors	distance from river source energy of flow (function of flow and slope) mean water width mean water depth mean water slope form and shape of main river bed river discharge (flow) category valley shape transport of solids acid neutralising capacity mean substratum composition chloride air temperature range mean air temperature precipitation

Whereas system A is in essence a catchment classification system rather than a river's (Gurnell et al., 2014), system B lists some minima characteristics to derive geomorphically consistent river typologies.

The rationale behind the *typologies* is to have characterizing information on river intrinsic behaviour. This information, together with those on pressures on the river system, elicits a further segmentation in "water bodies".

The *water body* is a management unit showing a homogeneous response to the pressures it undergoes, in terms of a same ecological and chemical status. As the water body is the fundamental management unit in the WFD, due attention should be paid on the criteria used to identify it.

In a second stage, a preliminary classification of the ecological status of water bodies is carried out, based on the pressures exerted on the different water bodies and the related risk to achieve their environmental objectives (e.g. good ecological status). The WFD requires indeed the consideration of any modifications to flow regime, sediment transport, river morphology, and lateral channel mobility (WFD All. V; Rinaldi et al. 2013).

The hydromorphological pressures (e.g. abstractions, damming, etc.) are identified and their impacts on water bodies (alteration) are estimated, filtered by the river types.

The risk to achieve the environmental objectives determines the type of monitoring to be adopted, the selection of the elements to be monitored ("*quality elements*") (table 2.2) and the minimum frequency of monitoring.
If there is no risk, the monitoring will be addressed to verify no deterioration is occurring in water bodies; if a water body is at risk, due to some significant pressures, an operational monitoring on those elements more sensitive to pressures has to be effectuated. For hydrology, though, the WFD establishes a continuous monitoring, recognizing its fundamental role. For morphology and continuity, the monitoring frequency is lower and depends on the type of river and on the relevant parameters chosen.

Table 2.2 Hydromorphological quality elements in rivers according to WFD Annexes V.1.1.1 and 1.3.5

Hydromorphological element	***Sub-element***	***Minimum monitoring frequency***
Hydrological Regime	Quantity and dynamics of flow Connection to groundwater bodies	Continuous
River continuity		6 years
Morphological conditions	River depth and width variation Structure and substrate of the river bed Structure of the riparian zone	6 years

The ecological status of a river water body is measured by the status of the “quality elements” that compose its ecosystem: biological, physio-chemical (e.g. temperature, dissolved oxygen) and hydromorphological. The latter two are considered as “supporting”, as they configure the conditions for biota to thrive in.
The ecological status of the water body is expressed into five classes, from high to bad, and it is a measure of the deviation of its conditions from *reference conditions*. Reference conditions are those occurring if the water body had no or negligible pressures acting on it.
A water body at reference shows no or negligible hydromorphological pressure.

Hydromorphology is evidently crucial (and in this sense, WFD considers it as supportive element), since the habitat conditions are determinant for biota to thrive in. If habitat conditions (i.e. hydromorphology at the meso-scale; Belletti et al., 2017) are impaired, the biotic ones will respond consistently by a deterioration in their status.
Therefore, as stated in Annex V, which provides indications on the assessment of the status of water bodies, there must be consistency between abiotic and biotic conditions. If this is not the case, it is likely that the metric used to detect impacts on biology is not responding to the pressures on the water body.

The presence of irreversible, severe and permanent impairment of hydromorphology due to socio-economic needs, which cannot be satisfied in a more sustainable way (e.g. drinking water supply, hydropower, navigation), can lead to the designation of the so called *heavily modified water bodies* (HMWB), whose environmental objective is measured in terms of *ecological potential*.
Such is the best possible status that can be achieved if any mitigation measure is put in place, which does not cause a significant impact on use (e.g. loss of power production) and has tangible effects on ecology.
The procedure to define GEP starts with the identification of all hydromorphological measures that can lead to the maximum potential. Evidently, the assessment and management of HMWB particularly relies on hydromorphological assessment.
If the status/potential are below the good, measures have to be put in place to reach that “good” class.
In the stage of designing measures, hydromorphological processes needs to be identified and actions to restore all of some parts of them planned. The majority of measures are focused on hydromorphology: abstraction management, environmental flows, sediment releases, dam removal, etc.
Obviously, the evaluation of measures efficiency is directly carried out through hydromorphological monitoring and assessment.

When the good status/potential cannot be achieved because of physical reasons, exemptions can be allowed to differ the delivery of such objectives in time (e.g. longer times than a cycle envisaged for river restoration; art. 4.4) or to achieve less ambitious objectives (e.g. good potential not achievable due to significant economic losses; art. 4.5).

Art. 4.7, in particular deals with new developments interfering with riverine environments and likely to undermine the achievement of the good status/potential (COM 2003c, COM, 2017).
The exemptions are assented if some conditions are met, related to cost/benefits analysis and the evaluation of different scenarios of developments.
This point is mutually relevant for the economic development of European countries and for the future of aquatic ecosystems.
It appears quite clear that in all those politically relevant decisions hydromorphology plays a determinant role, as any decision has to be supported by a simulation of the different alternative scenarios of impacts on riverine environment in order to accept or reject the proposed exemptions.

2.1.1.1 Hydromorphology in Flood risk management: the EU Floods Directive (Directive 2007/60/CE)

The EU Directive 2007/60 (Floods Directive - FD) aims at reducing and managing the risk of flood on human health, the environment, cultural heritage and economic activity, through the implementation of combinations of different measures envisaged by Flood Risk Management Plans (FRMP).

Hydromorphology has to be fully considered when defining flood hazard or risk and when designing flood mitigation measures (Rinaldi et al., 2015a; 2016d; Bussettini et al., 2017). Hydromorphological processes dictate the boundary conditions for defining the driving variables (water; water and sediments), running hydraulic models (channel geometry, flow, etc.) accepting the hypothesis underpinning the selection and applicability of a certain flood model (e.g. invariance of channel geometry; neglect of sediment loads) and selecting efficient mitigation measures.

In presence of floods with large quantities of sediments and avulsion, the conditions to apply reliably an hydraulic model decay and other approaches, based on geomorphological analysis, have to be adopted (Rinaldi et al., 2016; Comiti et al., 2016)

According to art.9 FD, *"Member States shall take appropriate steps to coordinate the application of FD and that of WFD focusing on opportunities for improving efficiency, information exchange and for achieving common synergies and benefits having regard to the environmental objectives laid down in Article 4 of Directive 2000/60/EC".*

In terms of measures, it means that priority should be given to the identification and implementation of those measures that can deliver on the objectives of both directives (win-win measures such as, for example, *natural water retention measures* or *room for the river*) but also those related to other environmental policies (biodiversity, birds, habitat, etc.) (Rinaldi et al., 2015d; 2016d; Nilsson et al., 2018). This requires a reliable hydromorphological assessment system, able to consider river processes and their functionality. A good functionality implies good connectivity, beneficial for ecological processes but also for flooding (Croke et al., 2016). Therefore, the same processes can be analysed and assessed just once to derive the implications on different objectives (ecosystem protection vs flood risk mitigation) (Rinaldi et. al., 2015d; 2016d).

In the case of existing flood protection schemes, the HMWB designation process has a built-in obligation to consider alternatives that maintain the benefits for flood protection but are better environmental options. Maintenance or rebuilding of existing infrastructure is only possible if there are no better environmental options ensuring those flood protection levels (Bussettini et al., 2017). The evaluation of such options, in a perspective of cause-effect, cannot but be effectuated through a process-based hydromorphological approach.

2.1.1.2 Hydromorphology and groundwater protection: The Groundwater Directive (Directive 2006/119/CE)

Hydromorphology supports the status assessment also within the EU groundwater directive (Dir 2006/118/EC or Groundwater Directive - GWD), as it determines the type and entity of exchanges between groundwater and surface waters.

Exchange between groundwater and surface water is a component of the hydromorphological quality elements, to be assessed according to the WFD (WFD, Annex V; par1.1.1).

The Groundwater Directive (GWD) focuses on the chemical and quantitative status of the groundwater bodies and on the links between surface, groundwater and terrestrial dependant ecosystems.

In order to evaluate the groundwater body status and the possible interactions with the connected ecosystems, the type and entity of exchanges between groundwater and surface water bodies needs to be estimated and the combination of different physical factors, climatic, hydrological and morphological, needs to be considered.

To that aim, it can be useful to adopt conceptual models of groundwater—surface water interaction and its feedbacks with morphology and ecology (Gurnell et al., 2016), figure 2.3.

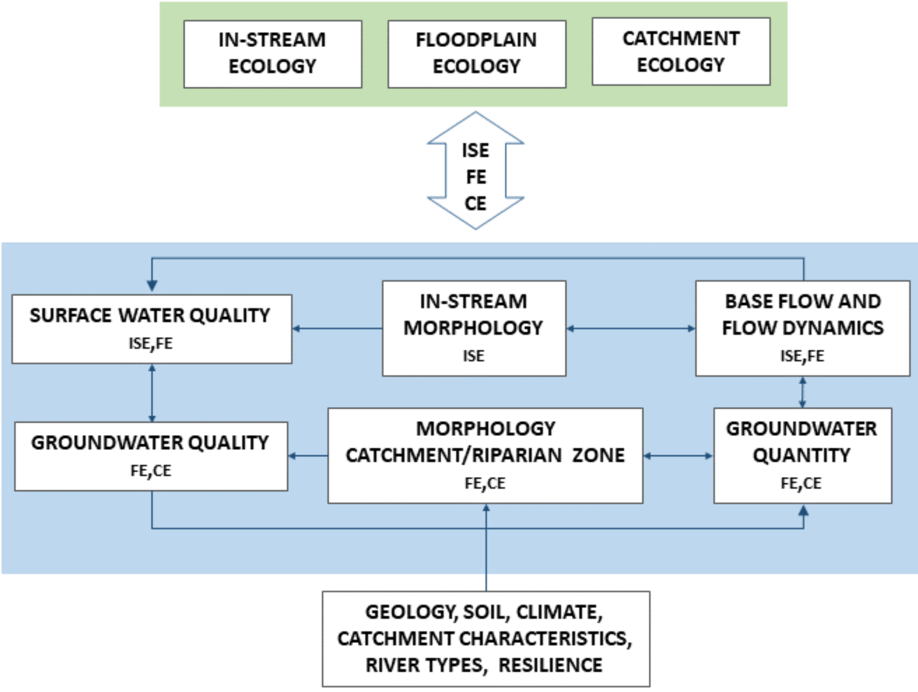


Figure 2.4 Schematic diagram of groundwater-surface water interaction and its feedbacks with morphology and ecology.

In the central box, the abiotic aspects and their interaction are shown.
The superscripts indicate feedbacks with the in-stream ecology (ISE), floodplain ecology (FE), and ecology in the rest of the catchment (CE). Revised from Gurnell et. al. 2016.

2.1.1.3 Centrality of Hydromorphological assessment in river management

River basin management is based on and measured by the conditions of water bodies.

If segmentation in river types does not account for geomorphological characteristics, identification of water bodies is unlikely to be representative, and, in turn, the monitoring design and its results. Consequently, this leads to unreliable classification with all the political and economic implications on measures.

If river dynamics is not accounted for in flood hazard assessment, management plans and protection measures will be ineffective, with severe repercussions on safety and the costs of failures.

In other words, if river assessment is not founded on process-based hydromorphological knowledge, river basin management objectives are unlikely to be achieved, with all the consequent relevant implications.

2.1.2 *Hydromorphology in Italian legislation*

The WFD was transposed into Italian legislation in several successive stages, finally converging into the Legislative Decree 152/2006 (also called "Testo Unico Ambientale", a sort of Environmental Law Act) and successive integrations were made to deal with specific parts of WFD implementation (table 2.4).

Table 2.3 References to WFD specific implementation in Italian legislation

WFD stage	***Relevant legislative acts***
The whole WFD	Legislative Decree 152/2006
Definition of river types and analysis of pressures	Ministerial Decree/ 131/2008
Monitoring and reference conditions	Ministerial Decree 56/2009 (repealed by Decree 260/2010)
Ecological Status assessment	Legislative Decree 260/2010
HMWB designation	Ministerial Decree 156/2013
Ecological Potential assessment	Directorial Decree 344/2017
Criteria for water abstraction licensing	Directorial Decree 29/2017
E-flows evaluation	Directorial Decree 30/2017

Classification into river types was carried out according to a customised version of System B (see table 2.1), leading to quite a large number of types (359 – whereas e.g. Spain has only 32) with no clear significance in terms of representativeness of river behaviour (figure 2.5).

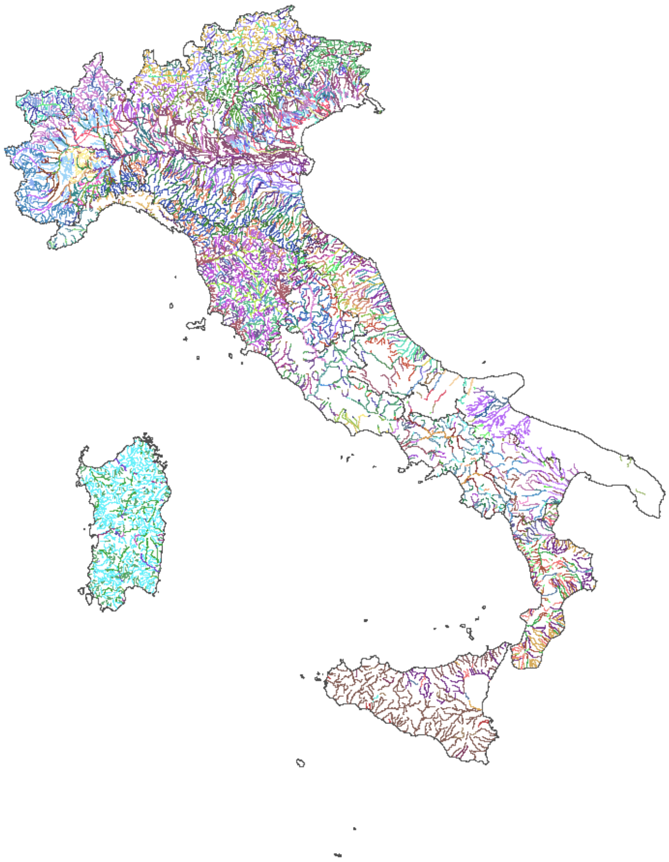


Figure 2.5 River types in Italy.

River types' identification was not founded on a real process-based approach.
This is the case, though, in the majority of European countries, probably because hydromorphological approaches were developed only relatively recently and anyway successively to river classification into types. The same applies to pressure analysis and monitoring, addressed in legislation before the development of the Italian river hydromorphological methodology and its enforcement into Italian legislation, through the Decree 260/2010 on river status assessment.

The analysis of pressures is based on a rough checklist with broad thresholds, elaborated in CIS Guidance n°3, which defines the pressures as significant to undermine river status only based on their presence, in terms of percentage on the water body. In this way, it fails to recognise that pressures off site can affect the water body status as well and that the same pressure has different effects on different river types.

The reference conditions, type specific, are defined only using a statistical approach, not founded on physical basis and often inconsistent with the actual context. The statistical approach might work out well only if the population encompassed the whole gradient of pressures and river types. Otherwise, it is likely to lead to erroneous outcomes (e.g. absence of pressures but the conditions are not considered as reference; presence of alteration, but those conditions are the best to be found for that site so they are considered reference).

According to the Decree 260/10, the hydromorphological conditions (or status) of a water body are given by the combination of its morphological conditions and its hydrological conditions, following the procedure indicated by the law itself.

The morphological conditions, including continuity and those hydrological aspects which have significant effects on geomorphological processes, are evaluated through a process-based approach summarised as the Morphological Quality Index – MQI (in Italian IQM - Indice di Qualità Morfologica; Rinaldi et al., 2011), which evaluates the deviation from reference conditions as explained in paragraph 4.2).

The overall changes in the hydrological regime, that is *the hydrological conditions*, are evaluated through a statistical hydrological approach summarised by the Index of hydrological alteration (Indice di alterazione idrologica – IARI; Bussettini et al., 2010). The approach considers the Indicators of Hydrological Alteration developed by Poff et al. in 1997 and consists in evaluating the distance between current hydrological conditions and the unaltered reference ones. The deviation is considered significant and the regime is altered if the distance is not contained within an interval of natural variability (Richter et al., 1997). The extent of the alteration is proportional to such a distance.

(A future revision of the national method is going to use only MQI as a hydromorphological assessment method, following the enhancements developed in this doctoral work. IARI will be used to better detail some aspects of hydrological alteration not eliciting morphological changes).

The MQI is one of the tools developed inside an overall framework for hydromorphological assessment, monitoring and analysis called IDRAIM, which also encompasses other tools (see chapter 4).

Since its issue, the hydromorphological methodology has underpinned all the relevant legislation, determining: criteria for the identification of heavily modified water bodies (MATTM 156/2013; Rinaldi et al., 2016d); criteria for evaluating the ecological potential of heavily modified water bodies (Directorial Decree 344/2016); criteria for licensing water abstractions (Directorial Decree 29/2017); methodology to evaluate river habitat integrity and calculate the environmental flows (Directorial Decree 30/2017; Vezza et al., 2017). The latter methodology models and evaluates river habitat integrity, by coupling geomorphic unit classification in the reach with a meso-scale approach called "MesoHABSIM – Mesohabitat Simulation Model". Specifically, the MesoHABSIM methodology is integrated with the "Geomorphic Unit Survey and Classification System – GUS" (Rinaldi et al., 2015a; Belletti et al., 2017) to describe the spatio-temporal variation of habitat availability for the fish fauna (or any selected ecological target), depending on the flow rate and the local morphological condition of the stream.

2.1.2.1 Competent authorities in hydromorphological assessment

Following a constitutional reform in 1997, competences in environmental monitoring were devolved to the regional administration, with a central governance from the Ministry of Environment and the technical scientific coordination from ISPRA; the Italian National institute for Environmental Protection and Research (ISPRA). ISPRA is a governmental research institute, dealing with all environmental matrices and problematics and mostly involved in bridging science into policy, also by developing standards and methodologies and exerting an intense training activity to the competent authorities. ISPRA is also the central node of a distributed and federated system of environmental protection agencies (SNPA), under the umbrella of their regional administration.

The agencies are in charge of WFD monitoring and assessment. Whereas the agencies have traditionally a strong experience in water quality assessment, competences and backgrounds in hydrology or fluvial geomorphology, formerly residing only in flood protection departments, are few and only recently acquired. Therefore, in some cases agencies have relied upon the experts in other departments of their regional administration.

Training on hydromorphology carried out by ISPRA has hence promoted a considerable step forward.

2.2 Hydromorphological assessment methods

2.2.1 State of the art in hydromorphological assessment methods

During the last decades, the development of methods to assess river hydromorphological conditions has noticeably increased, due to a scientific impetus in understanding the systemic nature of river systems and to the transposition of these concepts into consistent legislative frameworks for integrated management of river systems, such as the WFD.

The idea itself of hydromorphological assessment has evolved with time, from the survey of some abiotic characteristics of fluvial habitats (e.g. Raven et al., 1998), to the consideration of fluvial geomorphological processes in order to understand river functioning and evolution as a basis to interpret current conditions (Rinaldi et. al., 2016a), e.g. *processes based methods*.

Consequently, a wide range of methods to monitor and assess the hydromorphology of riverine water bodies has been developed, which differ extensively in terms of spatial scales, survey unit's type and extent, temporal horizon, data and expertise requested. The applicability of methods varies accordingly.

Up to a recent past, the hydromorphology assessment has been equalized to habitat survey, although that is only a component of hydromorphological evaluation, related to the occurrence of certain features or habitats. Habitat survey methods, (the most famous being the River Habitat Survey, developed in UK by Raven in 1997) monitor site –specific river habitat features and statistically infer the hydromorphological conditions of a fixed-length reach, attributing the highest score to the higher diversity in habitats (e.g. Raven et al., 1998), unconnectedly from what occurs at the upper scales or in time.

Only in the last decades physical processes have been included as a basis for hydromorphological evaluation, and process-based methods such as the River Styles Framework (Brierley & Fryirs, 2005) or the Morphological Quality Index (Rinaldi et al., 2011; 2013) have come into play.

In the recent years, extensive reviews of hydromorphological methods have been carried out, both at the European level (Fernandez et al., 2011; Bussettini & Kampa, in preparation) and at the international one (e.g. Tadaki et al., 2014; Rinaldi et al., 2013; 2015d; Belletti et al., 2015; Fryirs, 2015). The scope and extent of the reviews is often related to a limited group of methods or to a specific purpose (e.g.; Parsons et al., 2002. Fernandez et al., 2011; Tadaki et al., 2014).

The most extensive and comprehensive review, from Belletti et al. (2015), examined a wide set of methods (121), subdividing them among hydrological, morphological, riparian vegetation and habitat surveys and analysed their general characteristics, the recorded features and the related consideration of processes.

The review identifies a number of limitations the habitat survey methods present. Firstly, the site specific scale of investigation (some hundred meter length), is inapt for comprehending the causes of morphological alteration, because site conditions usually derive from causes at a wider scale. Secondly, the definition of reference conditions is based on a statistical analysis of recorded features, which are unlikely to represent all the possible morphological conditions of streams. Thirdly, the selection of reference "natural" sites is based only on the absence of in-stream artificialities, ignoring off-site and past pressures. Moreover, these approaches tend to identify the high status with the maximum diversity of features, independently from river types and the inherent diversity of each. All these limitations make those methods unfit for understanding physical processes and the causes of alterations.

According to the authors' conclusions, most of the methods show scarce consideration of river processes. This affects their capacity to diagnose river character and status and therefore the ability to find efficient strategies for river restoration and management. Therefore, the authors advocate including physical processes into hydromorphological assessment methods.

The consideration of physical processes in the methods was specifically targeted in a recent review of European hydromorphological assessment methods aimed at exploring their skills in implementing the WFD (Chapter 3). Ten over fifty-five surveyed methods are declared to include consideration of both geomorphic processes and the temporal dimension, but the specific analysis carried out inside this work shows that only three have the potential to connote as a process-based approach, among which the Morphological Quality Index (Rinaldi et al., 2011;2013).

The review also proves that a sufficient amount of methods for hydromorphological assessment has been already developed, but their application to a wide extent of rivers is needed in order to verify the capacity of these methods to really support river monitoring, assessment and management.

This requires analysing their capacities and limitations in terms of: i) diagnostic skill (i.e. whether the method considers both pressures and responses in the light of the past evolution, that is if it is process-based); ii) objectivity of assessment (i.e. the bias introduced by the operator is not affecting the evaluations) and iii) applicability to different context from those where the methods were developed (Fryirs, 2015).

As MQI has been extensively and nationwide applied over a long period, those conclusions will constitute the basic questions that the experimental part of this doctoral work will try to answer.

2.2.2 *Hydromorphological assessment*

Rivers are hierarchical complex systems, which adjust their morphology to changes in boundary conditions, in particular to flows and sediment flux variation (Brierley & Fryirs., 2008; Dufour & Piégay, 2009; Wohl et al., 2015e), following an evolutionary trajectory (figure 2.6).
The current hydromorphological conditions of a river reach, which result from its past evolution and current pressures, are hence just a point in such a trajectory of change.

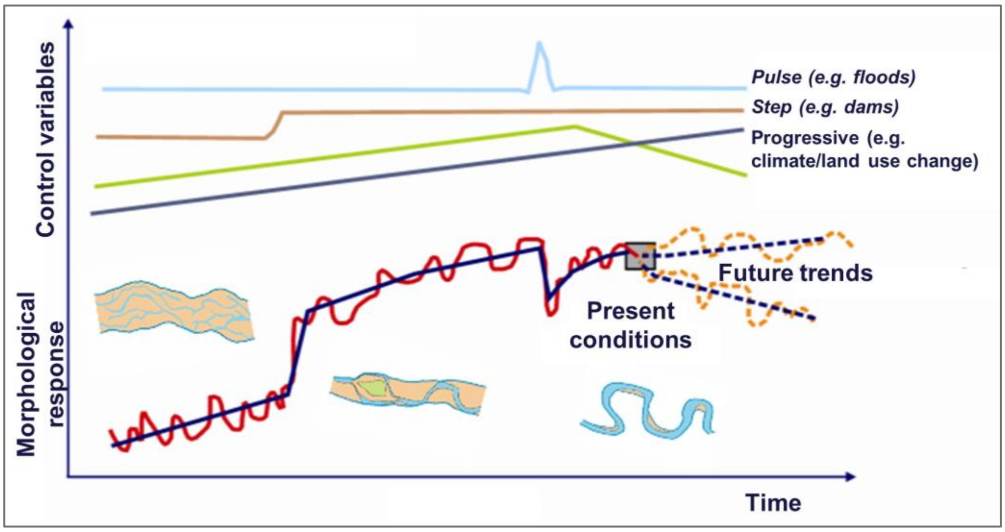


Figure 2.6: Temporal trajectory of changes and current conditions (Rinaldi, 2014).

The adjustments occur at different temporal and spatial scales. Since rivers are nested hierarchical systems, (figure. 2.7), processes and forms at larger scales govern and define processes and forms at smaller scales (e.g., Frissell et al., 1986; Brierley & Fryirs, 2005; Rinaldi et al., 2013).

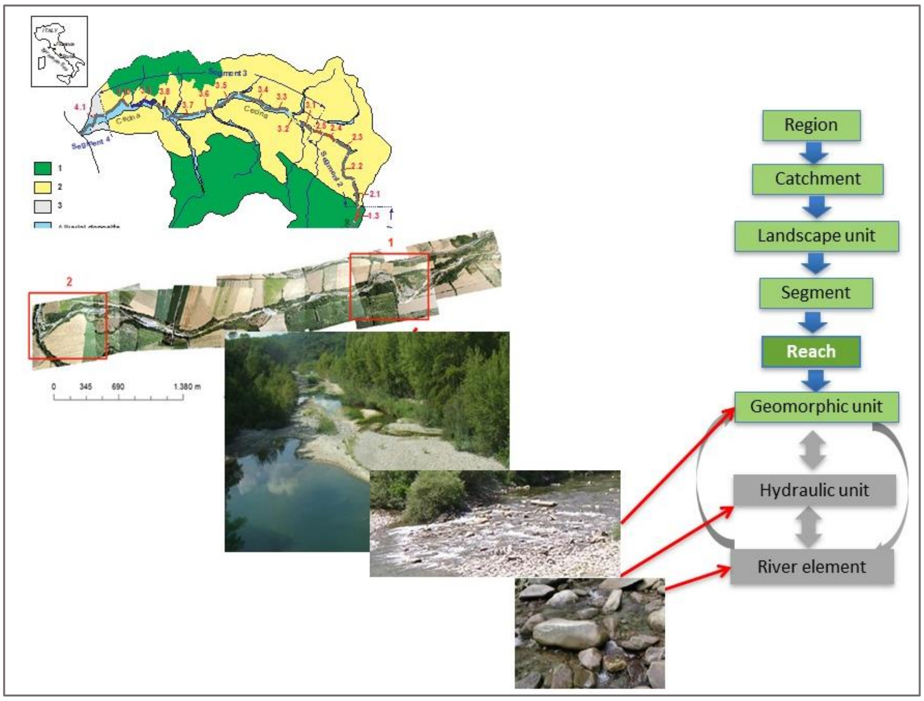


Figure 2.7 Spatial scales of river systems.

Any alteration of water and sediment fluxes at the upper scales, filtered by the valley context and by the erosional resistance opposed by vegetation and substrate, reflects on the geometries at the lower scales.

At the reach scale, the boundary conditions can be considered uniform (e.g. no significant changes in valley setting, channel slope, water and sediment flows). In response, the river adjusts acquiring a homogeneous channel morphology and a uniform behaviour in terms of processes and assemblage of forms (i.e. geomorphic units). Therefore, the reach constitutes the survey unit for the assessment (e.g. Rinaldi et al., 2013, Gurnell et al., 2016).

The aim of a method for hydromorphological assessment is to evaluate the status of river hydromorphological conditions, to understand the causes and inform river management actions (e.g. restoration measures).

The *assessment of river condition*s consists in measuring the deviation of current conditions from reference, i.e. comparing current conditions with the reference for the same type.
It thus preliminarily requires defining the “river types” and the “reference conditions”.

The *definition of river types* (or “classification”), consists in grouping like-with-like morphologies (e.g., Schumm, 1977; 1981; Church, 1992; Montgomery & Buffington, 1997; Figure 2.8), which share a similar behaviour and typical features (e.g. confined, sinuous, riffle and pool channel).
Indicators for classification are descriptive of the river configuration (e.g. sinuosity index; number of channels; confinement).

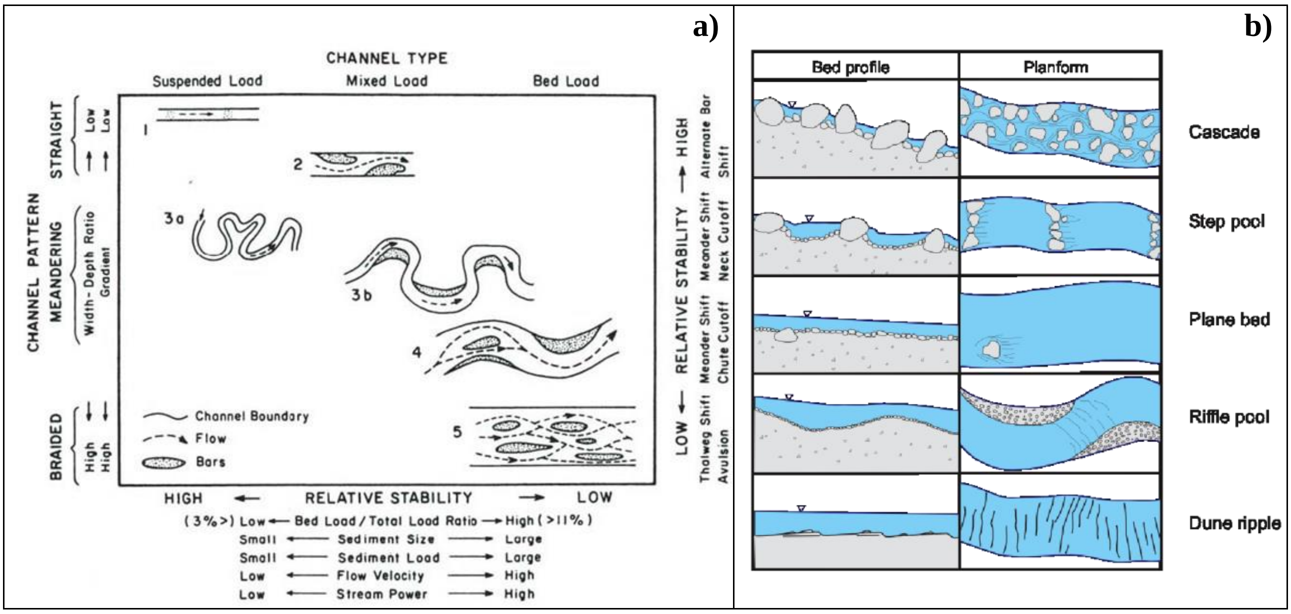


Figure 2.8 Process-based channel classification scheme. a) Schumm, 1981; b) Halwas and Church, 2012

The *definition of reference conditions* has been debated in the last three decades (e.g. Dufour & Piégay, 2009; Kondolf et al., 2006; Nilsson et al., 2007), and still no unanimous agreement has been achieved.

Nevertheless, the dynamic nature of river systems is now widely accepted and consolidated, that a river is a complex system adjusting its morphology to changes in boundary conditions.

Therefore, reference conditions must represent the dynamic processes and functions that are expected to normally occur in a given physical context (rather than precise channel configuration or characteristics).

In this sense, we can define the reference conditions as the best conditions that can be attained by a river, altered by humans, given the prevailing catchment boundary conditions (Brierley & Fryirs, 2005).

Hydromorphological conditions can be expressed through a series of indicators that need to account for pressures, responses and evolution of past conditions in such a way to detect changes and their causes, and to relate causes and effects for a particular river type.

Assessment indicators are type-specific. Indeed, some processes and forms, which may be considered “natural” for certain river types (e.g. erosion of river bends in meandering rivers) are instead signs of alteration for others (e.g. erosion of river bends in low energy fine-sediment streams).
Another example is the lateral dimension of the channel, which is very relevant in unconfined and partly-confined streams, given their lateral mobility, whereas it is not at all indicative in confined streams, whose lateral dynamics is constrained by the hillslopes. This is a major discriminant in selecting relevant indicators.

2.2.2.1 Minimum requirements for a process-based hydromorphological assessment method

Process-based methods can be defined as those methods that emphasize the consideration of the occurrence of expected geomorphic processes and include the explicit consideration of temporal changes and dynamics (Rinaldi et al., 2016a) to understand current conditions.

Indeed, in order to be diagnostic, an assessment method has to analyse the causal nexus between pressures and response (river conditions) in the context of past evolution of the river (e.g. Fryirs, 2015). Therefore, the method must consider and account for all three components: pressures, responses and past evolution.

Beyond the assessment, the knowledge of past evolution and current conditions is also crucial to forecast the future trajectory of adjustment for a river reach in a certain context.

Consequently, the minimum requirements for a hydromorphological assessment method to have effective diagnostic skills, which equates to being process-based, can be summarised as follows:

1. It has to define the spatial unit for the assessment, i.e. the reach, with almost homogeneous boundary conditions (i.e. confinement, topographic gradients, flow and sediment fluxes) and channel morphology (e.g. meandering, braiding).

2. It has to account for different river types, which share the same behaviour (process) and character (forms).
3. It has to define reference conditions for each type, considering the boundary conditions.
4. Consequently, the assessment will consider only the relevant type specific indicators, which are able to account for the deviation from the reference conditions (i.e. the assessment is type-specific)
5. It has to account for temporal dimension, considering the past evolution of the river reach under analysis.
6. It has to account for the multiple spatial dimensions, putting the reach in the context of the catchment.
7. It has to consider separately pressures, responses and the past conditions in order to understand the casual nexus among them and provide a reliable diagnosis.

Many assessment methods, though, do not possess the requisites to be process based, and their diagnostic skills are scarce or null (e.g. habitat survey methods), and consequently null is their capacity to support river management and restoration.

2.3 River management and restoration

River restoration is a form of river management designed to assist the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed and to replace lost, damaged, or compromised elements of the natural system (Wohl et al., 2005).

Traditionally, river management has focused on controlling river corridors through engineering works, and its cumulative effects are increasingly evident (Vorosmarty et al., 2010; Jongman et al., 2012, Williams et al., 2014).

The recognition that rivers have been endangered by such an approach moved river management towards river protection and restoration. Such a shift was even legislated in the WFD, where river protection is an objective and restoration a mean to achieve it. Beyond the European obligation, river management now endeavours to get a trade-off between consumptive uses of river resources and restoration of river ecosystems (e.g. Wohl et al., 2005).

River management, and restoration in particular, is now called to correct the anthropogenic disruption of hydromorphological and ecological processes, adopting a more holistic and “process-based” approach, as publicly asked by river scientists and practitioners after decades of “form-based restoration” failures (e.g. Kondolf et al., 2006; Beechie et al., 2010).

Process – based restoration aims “to re-establish normative rates and magnitudes of physical, chemical, and biological processes that create and sustain river and floodplain ecosystems” (Beechie et al., 2010), like restoring channel-floodplain connectivity (e.g. Tockner et al., 2000; Gumiero et al., 2013) or restoring the space for river to adjust to changes in water and sediment inputs (Kondolf, 2011).

Form-based restoration aims to create specific habitat features according to some perceived “good” conditions, and somehow to “control” processes instead of restoring them (Beechie et al., 2010).

It focuses on the creation of forms, at the small scale, to get some improvements in ecology, not necessarily achieved, because of aesthetic objectives (Kondolf et al, 2006; Bernhardt et al., 2007) or due to scales and conditions inappropriate for a specific river corridor (Brierley & Fryirs, 2009; Kondolf, 2011).

The failure of the form-based actions, mainly imputable to not targeting the causes of river degradation, has been widely demonstrated and discussed (e.g. Beechie & Bolton, 1999; Kondolf et al., 2001; Kondolf et al., 2006; Palmer et al., 2005) and the effectiveness and success of process-based restoration is now widely recognized. Nevertheless, process-based restoration involves the consideration of the hierarchical structure of river systems, ideally acting on the whole catchment and the full river processes. As this is rarely possible, the restoration strategies range from the full restoration of processes to habitat reconstruction as a surrogate (Beechie et al., 2010; table 2.4).

Table 2.4 Restoration strategies according to Beechie et al., 2010.

Action class	*Definition*
Full restoration	Restore processes that create and maintain habitats and biota, thereby returning a river ecosystem to its normative state.
Partial restoration	Restore or improve selected ecosystem processes, thereby partially restoring a riverine ecosystem.
Habitat construction	Improve quality of habitat by treating specific symptoms through creation of locally appropriate habitat types; used where causes of degradation cannot be addressed

The success of restoration actions is equally dependant on the definition of appropriate objectives and the capacity to quantitatively monitor and evaluate the achievement of those objectives.
Yet, many projects still include scarce or no strategies to evaluate their success (e.g. Palmer et al., 2007; Morandi et al., 2014; Nilsson et al., 2016). When they do, they reveal an inconsistency between the large scales of channel dynamics and processes and the small scales of the adopted evaluation approach (e.g. Kail & Hering, 2005; Poppe et al., 2016). Thus, unproductively, success is still measured by means of biological metrics inapt to discriminate the effect of hydromorphological pressures (e.g. Friberg, 2014; Muhar et al., 2016) and habitat metrics by nature incapable to distinguish the levels of complexity naturally inherent in a particular river context.

A major reason for it is that process-based approaches are still very few (e.g. Belletti et al., 2015) and have only recently been applied to evaluate restoration success (e.g. Habersack & Piégay, 2007; Campana et al., 2014).

Traditionally, the effect of hydromorphological alteration or the success of restoration actions has been investigated at the small scales through habitat methods (e.g. Kail & Hering 2005, Poppe et al., 2016). The conclusions of such analysis have proven to be biased by the scale of investigation and the scarce diagnostic capacity of such approaches.

Belletti et al. (2018), compared the results of a process-based method with a conventional site-scale habitat method and observed that whereas the process based method could detect the response of river reaches, the habitat method could not because of its inherent limitations (inappropriate scales and parameters; lack of consideration of processes). The paper also compared the spatial scales of the assessment, stressing how crucial the reach scale (*sensu* Gurnell et al., 2016) is in comprehending the features and processes involved (see also paragraph 2.2.2).

Process based restoration, and anyway restoration in general, calls for adequate assessment methods, which can allow understanding the context of the river portion to be restored and its trajectories of change, i.e. process-based methods. Such methods indeed allow defining consistent restoration objectives and quantitatively measuring their achievement across time (e.g. Palmer et al., 2005; Wohl et al., 2015e; Brierley & Fryirs, 2009; Fryirs & Brierley, 2016).

3 Implementation of hydromorphological methods at the European scale

This chapter addresses the review of the European methods currently in use for hydromorphological assessment, which constitutes an integral part of my doctoral work.

The review developed inside this doctoral work differs from the preceding ones (e.g. Fernandez et al., 2011; Tadaki et al., 2014; Rinaldi et al., 2013a; Belletti et al., 2015; Fryirs, 2015), because it aims specifically to 1) evaluate the ability of methods to support river management and restoration, as envisaged by the different steps of WFD (e.g. identification of river types, analysis of pressures, status assessment, and design of measures) and so 2) to appraise at which extent process-based methods are currently used for supporting the WFD implementation in Europe.

European river practitioners have only recently acknowledged the importance of hydromorphological assessment for ecological assessment and restoration, consequent to the extensive implementation of WFD in the last eighteen years and to the bad performance of many biological methods in detecting the response to hydromorphological pressures.

Many of those methods were in facts designed to respond to organic pollution (e.g. Friberg, 2014) and inherently scarcely sensitive to hydromorphological pressures. Moreover, the sampling strategies of many biological methods do not really take into account the variety of geomorphic units in a reach, failing to catch the link between biota and the relevant habitat (e.g. Friberg, 2014).

In addition to this, river types and the managing unit for WFD, i.e. the water body, are generally not delineated according to geomorphic characteristics and in this way they are not representative of the processes they are called to assess, with unpleasant implications for the assessment itself and also for the evaluation of the success of restoration measures.

Recent research within the EU FP7 REFORM project, recommends using the hydromorphological assessment along the entire gradient of ecological conditions, given that biological quality elements cannot differentiate with sufficient precision between different degrees of hydromorphological degradation (Mosselman et al., 2015).

Hydromorphological assessment is therefore crucial to correctly carry out the different stages of WFD implementation and get to a sound realistic evaluation of river conditions and to deliver efficient restoration measures. The question arises on the ability of European hydromorphological methods to support those management stages and so to successfully implement WFD.

Such a question informed this part of my doctoral work.

3.1 Materials and methods

This review regards 55 hydromorphological methods currently in use in Europe to support the implementation of WFD (table 3.1). Ten of them are in development or in the first stage of testing.

As already mentioned, hydromorphological assessment has been interpreted differently in time, mainly coinciding with physical habitat methods and the scales and the aspects to survey and evaluate differ sometimes substantially. The habitat methods focus only on some hundred meters scale where to sample fine features, with no consideration of catchment scale processes over time, whereas the process-based methods consider features and aspects of process at representative scales (the morphological reach), in the context of the spatial and temporal scales of the process they aim to evaluate (Belletti et al., 2015).

That shows the necessity of a common understanding of hydromorphological processes and their assessment across Europe and the survey constitutes a step towards such an achievement.

The survey took place between October 2016 and November 2018 and was informed by a detailed questionnaire, which was sent out to the European experts in ecological and hydromorphological assessment, officially nominated by their National Water Directors (i.e. the competent authorities for WFD implementation), within a specific working group on hydromorphology constituted by the European Commission (COM).

The questionnaire is an Excel file structured in eight sections, which address all the aspects that can characterize a hydromorphological method, amounting to 86 (table 3.2).
The sections group various aspects, among which the characteristics of the method (e.g. scales, hydromorphological types), the pressures they consider (section 6); the responses in term of recorded hydrological and morphological features (sections 3 and 4), and the components of geomorphological processes they take into account (section 5). Section 8 deals with the pro and cons of the methods as reported by their national referents.

The questions mostly have standardized answers. In addition to that, a field is left for explanation when needed. The responses underwent consistency checks before the analysis and were then collected in a database.

Table 3.1 Analysed national methods and addressed hydromorphological quality element(s). H= hydrology; M=morphology; C=continuity

Country	***Method***	***Element(s) addressed***
Austria	Austrian Guidance on hydromorphological assessment of rivers	HMC
Flanders (Belgium)	Meetnet Hydromorfologie	CM
BE (Wallonia)	Qualphy	CM
Belgium Wallonia	Walloon method derived from SYRAH (Fr) (National method)	HMC

Country	***Method***	***Element(s) addressed***
Belgium / Wallonia	Riparian Remote Monitoring - RiReMo (future development)	HMC
Switzerland	Modul-Stufen-Konzept (MSK) Methode Ökomorphologie Stufe F (Flachdekkend)	CM
Switzerland	Modul-Stufen-Konzept (MSK) Methode Hydrologie Stufe F (Flachdekkend) Konzept HYDMOD-F	H
Cyprus	Integrated Pressure Index (IPI)	M
Czech Republic	HEM 2014 Metodika monitoringu hydromorfologických ukazatelů ekologické kvality vodních toků	HMC
Germany	The hydromorphological classification tool Valmorph for large and navigable surface waters	HMC
Germany	Klassifizierung des Wasserhaushalts von Einzugsgebieten und Wasserkörpern	H
Germany	LAWA-Verfahrensempfehlung zur Gewässerstrukturkartierung – Verfahren für mittelgroße bis große Fließgewässer	CM
Germany	Evaluation of sediment continuity (Bewertung der Durchgängigkeit von Fließgewässern für Fische und Sedimente, hier: Sedimentdurchgängigkeit)	C
Germany	LAWA-Verfahrensempfehlung zur Gewässerstrukturkartierung – Verfahren für kleine bis mittelgroße Fließgewässer	CM
Denmark	Dansk fysisk indeks, DFI (Danish physical Index)	HM
Estonia	River HYMO EST	HMC
Spain	Protocol for the hydromorphological characterization of water bodies	HMC
Spain	DRAINAGE	HMC
Spain	Índice para la evaluación de la calidad hidrogeomorfológica (IHG)	CM
Finland	HyMo method (Kevomu-menetelmä)	HMC
France	AURAHCE (AUdit RApide de l'Hydromorphologie des Cours d'Eau / Hydromorphology auditing)	M
France	CARHYCE (CARactérisation HYdromorphologique des Cours d'Eau / Hydromorphological characterization of rivers)	M
France	ICE project (for “Informations sur la Continuité Ecologique”)	C
France	RHUM (Référentiel Hydromorphologique Ultra-Marin) (SYRAH-CE adapted to the tropical systems)	HMC
France	ROE (Référentiel des Obstacles à l'Ecoulement)	C
France	SYRAH-CE (SYstème Relationnel d'Audit de l'Hydromorphologie des Cours d'Eau) Relational, multi-scale system for auditing the hydro-morphology of rivers	HMC
Hungary	Planned_HU	HMC
Hungary	HU_RBMP2	HMC
Ireland	Abstraction impact screening assessment	H
Ireland	River Hydromorphological Assessment Technique/RHAT	CM
Italy	MQI Morphological Quality Index	HMC
Italy	Indici di hydropeaking	H
Italy	IARI indice di alterazione del regime idrologico	H
Lithuania	Lithuanian River Hydromorphology Index	HMC
Luxembourg	Klassifizierung des Wasserhaushalts von Einzugsgebieten und Wasserkörpern	H
Luxembourg	Strukturgütekartierung (LANUV 2012)	HMC
Latvia	HAP-LR	HMC
Netherlands	Handboek Hydromorfologie 2.0 (Oste et al. 2013)	HMC
Norway	Characterization, analysis and risk assessment of water bodies as per WFD art. 5	HMC
Poland	Hydromorphological Index for Rivers / HIR	HMC
Portugal	River Habitat Survey (RHS)	HMC
Romania	Methodology to determine the hydromorphological indicators for Romanian rivers	HMC
Sweden	HVMFS 2013:19 (Agency regulation)	HMC
Slovenia	Hydromorphological Monitoring in Slovenia - HIMO.SI	HMC
Slovakia	Hydromorphology Quality Assessment	HMC
Slovakia	Physical habitat assessment	HMC
Turkey	Nehir Hidromorfolojisi Değerlendirme İndeksi (NHDI) (Turkish)	HMC
England & Wales - UK	Designation of A/HMWB	HMC
England & Wales - UK	Mitigation Measure Assessment	HMC
England - UK	Hydrology - Water Resources GIS (WRGIS)	H
England & Wales - UK	Morphology Risk Assessment	CM
Northern Ireland - UK	River Hydromorphology Assessment Technique (RHAT)	HMC
Northern Ireland	Hydrological alteration	H
England & Wales - UK	River habitat Survey (RHS)	CM
Scotland - UK	Hydrology water body classification	H

Table 3.2 Structure and fields of the European questionnaire.

("Hydromorphological" has been shortened into "hymo").

Section 1

N	*Question*	*Answers*
Section 1 - General information		
1.1	Components covered by the method	hydrology; morphology; continuity
1.2	Use of the method	hymo classification (WFD-related);supporting ecological classification (WFD-related);used as a proxy of biological quality elements; hymo monitoring; hymo assessment (non-WFD);diagnosis for designing measures (e.g. rehabilitation, mitigation, etc.);as a prognostic tool (e.g. for Environmental Impact Assessment);other
1.3	Use of method for the WFD planning process	water body delineation; typology; pressures & impacts analysis; status classification (for high status only);status classification (for classification in all status classes);risk analysis; HMWB designation; definition of food ecological potential; design of program of measures; exemptions; other; not applicable
1.4	Use for other Directives	Habitats Directive; Floods Directive; Environmental Impact Assessment Directive; other; not applicable
1.5	Biological considerations	the method includes biological considerations but does not address fish continuity; the method indirectly addresses fish continuity; the method does not include any biological considerations; other; not applicable
1.6	Status of method	this is the official method in the country; used in the 1st RBMPs; used in the 2nd RBMPs; used for management; restoration but not yet included in the RBMPs; in development; emerging method but not yet practically applied; other; not applicable
1.7	Level of application	applied in the whole country (national level); applied in part of the country (regional; basin level); aims to assess the whole river network (i.e. every km); aims to assess specific sites in the river network; results of assessed sites are extended to larger river portions (e.g. water bodies); other; not applicable
1.8	Extent of application	indicate the percentage of water bodies (WFD) to which the method has been applied; information not available; not applicable
1.9	Inclusion in legislation	national legislation; regional legislation; national guidelines; regional guidelines; other; not applicable
1.10	Relevance for specific pressures	the method is relevant for all types of hymo pressures; the method is relevant for specific types of hymo pressures (indicate which ones in the explanation text box); other; not applicable
1.11	Key reference	Indicate reference (available report, scientific paper, web page, etc.)
1.12	Available supporting material	guidebook; field sheet forms; compilation sheet forms; databases; software; other; not applicable
1.13	Users qualification	Describe the specific expertise required to apply the method (e.g. expertise in fluvial geomorphology, specific level of education, etc.)
1.14	Requirement for accreditation	accreditation not required; accreditation required (e.g. by certificate or training);other; not applicable
1.15	Resource intensity	High/medium/low resource-intensity; high resource-intensity; no information; other; not applicable
1.16	Feedback on this section	If you were not able to fill in this section or part of this section of the questionnaire, please explain briefly why

Section 2

Section 2 - General Characteristics of the method		
2.1	Components covered by the method	historical maps; present topographical maps ;aerial photos; satellite images; drone images (including low flights with Unmanned Aerial Systems);LiDAR data ;field survey; existing GIS data; GIS derived parameters; existing databases; modelling derived parameters; other; not applicable
2.2	Longitudinal spatial scale	fixed length (indicate length in m);length scaled to bankfull or low-flow channel width; variable length (not including the previous case);exact location of alteration; other; not applicable
2.3	Criteria for selection of variable length	morphological segmentation; homogeneity of some specific characteristics (indicate which one in the explanation text box);accessibility; random; other; not applicable
2.4	Lateral spatial scale	stream channel; banks; riparian zone; floodplain; hillslopes; fixed width (indicate width in m);width scaled to channel width; other; not applicable
2.5	Approach used by the method to define reference condition	empirical; statistical; historical (indicate which period); theoretical; other; not applicable
2.6	Use of HyMo types (indicate in the explanatory text if type is intended as "reference type" or as "current morphological type")	attribution of a hymo type to the assessment site; reach; no consideration of hymo types; other; not applicable
2.7	Criteria/parameters for definition of HyMo types	size (e.g., stream order, catchment size, distance from source); gradient; geology; geographical location; altitude; hydrological regime; confinement; channel morphological pattern (based on sinuosity, braiding, anabranching); other; not applicable
2.8	Differentiation of the method for HyMo types	the method is applied in the same way for all hymo types; all or some indicators are applied in a different way dependent on the hymo type; other; not applicable
2.9	Temporal dimension	no consideration of past channel morphology condition; some consideration of past channel morphology condition; other; not applicable
2.10	Severity of hymo pressures	method attempts to evaluate or account for the severity of hymo pressures; method attempts to evaluate or account for the ecological significance of hymo pressures; no attempt to evaluate or account for the severity of hymo pressures; other; not applicable
2.11	Feedback on this section	If you were not able to fill in this section please explain briefly why

Section 3

Section 3 - Recorded Hydrological Features		
3.1	Components of flow regime	Low flows; average flows; high flows (e.g. small floods, large floods, etc.); other
3.2	Type of flow year (avg., wet, dry year)	the method considers the type of flow year; the method does not consider the type of flow year; not applicable
Characteristics of flow regime		
3.3	Magnitude (e.g. average monthly flow)	is feature recorded?;is the feature used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
3.4	Duration (e.g. duration of annual minima and maxima)	*idem*
3.5	Timing of specific events (e.g. extreme discharge, including Julian date of annual 1-day maximum and minimum)	*idem*
3.6	Frequency (e.g. number of low pulses)	*idem*
3.7	Rate of change (e.g. rise and fall rates)	*idem*
Surface-groundwater interactions		
3.8	Surface-groundwater interactions	is feature recorded?;is the feature used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
Time related information		
3.9	Time resolution	daily resolution; hourly resolution; sub-hourly resolution
3.10	Minimum length of time series	Please respond to the right and explain if needed
Pressures on hydrology		
3.11	Pressures causing hydrological alteration	hydropeaking; abstraction; flood mitigation; water level change (e.g. artificial waves from navigation); urbanization; agriculture; other
Other related information		
3.12	Reference (natural) flows	Are the natural flows identified as the pre-impact condition (past condition) to assess the hydrological alteration? Are the natural flows identified as the current condition without pressures (modelled current catchment condition where the pressures are removed) to assess the hydrological alteration? Are the natural flows identified in both ways, depending on data availability?
3.13	E-flows	a method to define ecological flow requirements is available; a method to define ecological flow requirements is not available
3.14	Feedback on this section	If you were not able to fill in this section please explain briefly why

Section 4

Section 4 - Recorded Morphological Features		
4.1	Planform pattern (e.g. sinuous, meandering, etc.)	is feature recorded?;is the feature used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
4.2	Longitudinal profile/gradient	*idem*
4.3	Variability of cross-section by width/depth	*idem*
4.4	Erosion/depositional features (bars, eroding banks)	*idem*
4.5	Fluvial landforms in the floodplain	*idem*
4.6	Bad substrate (substrate composition)	*idem*
4.7	Bed configuration (e.g. riffle, pool, etc.)	*idem*
4.8	Flow pattern (e.g. rippled, smooth, etc.)	*idem*
4.9	Flow velocity	*idem*
4.10	In-channel large wood	*idem*
4.11	Macrophytes	*idem*
4.12	Vegetation lateral/longitudinal extension in the river corridor	*idem*
4.13	Vegetation type/structure in the river corridor	*idem*
4.14	Feedback on this section	If you were not able to fill in this section please explain briefly why

Section 5

Section 5 - Consideration of processes		
5.1	Consideration of geomorphic processes	method explicitly includes consideration of occurrence of expected geomorphic processes; method does not explicitly include consideration of geomorphic processes; other; not applicable
5.2	Longitudinal continuity/alteration of channel forming discharge	is the process recorded ; considered?;is the process used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
5.3	Sediment transport	*idem*
5.4	Longitudinal continuity/alteration in sediment and wood flux	*idem*
5.5	Lateral continuity of flows	*idem*
5.6	Connectivity between hillslopes and river corridor	*idem*
5.7	Occurrence of bank erosion processes	*idem*
5.8	Presence of a potentially erodible corridor	*idem*
5.9	Alteration of bed sediment structure/substrate composition/vertical continuity (e.g. armouring, clogging)	*idem*

5.10	Consideration of temporal changes and dynamics	method explicitly includes consideration of temporal changes and dynamics (indicate in the explanation the time scale considered);method does not explicitly include consideration of temporal changes and dynamics; other; not applicable
5.11	Adjustments in channel pattern	is the process recorded ; considered?;is the process used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
5.12	Adjustments in channel width (e.g. narrowing, widening)	*idem*
5.13	Bed-level adjustments (e.g. incision, aggradation)	*idem*
5.14	Feedback on this section	If you were not able to fill in this section please explain briefly why

Section 6

Section 6 - Recorded artificial elements		
Structures with impacts on longitudinal continuity		
6.1	Dams	is the feature recorded ; considered?;is the feature used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
6.2	Check dams/abstraction weirs	*idem*
6.3	Other structures with impacts on flow and/or sediment discharge (retention basins/diversion channels/spillways	*idem*
6.4	Crossing structures (bridges/fords/culverts)	*idem*
Structures with impacts on lateral continuity		
6.5	Bank protections	is the feature recorded ; considered?;is the feature used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
6.6	Artificial levees or embankments	*idem*
Structures with impacts on channel morphology and/or substrate		
6.7	Artificial changes of river course	is the feature recorded ; considered?;is the feature used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
6.8	Bed structures (sills, ramps, bed revetments)	*idem*
Management interventions		
6.9	Sediment management	is the feature recorded ; considered?;is the feature used to evaluate river condition?;is recording and/or evaluation done periodically?;not considered; not relevant
6.10	Large wood management	*idem*
6.11	Vegetation management	*idem*
6.12	Land use in the surrounding area	*idem*
6.13	Off-site in-channel pressures (e.g. dam upstream or weir downstream the assessed reach)	*idem*
6.14	Off-site catchment pressures (e.g. land use in the sub-catchment)	*idem*
6.15	Feedback on this section	If you were not able to fill in this section please explain briefly why

Section 7

Section 7 - Assessment output		
7.1	Type of output of the assessment	scoring; establishment of a typology; maps; report; other; not applicable
7.2	Type of scoring	qualitative evaluation (e.g. qualitative class); quantitative scoring (e.g. one or more quantitative index); other; not applicable
7.3	Scoring information	scores and algorithms are transparent; scores and algorithms are not transparent; other/not applicable
7.4	Upscaling of the score of a site/reach to the water body (for WFD)	the method is applied to only one portion of the water body (i.e. one or more sites/reaches) and the score is then extended to it; the method needs to be applied to all reaches included in the water body and an average or the minimum of the scores (or qualitative classes) is assigned to the water body; other/not applicable
7.5	Degree of confidence	some indication about the degree of confidence (uncertainties) is included; no information on the degree of confidence; other/not applicable
7.6	Feedback on this section	If you were not able to fill in this section please explain briefly why

Section 8

8 - Lessons Learned	
8.1	Lessons learned from the application of this method in WFD implementation
8.2	Strengths of the method
8.3	Weaknesses of the method

The analysed fifty-five methods refer to twenty-seven countries.

The methods were examined according to the different categories already identified in the questionnaire (see Table 3.2). The results were then sent out to the data providers, in order to verify the consistency with their replies and to include some clarifications.
Where doubts remained, information has been clarified and integrated through the reference literature for the method, indicated in response to a specific field of the questionnaire itself.

The successive analysis verified the capacity of the methods to support WFD and in particular their diagnostic skill, also by screening them against the criteria for a method to be process-based (par. 2.2.2.1; Rinaldi, 2016a).

3.2 Results

The analysis of the received questionnaires regards 55 European methods.

The majority of them (42) are the official methods for hydromorphology (or for a component of hydromorphology) in the respective countries (figure 3.1). Some methods (11) are still in development or are recently developed but yet not much used in practice.

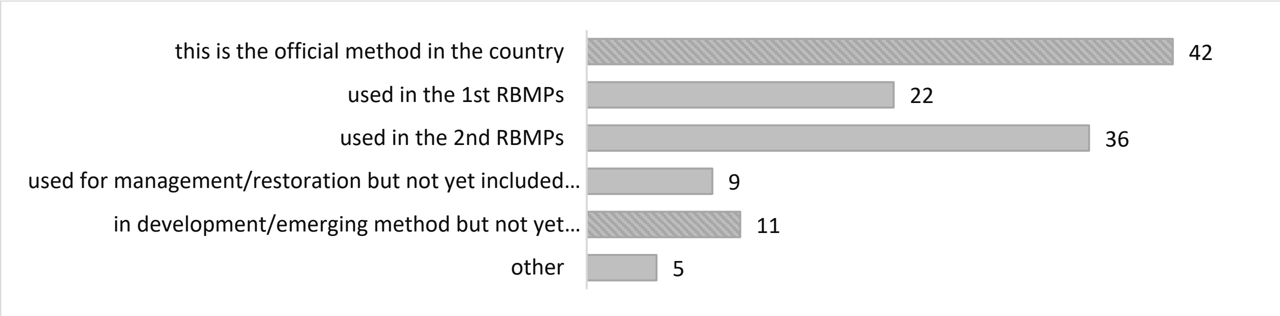


Figure 3.1 Official use of the methods

The methods cover the three hydromorphological components envisaged by WFD (hydrology, continuity and morphology), in combination or singularly (figure 3.2).

The majority of the methods reported (31 out of 55 methods) covers all three components. Some methods cover only one component with an emphasis on hydrological methods (9 methods).

They address hydrological alteration in terms of long time-series statistics, and their characteristics were analysed as well, but they are not relevant in this context, thus they will not be discussed in this work. Three methods address continuity only, but they are just used for pressure analysis (e.g. surveying obstacles to longitudinal continuity). Three address only morphology and are used either for pressure analysis only (1) or also for status assessment (2).

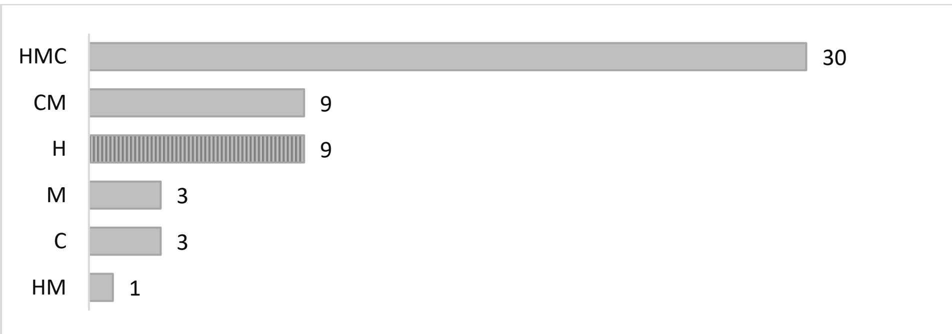


Figure 3.2 Hydromorphological methods per quality element or their combination.

H= hydrology;
C= continuity;
M= morphology

All methods support some or all river management stages (figure 3.3), but they are chiefly used for the analysis of pressures and the design of the program of measures. All the other stages are least supported, but one stands out, that is the designation of HMWB. In facts, only 38% of the reported hydromorphological assessment methods support decisions on the designation of HMWB, which by definition should indeed rely on the hydromorphological characterization and assessment.

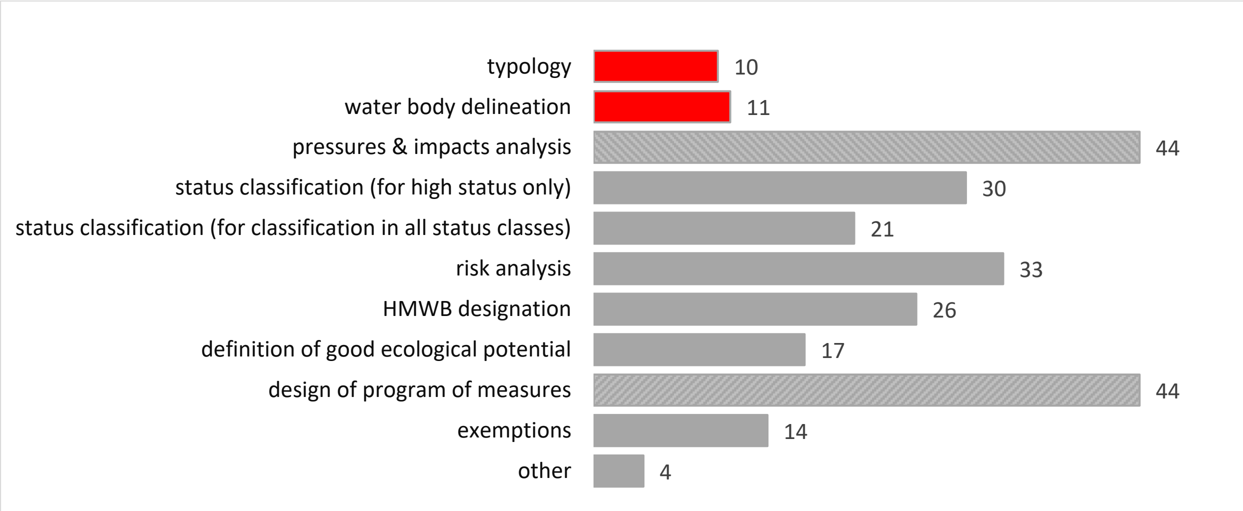


Figure 3.3 Use of methods for the WFD planning process

Only scarcely are the method used to support the stages of identification of river types and delineation of water bodies (20%), necessary to identify the representative units for the survey and assessment, at the basis of any evaluation of hydromorphological conditions.

The majority of the methods (42%) envisages some hydromorphological types (figure 3.4).

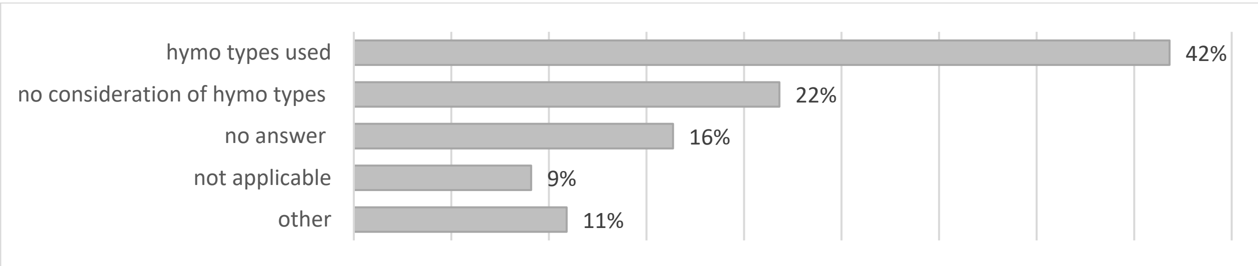


Figure 3.4 Consideration of hydromorphological types in the methods

When methods are used to define hydromorphological types, which should, by definition, be homogeneous in character, with respect to hydromorphological processes (e.g. Gurnell et al. 2014), the relevant drivers of such processes (e.g. confinement) are least considered (figure 3.5).

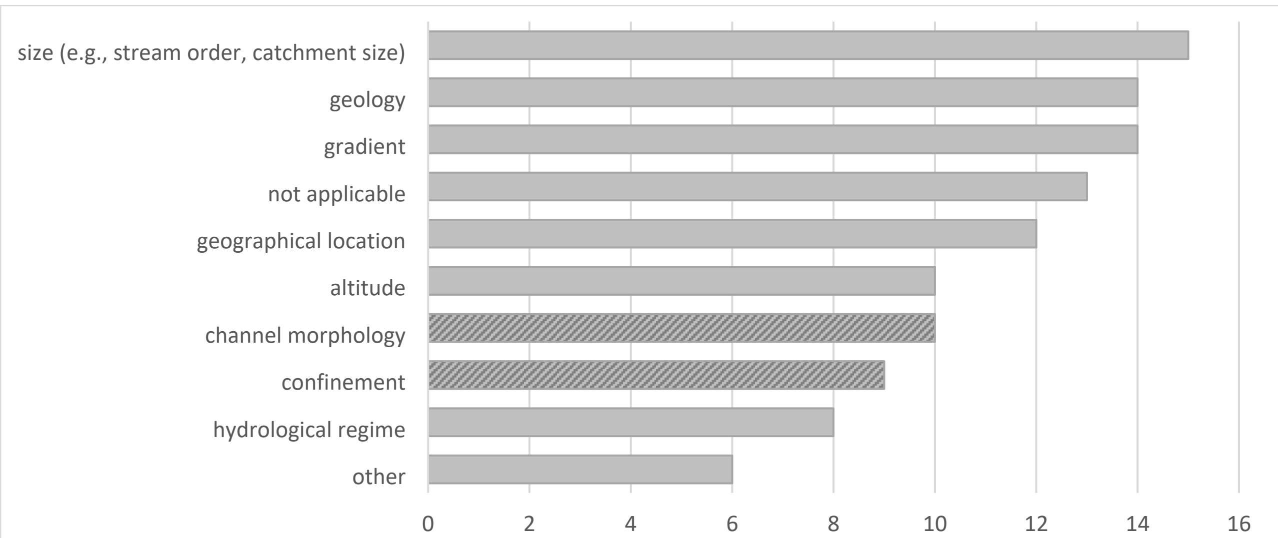


Figure 3.5 Criteria to define hydromorphological types for rivers

Although 23 methods use hydromorphological types, only 12 of them are applied differently according to types (e.g. all or most of the indicators are type-specific). Like the entirety of methods (55), the remaining are applied in the same way for all (hydromorphological) types, i.e. they are independent, in all their parts of assessment, from the hydromorphological type.

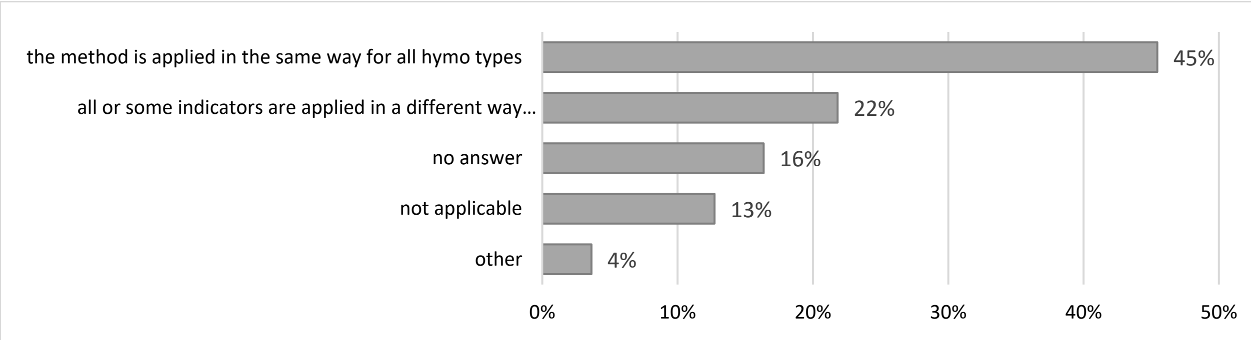


Figure 3.6   Type-specific application of methods.

The spatial dimensions considered in the assessment are disparate (figure 3.7). In the 51% of the methods, longitudinal scales of assessment are either fixed or site-specific (i.e. some hundred meters); uncorrelated to the hydromorphological processes they are called to represent and therefore unlikely to be meaningful (see Chapter 2).

The focus on the local scales is also evidenced by the fact that only 28% of the methods evaluates the effects of catchment pressures off-site (e.g. in the upstream sub-catchment). In-channel structures located upstream or downstream, which may have caused channel adjustments or other impacts in the assessed reach, are only considered in 52% of the methods.

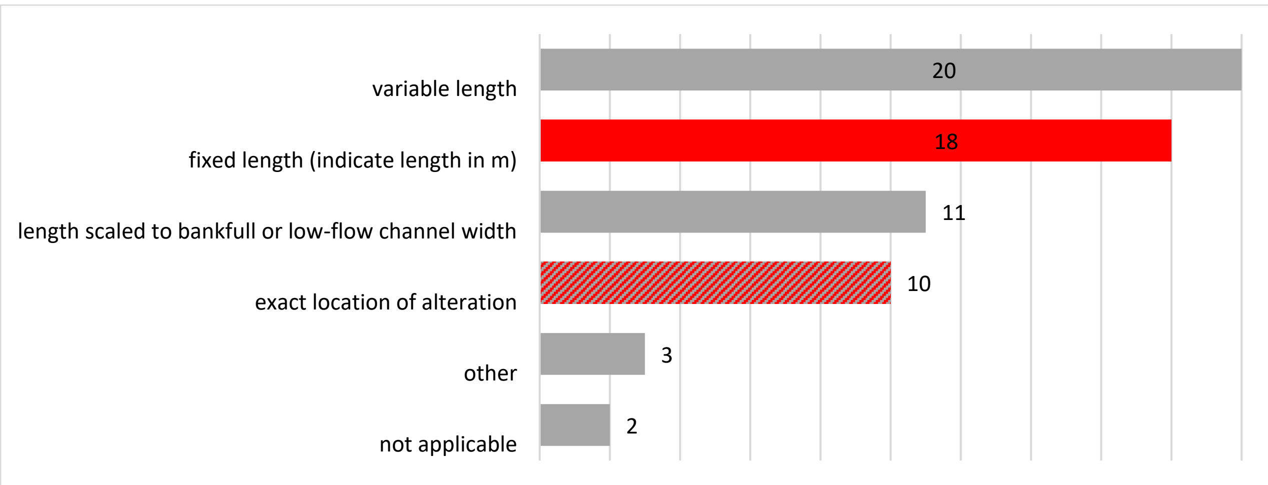


Figure 3.7   Spatial dimension of the assessment, Longitudinal scales.

For the lateral scales, 31 methods seem to consider the floodplain and the riparian zone; 30 limit their survey to the banks and the stream channel; 11 consider fixed width and 6 channel width-scale extent.

In unconfined or semi-confined streams, the connection with floodplain is crucial for ensuring good hydromorphological and ecological processes (figure 3.8). In naturally confined streams, the connection with hillslopes serves the same functions (e.g. the provision of sediment and organic matter). Nevertheless, few methods consider hillslopes in determining the lateral spatial scale (13).

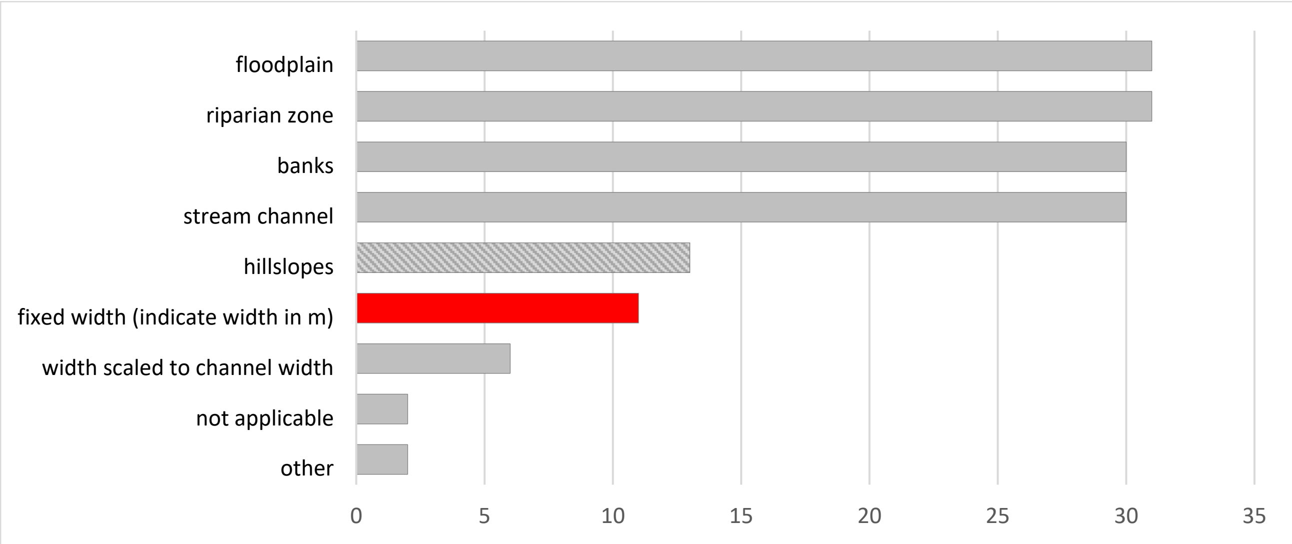


Figure 3.8 Spatial dimension of the assessment, Lateral scales.

The temporal dimension is taken into account in 22 of the reported methods, which reportedly give some consideration to past morphology or other river conditions (e.g. channel adjustments) in the assessment. For 13 methods, no consideration of the past is given (figure 3.9).

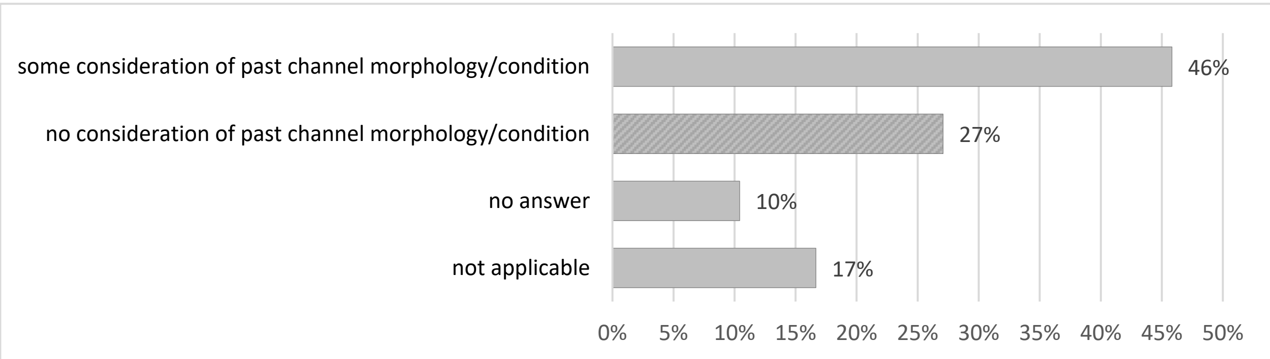


Figure 3.9 Temporal dimension of the assessment: consideration of past conditions.

The morphological characteristics, which are recorded by more than 30 of the reported methods, are the planform pattern and variability of cross-section (34), the extension of the vegetation in the river corridor (31) and its type and structure (30); the erosional/depositional features and the bed substrate and configuration (30).

The same morphological characteristics are also used to evaluate river conditions in the majority of reported methods (figure 3.10).

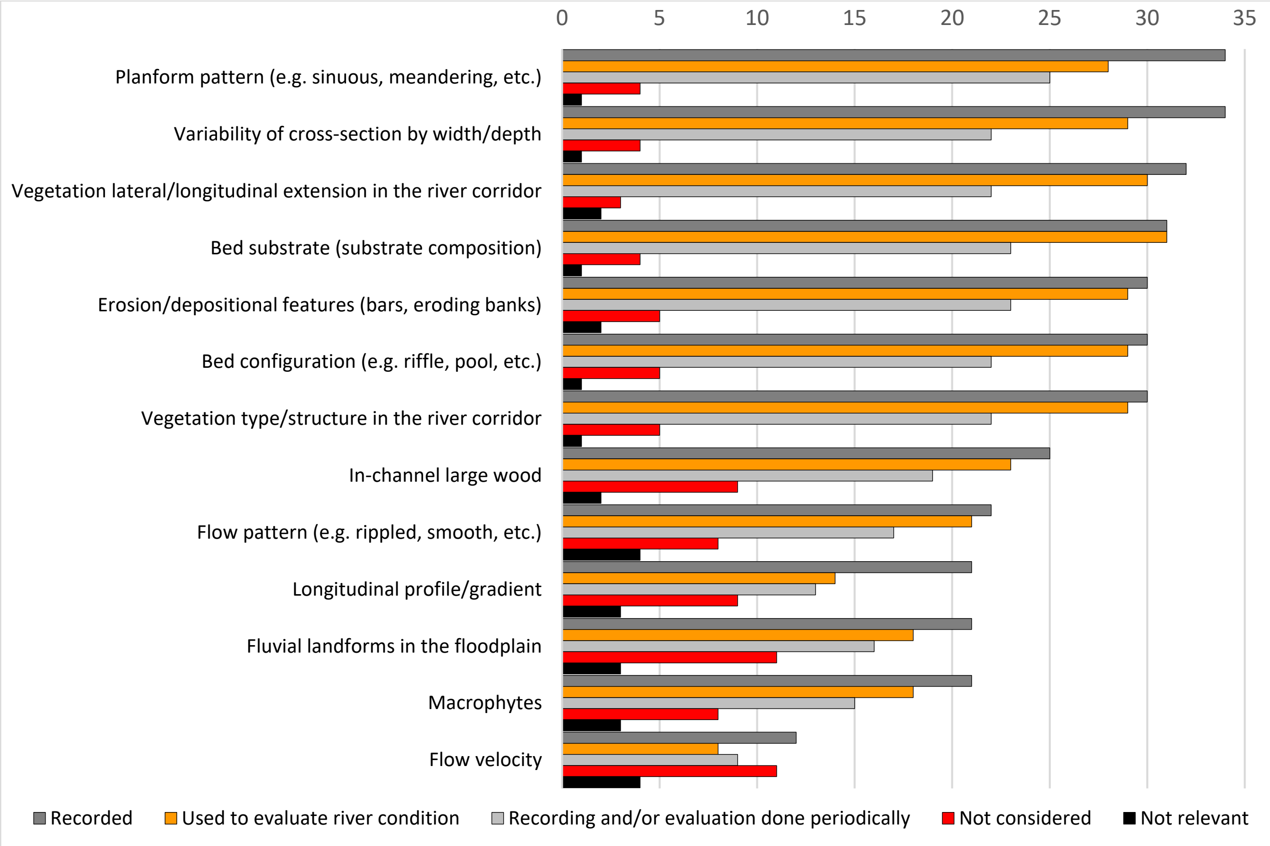


Figure 3.10 Morphological features considered in the methods

The information on the assessment of continuity has been collected both in terms of pressures, as part of the recording of artificial elements (structures with impact on longitudinal and lateral continuity), and in terms of response, as a part of the geomorphic processes considered in the methods.

In general, the majority of methods (figure 3.11) considers all artificial elements with impacts on longitudinal continuity, with the prevalence on dams (42).

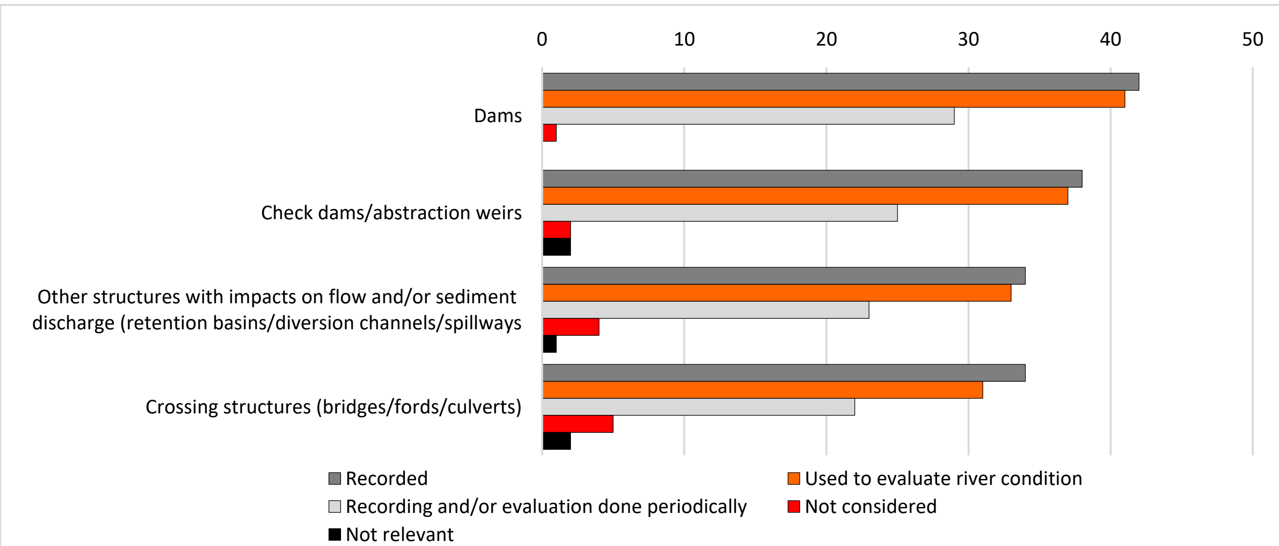


Figure 3.11 Consideration of structures impairing longitudinal continuity in the methods

Interruptions of lateral continuity such as artificial levees (or embankments) and bank protections are considered by a similarly high number of methods (36 and 40 methods respectively; figure 3.12).

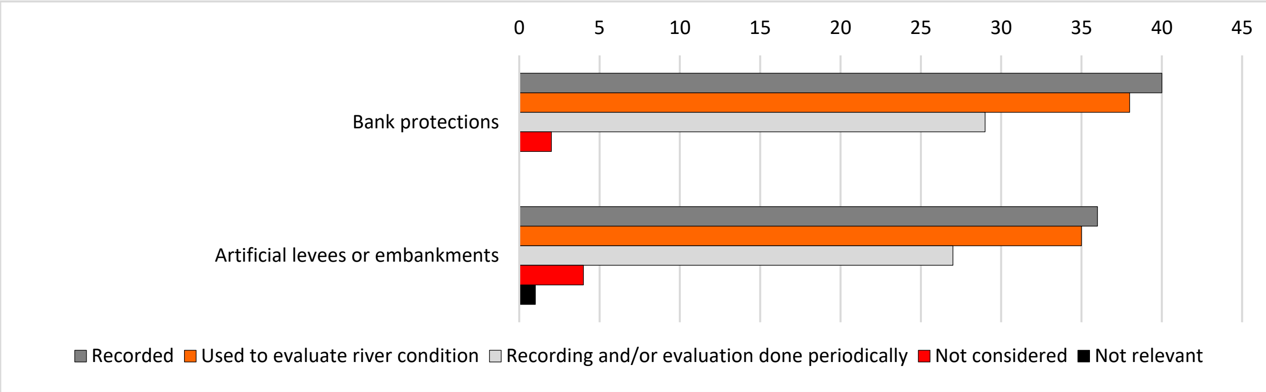


Figure 3.12 Consideration of structures impairing lateral continuity in the methods

Pressures on vertical continuity can be expressed in terms of bed structures (sills, ramps, bed revetments), which are considered in 32 methods, and in terms of responses, i.e. the alteration of bed sediment structure/substrate composition/vertical continuity (e.g. armouring, clogging), but this latter are considered only in 22 methods.

Indeed, the responses to the pressures on continuity, in terms of geomorphic processes, are not recorded in the same amount as the pressures they are impaired by (figure 3.15).

Over 42 methods considering dams in the evaluation, only 24 verify their response in terms of alteration of longitudinal continuity of sediment and wood fluxes upstream of the examined reach and only 18 evaluate alteration in sediment transport in the reach. The alteration of formative discharges is considered just in 17 methods.

Among 32 methods, 24 consider the alteration of lateral continuity of flows and only 14 consider the connectivity with the hillslopes, consistently.

Sediment, large wood and vegetation management exert a relevant pressure on any hydromorphological process, but they are only recorded in less than half of the methods (figure 3.15).

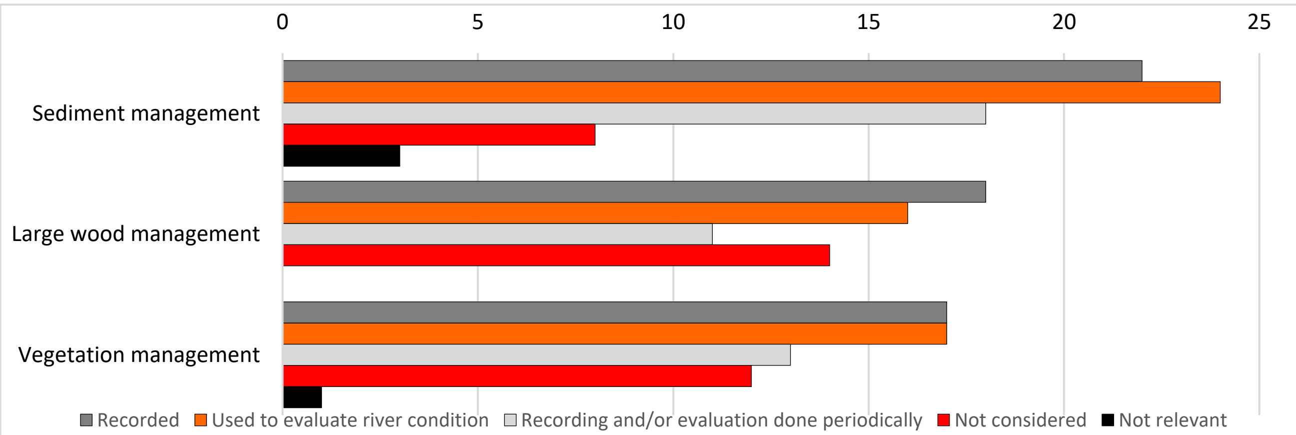


Figure 3.13 Consideration of pressures exerted by management actions in the methods

Pressures at the wider scale and/or off – site are least considered than the in-site ones (figure 3.16).

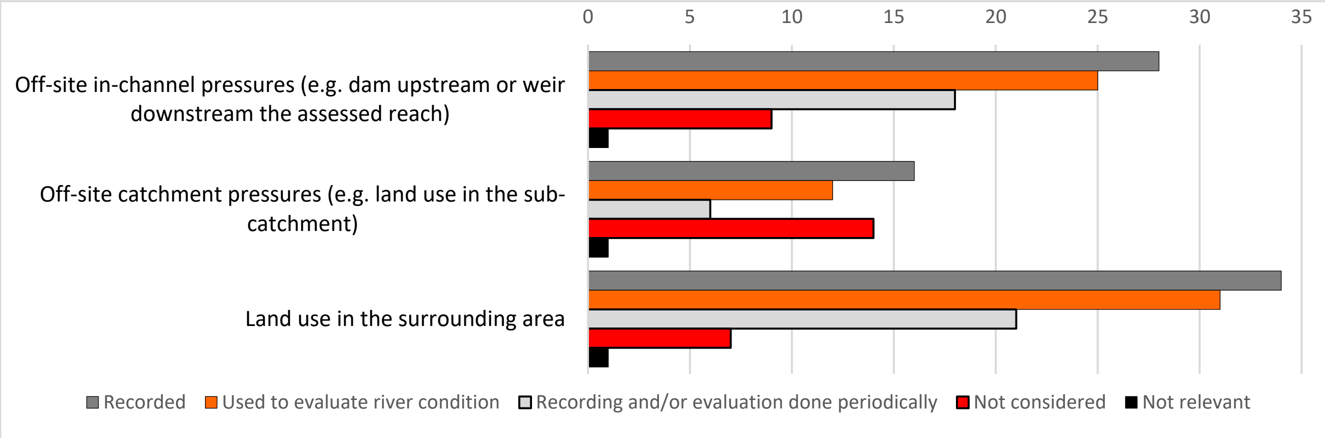


Figure 3.14 Consideration of pressures off-site in the methods

Reportedly, 18 on 55 methods (33%) include consideration of the occurrence of expected geomorphic processes, whereas 16 (29%) do not. Nevertheless, when analysing the different processes in terms of relevant indicators, those more related to the temporal dynamics of the river channel, i.e. channel adjustments in the three dimensions, are the least considered.

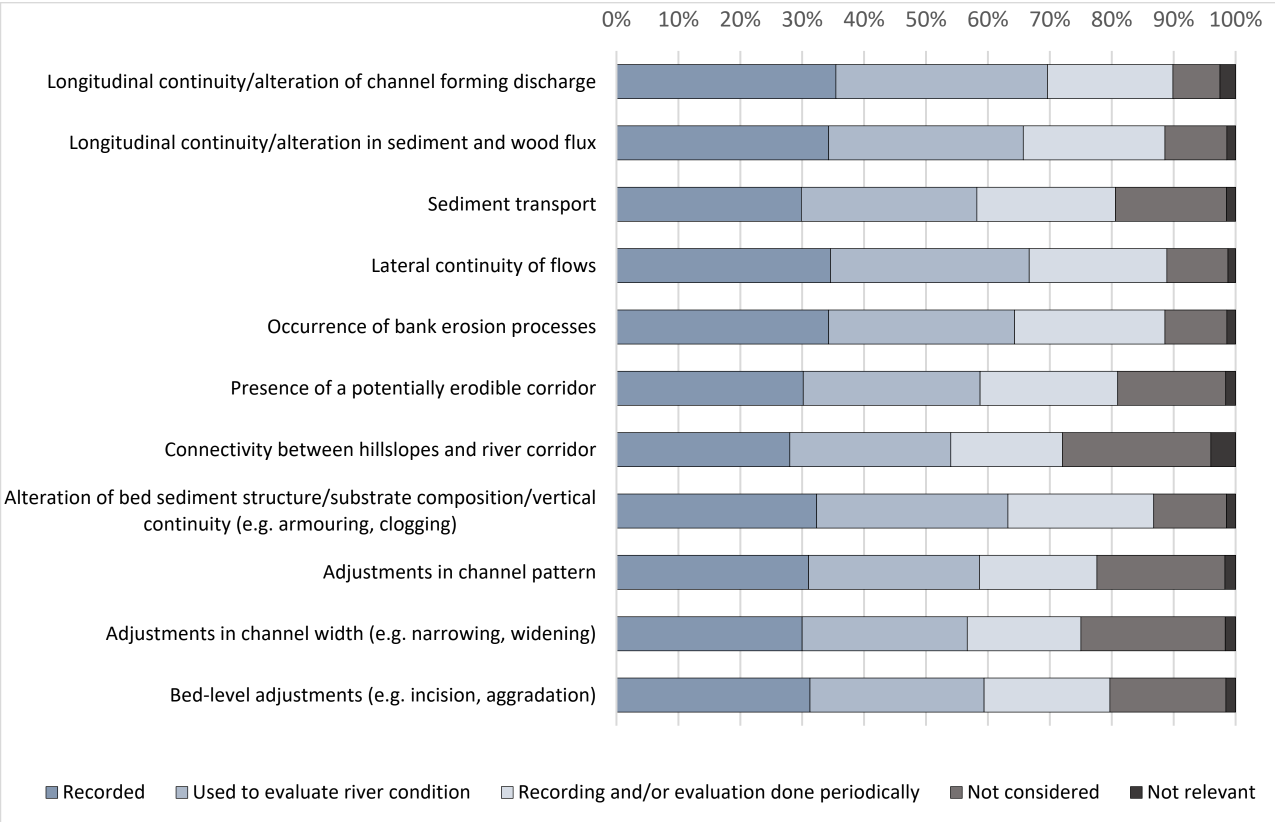


Figure 3.15 Indicators of geomorphic processes in the methods

This is quite consistent with the fact that only 10 of the methods (18%) are reported to include consideration of temporal changes and dynamics, whereas 24 (44%) neglect it.

For seven methods, the answer was not delivered (excluding the nine hydrological methods and the two continuity ones) and three of them are mostly inventories of observed current features.

The statistical analysis just presented was corroborated by a successive verification of the diagnostic capacity of the methods.

In order to do that, the methods were screened out against the seven basic criteria listed in par.2.2.2.1, which are:

Criterion 1) Identification of a morphologically significant unit of assessment.

Criterion 2) Definition of hydromorphological types.

Criterion 3) Definition of type-specific reference conditions and, consequently:

Criterion 4) Type-specific assessment.

Criterion 5) Consideration of temporal dimension, i.e. the past evolution of the river reach under analysis.

Criterion 6) Consideration of the multiple spatial dimensions, putting the reach in the context of the catchment.

Criterion 7) Separate consideration of pressures, responses and the past conditions in order to understand the casual nexus among them and provide a reliable diagnosis.

The number of methods, per criteria satisfied, is reported in table 3.3.

Table 3.3 Distribution of methods per criteria satisfied

Criterion	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Number of methods satisfying the criteria	25	10	18	14	13	26	4

Considering the criteria satisfied within each method, only eight methods, which reportedly consider geomorphological processes, sequentially satisfy four or more criteria, among which the consideration of temporal dimension, which is fundamental to contextualize the current conditions of the reach.

Table 3.4 Methods resulting from the screening

	Criteria						
	1	*2*	*3*	*4*	*5*	*6*	*7*
1. MQI Morphological Quality Index	X	X	X	X	X	X	X
2. HVMFS 2013:19 (Agency regulation)	X	X	X	-	X	X	X
3. Protocol for the hydromorphological characterization of water bodies	X	X	X	X	X	X	-
4. DRAINAGE	X	*	X	X	X	X	-
5. Indice para la evaluación de la calidad hidrogeomorfológica (IHG)	X	**	**	**	X	X	X
6. Handboek Hydromorfologie 2.0 (Oste et al. 2013)	-	X	X	X	X	X	-
7. Hydromorphology Quality Assessment	X	*	X	X	X	X	-
8. The hydromorphological classification tool Valmorph for large and navigable surface waters	-	*	X	X	X	X	-

X criteria satisfied; - criteria not satisfied; * hydromorphological types as reference types; ** implicitly from expert judgement

Only one method satisfies all the criteria (MQI; Table 3.4).

The Swedish method, strongly geomorphologically based, satisfies six criteria but needs to more diversify the assessment according to morphological types.

The first of the three Spanish methods, the *Protocol for the hydromorphological characterization of water bodies,* satisfies six criteria too, but not the last, which is the separate consideration of pressures, responses and past evolution. The method is still under test and the same authors report that it already needs modifications, as the bias introduced by operators is too high. The second, the *Drainage* method, satisfies six criteria as well, but it is used only for research and applies only to meandering rivers. The third, the IHG method, is also mainly for academic use, with three out of seven criteria implicitly derived from expert judgment.

The Dutch method seems to respect five criteria, as it tends to equalize hydromorphological and WFD types. It can hardly be applied out of the Netherlands, anyway addressing only lowland unconfined streams.

The Slovak method respects five criteria, but is still in modification to better include the spatial and temporal scales in the assessment.

The German method *Valmorph* fully respects only four criteria and is only applicable to large and navigable surface waters or Federal Waterways. More than a method to assess river conditions, it is a method to estimate sediment-balance in continuous along the river length.

3.3 Discussion

The methods are evidently very different in scopes and approaches, proving there is still a lack of a common understanding on hydromorphological assessment.
Indeed, some aspects of hydromorphology are still not clear among the WFD community, due to the lack of focus on this element in the recent past and also to the different scientific backgrounds of WFD actors, where fluvial hydromorphologist are still very few.

The replies to the different questions for the same methods often show some aspects of contradiction. As an example, 23 methods seemingly consider hydromorphological types, but only half of them (12) uses those types as a basis to differentiate the aspects that have to be observed and assessed. The remaining methods are applied in the same way for all types. This already precludes their evaluative capacity, given that the identification of a representative survey unit and the classification into types is the basis for a realistic assessment (e.g. Brierley and Fryirs, 2008; Brierley et al., 2010; par. 2.2.2.1). Many methods disregard the identification of hydromorphological types and the segmentation into morphological reaches because they are based on a site-specific approach, which is typical of the habitat survey methods, where the underlying hypothesis is that all river contain the same habitat-process relationships, as long as the measured variables are statistically controlled (e.g. Tadaki et al., 2014). In many of such habitat methods, the quest for comparability, interpreted as an abstract statistical rigour in the selection of survey units, seems to prevail on identifying morphologically representative reaches, where to survey those aspects that are more meaningfully associated with a particular river type (Brierley et al., 2010).

Only few methods account for the river multiple spatial dimensions, be it through a consistent segmentation into morphological reaches or through the collocation of reaches in the context of the catchment drivers of change. In fact, roughly half of the methods considers off-site in-channel structures, and only a quarter evaluates the influence of the other off-site catchment pressures. Such limitation evidences the scarce or null recognition of the hierarchical character of rivers, which incapacitates the comprehension of the causes of current conditions, and so prevents the elaboration of measures to enhance those conditions.

Some consideration of past channel morphology and conditions is reported for 22 methods, but only 10 methods explicitly consider their temporal dimension and dynamics, which is a fundamental requisite for a diagnostic assessment method. The knowledge of past evolution is indeed needed to interpret why the contemporary river is in the condition it is and so to correctly link causes and effects (e.g. Brierley & Fryirs, 2005; Sear et al., 2008).

A crucial requisite for a method to have diagnostic skills is to separately evaluate pressures and responses in the frame of past evolution. The results of the analysis show instead that whereas the pressures are considered in the majority of the methods, the related responses to those same pressures, in terms of the relevant affected geomorphic processes, are either not recorded or not related to them. Channel adjustments are also least considered in methods, consistently with the fact that the temporal dynamics is only addressed by 10 methods.

With those results, the implications for a correct implementation of the different stages of WFD are manifold.

To begin with, the scarce consideration of hydromorphological types endangers the entire WFD river classification.

The WFD criteria for type identification are indeed too broad (Gurnell et al., 2014) and do not catch the differences in river character and behaviour. Thus, the reference conditions, which should be type specific, are likely not to be meaningful. WFD typologies should reflect the natural variability in hydromorphological characteristics and processes, which in turn will result in different reference values in the BQE methods (COM, 2003a; COM, 2003d; COM, 2015).

Consequently, the resulting segmentation in water bodies is also likely to be unrepresentative, as a key requirement for water bodies identification is that response of the channel morphology to pressures should be homogeneous. This implies that homogeneous channel morphology should be verified.

The selection of sampling sites, ignoring the morphological diversity overlooked by WFD types, is inappropriate, and monitoring is reduced to a casual exercise, especially when hydromorphological alteration is the main cause of impairment of water bodies' conditions (e.g. Brierley et al., 2010; Belletti et al., 2018; COM, 2017; COM 2018).

Most of the methods can only be suitable for pressure analysis, but fail to be effective in evaluating the risks those pressures can exert, because they fail to consider that the same pressure on different river hydromorphological types may have quite different effects.

The diagnostic power of the methods is plagued by the scarce correlation between pressures and responses in the context of the past evolution (and of the position of the analysed reach in the catchment), which is needed for a correct assessment of river conditions and to design and monitor efficient measures.

The implications are enormous, not only for natural water bodies. The whole evaluation of the heavily modified water bodies, by definition related to the impairment of hydromorphological processes, is hampered, as their designation and ecological potential evaluation need a solid diagnostic assessment procedure.

Process-based methods in Europe are still very few.

The majority of the methods are, basically, habitat methods, aimed to verify the occurrence and abundance of certain site conditions that are favourable for biocenosis, where the survey units are identified in the proximity of biological sampling.

Roughly ten methods candidate for being process-based, but after a screening against the basic criteria, only eight respect at least five criteria, and only three of them can be considered to have skills at supporting river management and restoration.

The Swedish method satisfies five criteria but still needs some modifications in order to get a really type-specific assessment.

The Spanish "Protocol for the hydromorphological characterization of water bodies" is still at the experimental stage and the implementers declare it is still much too sensitive to the operator's bias, so it needs to undergo major revisions. It is therefore too immature to be applied.

The MQI satisfies all the criteria and is the more mature of the suite of methods, having been implemented for almost eight years, countrywide, with 5000 river reaches assessed.
This is a strong reason to select MQI and analyse its skill to support river restoration and management, including its potential to be applied outside Italy.

4 Analysis of the Morphological Quality Index (MQI)

4.1 The IDRAIM framework

The “Morphological Quality Index”, in short MQI (in Italian IQM - indice di qualità morfologica, Rinaldi et al., 2011), assesses the current hydromorphological conditions of a river reach (i.e. its *hydromorphological status*). The index is part of a wider framework for hydromorphological assessment, analysis and monitoring named IDRAIM (Rinaldi et al., 2015d; 2016d).

IDRAIM was developed with the specific aim of supporting the management of river processes by integrating the WFD objectives of ecological quality and flood risk mitigation. The system, thus, includes not only the assessment of hydromorphological quality (e.g. MQI), but also a component addressing the hazards related to fluvial dynamics. The approach is also suitable for other purposes in river management (e.g. environmental impacts assessment, hydropower licensing, etc.).

The general structure of IDRAIM includes four phases: (1) catchment-wide characterization of the fluvial system; (2) past evolution and assessment of present river conditions; (3) future trends; (4) management (figure 4.1; table 4.1).

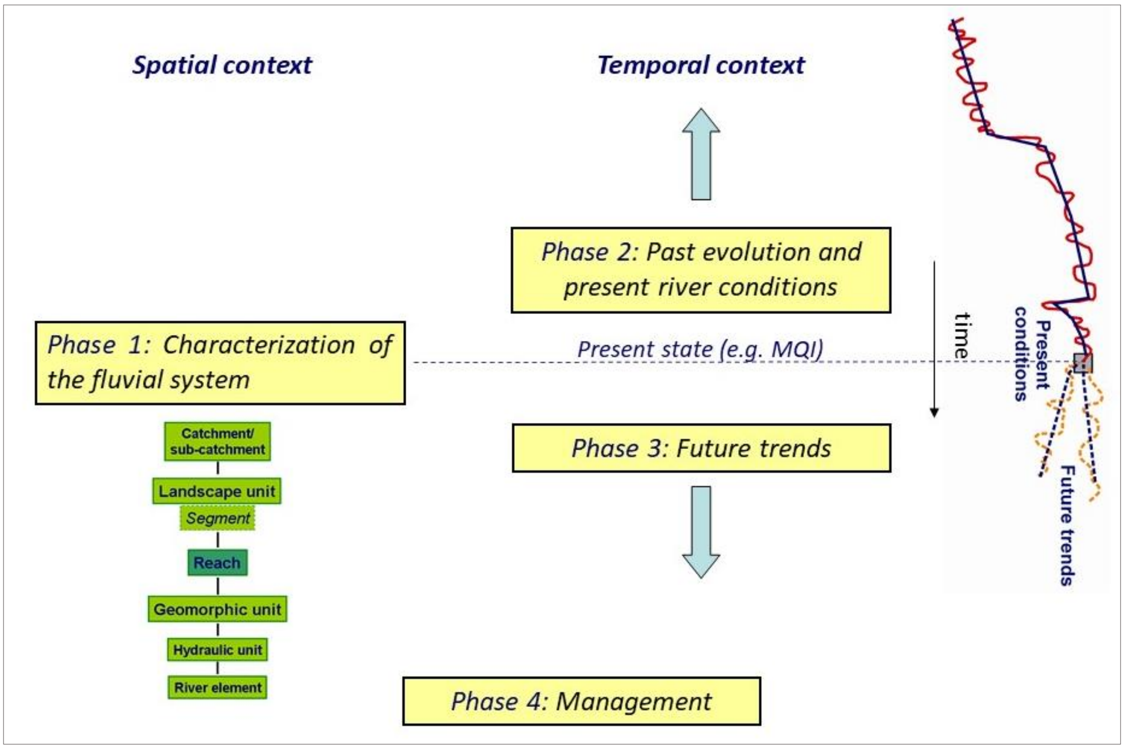


Figure 4.1 Articulation of the IDRAIM framework.

Phase 1 provides the spatial context and is aimed to characterize the river system in its present conditions. Phases 2 and 3 provide the temporal context, with phase 2 investigating the past evolution and the resulting present river conditions, and phase 3 considering possible scenarios of future channel changes. Finally, phase 4 focuses on the identification of an integrative river management strategy that should take into account the results stemming from the whole analysis.

Phase 1 (Characterization of the fluvial system) provides the spatial context for the river system analysis, including an initial characterization and segmentation of the fluvial system. This is based on a catchment-wide, spatially hierarchical framework following the scheme proposed by *Brierley & Fryirs (2005)*, consistently with the adaptation to Italian (*Rinaldi et al, 2013*) and European streams (*Gurnell et al., 2014*; *2016*). The final product of the segmentation is the delimitation of river reaches, defined as river stretches along which the present boundary conditions are relatively uniform (i.e. with no significant changes in valley setting, channel slope, water and sediment flows).
The reach is the unit of assessment of hydromorphological conditions.

Phase 2 (past evolution and current conditions) starts from a retrospective analysis of past evolutionary trajectories of channel morphology. This analysis suits alluvial, relatively large, rivers, (≈ 30 m.). In the case of small, confined streams and controlled rivers, morphological changes are quite limited and difficult to examine.
The reconstruction of evolutionary trajectories is based on a series of key parameters, including channel pattern (based on sinuosity, braiding or anabranching indices), channel width, and bed-level changes. Planimetric changes are examined by a multi-temporal series of aerial photos, while bed-level adjustments are based on the comparison of cross-sections or longitudinal profiles, when available, and field evidence.

Present river conditions are investigated using a series of tools related to different components of the analysis, i.e. hydromorphological quality and dynamics (i.e. flood hazard). The former include the Morphological Quality Index (MQI) and the Geomorphic Unit Survey (GUS). The latter refer to flood hazard and include the Morphological Dynamics Index (MDI), the Event Dynamics Classification (EDC), and the Morphological Dynamics Corridors (MDC).

The *Morphological Quality Index (MQI)* provides the assessment of current hydromorphological conditions (state) of a river reach analysing the links between pressures (artificiality) and responses (functionality; long-term channel-adjustments), through a set of 28 indicators that compose the final index (see next paragraph).
The assessment is type-specific; each type of channel morphology usually exhibits a typical assemblage of geomorphic units, unless the reach is altered. Therefore, classification of geomorphic units in a reach helps better characterize the reach scale and also detect small-scale changes induced by human activities (e.g. effect of small hydropower or restoration actions).

The *Geomorphic Unit Survey (GUS)* (Rinaldi et al., 2015c; 2015b; Belletti et al., 2017) provides such a classification and monitoring of geomorphic units in a reach according to an up to date geomorphic-consistent taxonomy. Geomorphic units (e.g., bars, pools) are the most appropriate scales for assessing physical habitats, as they constitute distinct habitats for aquatic fauna and flora, providing also temporary habitat requirements such as refugia and spawning grounds.

In this perspective, a geomorphically meaningful characterization of their assemblage will provide information about the existing range of habitats occurring in a given reach. In turn, this allows the establishment of consistent links between hydromorphological conditions at the reach scale, characteristic geomorphic units, and related biological conditions with relevant effects in informing significant and efficient restoration actions.

The *Morphological Dynamics Index* classifies the degree of channel dynamics related to progressive changes occurring in a relatively long-term (i.e., 50-100 years), not including possible responses to extreme flood events (which are addressed in the following EDC). The index is applied only to partly confined or unconfined reaches. The structure is similar to the MQI, and is based on a set of 11 indicators assessing the main factors that control channel dynamics (e.g., river typology, bed and bank erodibility, past changes and present trends of adjustment).

The Event Dynamics Classification (EDC) aims to investigate possible channel dynamics associated with extreme flood events (i.e. >100 years return period), and is applied to all river typologies (including confined channels). The classification is carried out by means of a guided procedure consisting of two phases: (1) assessment of expected types of morphological processes and changes during the event; (2) assessment of the probability of occlusion in critical cross sections (e.g. bridges).

The Morphological Dynamics Corridors (MDC) represents a further development of the functional mobility corridor (Rinaldi et al., 2009). The MDC procedure includes a reconstruction of historical river courses and a definition of possible future erosion by calculating the mean rate of bank retreat for a given reach. Three different corridors are defined, the former two related to progressive channel adjustments occurring during recurrent flow events (similarly to the MDI); the latter, associated to extreme flood events (similarly to the CDE) and does not account for existing protection structures.

Phase 3 (future trends) considers potential future trajectories of channel morphology, in response to actual or hypothetical scenarios of management, and their implications in terms of morphological quality and dynamics. The phase includes two steps: (1) monitoring, consisting of periodic measurement of morphological indicators and parameters and analysis of monitored trends of adjustment; (2) modelling, consisting of prediction of possible future trends of channel evolution.

A specific tool, the *Morphological Quality Index for monitoring (MQIm)* has been developed, to take into account small changes (e.g. small portion of a reach) and short time scales (i.e. a few years), and is particularly suitable for the assessment of interventions (e.g. restoration actions, flood mitigation works). Whereas the MQI quantifies the hydromorphological conditions (i.e., good, poor), the MQIm evaluates their tendency (enhancement or deterioration).

In order to predict the channel changes consequent to specific scenarios, different modelling approaches and tools in the field of fluvial geomorphology (e.g. conceptual, empirical/statistical, analytical, numerical models) can be used, dependently on the objectives of the modelling, the spatial and temporal scales, the available resources and data.

Table 4.1 IDRAIM: phases and related tasks (Rinaldi et al., 2015d)

Phases	***Tasks***
1. Characterization of the fluvial system	Catchment-wide general setting (geology, topography, climate, hydrology, land cover, land use)
	Multiscale 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, stream power, etc.)
2. Analysis of past evolution and assessment of current 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.)
	⇨ Geomorphic units Survey (GUS)
	⇨ 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 modelling 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

Phase 4 provides guiding principles towards integrated management aimed at improving river morphological quality and/or the mitigation of hazards due to channel dynamics. Following a decision-making framework, possible scenarios for quality enhancement or risk mitigation are formulated and their effect on morphological quality and dynamics evaluated, so that the best scenario at the reach scale can be identified, followed by additional considerations about the effects and the best scenario on a wider spatial scale (e.g. effects on upstream and downstream reaches). The analysis ends with the identification of management priorities.

4.2 The Morphological Quality Index (MQI)

The process-based method MQI is the Italian official method for the assessment of river hydromorphological status (MATTM, 2010) and was developed to comply with WFD requirements (nevertheless, it can be used for other purposes in river management).

It specifically targeted competent authorities for its extensive implementation countrywide, so it was designed to be relatively simple and not excessively time consuming. Its application, however, requires an appropriate background and sufficient skills in fluvial geomorphology.

The method adopts a multiscale, hierarchical approach (see par. 2.3), where the 'reach' is the basic spatial unit for the application of the evaluation procedure. Thus, a phase of delineation precedes and underpins the evaluation of MQI.

4.2.1 Delineation of reaches

The delineation of the reach precedes the assessment and consists of four steps.
Step 1 regards general setting and identification of landscape (or physiographic) units and segments (figure 4.2).

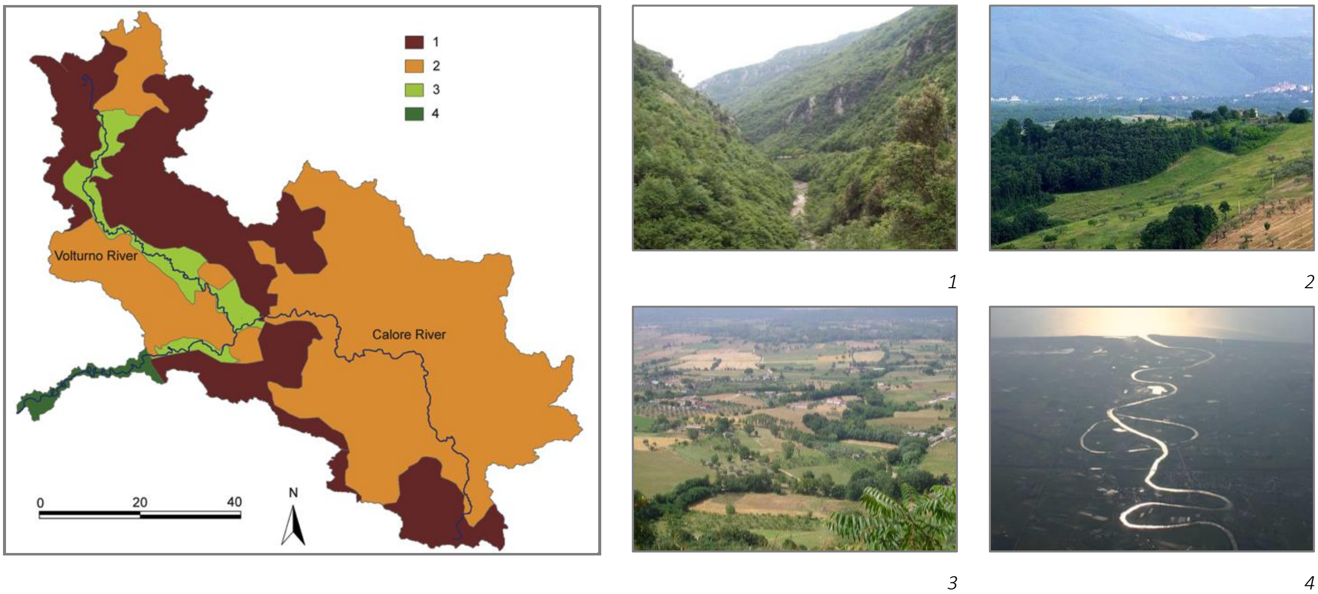


Figure 4.2 Delineation of the catchment of the Volturno River (Italy) into landscape units.

(1) Mountainous unit; (2) Hilly unit; (3) Intermountain plain unit; (4) Low plain unit.

Step 2 defines the confinement typologies, which separate quite different behaviours, as the hillslope constrain channel mobility. Based on the values of the *confinement degree* (percentage of river banks in direct contact with hillslopes or *ancient terraces*, over the total length of the two banks; Brierley & Fryirs, 2005) and *confinement index* (ratio between the floodplain and the channel widths), we distinguish three classes of confinement: confined, partly confined and unconfined (figure 4.3)

Figure 4.3 Different confinement classes: a) confined; b) partly-confined; c) unconfined.

Step 3 identifies the reach morphological type based on the channel planform pattern (figure 4.4.a). During the assessment of confined, single thread, alluvial reaches, a further classification comes into play, which considers the bed configuration in terms of assemblages of geomorphic units (figure 4.4.b).

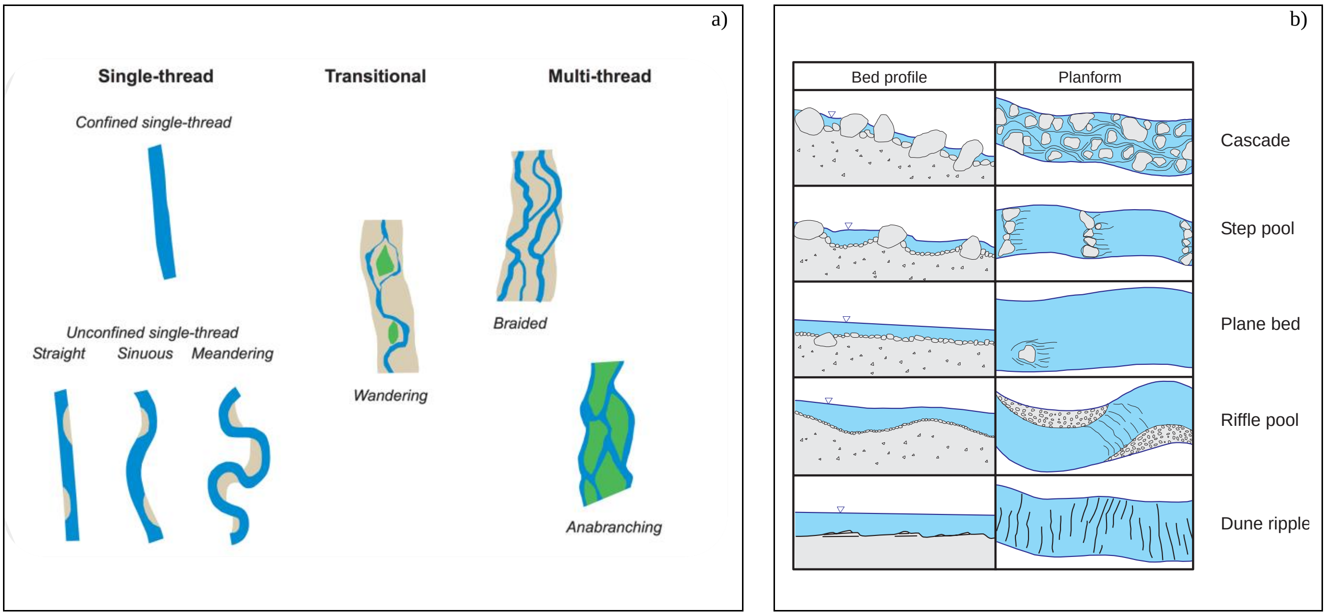


Figure 4.4 Classification into river types.

a) Broad morphological channel types (BRT) for reach delineation (Rinaldi, 2011).b) second- level classification of bed configuration used in the assessment of confined, single-thread alluvial streams.

Step 4 considers other elements for reach delineation, like significant discontinuities in slope, geology, hydrology (e.g. important tributaries) or dams.

4.2.2 Evaluation of MQI

MQI includes a set of 28 indicators, assessing longitudinal and lateral continuity, channel pattern, cross-section configuration, bed structure and substrate, and vegetation in the riparian corridor, compliantly with WFD and the indications from the relevant European standard (CEN, 2004).

These characteristics are evaluated in terms of three components: geomorphological functionality, artificiality, and channel adjustments (table 4.2).

The *geomorphological functionality* evaluates whether the processes, and related forms, responsible for the correct functioning of the river, are prevented or altered by artificial elements or by channel adjustments.

The *artificiality* assesses the presence and frequency of artificiality (artificial elements, pressures, interventions, management activities) independently of the effects of these artificial elements on channel forms and processes.

Channel adjustments assess relatively recent morphological changes (i.e. over about the last 100 years) that are indicative of a systematic instability related to human factors.

Table 4.2 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*	

Indicators of *geomorphic functionality* and *channel adjustments* can be considered as '*response indicators*', whereas indicators of *artificiality* are *'pressure indicators'*. Including both 'response' and 'pressure' indicators provides a basis for understanding causes of current river conditions. The same type of pressure may result in different responses for different river (e.g. Rinaldi et al., 2011; Fryirs, 2015). Therefore, the artificiality indicators identify the potential elements of alteration, whereas the functionality and channel adjustment indicators assess the geomorphic responses (effects) to these disturbances, including past off-site impacts and adjustments. This synergistic use of the different components of the assessment and their mutual feedbacks promotes a sound understanding of the river conditions and causes of alteration, which can be used to select the appropriate management actions.

A simplified analysis of past evolution, allows distinguishing changes related to human interventions from those reflecting natural tendencies of the channel (e.g. due to climatic variations or channel response to large floods).

Reference conditions are defined in terms of functionality, artificiality and channel adjustments.
The reference conditions for functionality correspond to the channel form and processes that are expected for the morphological type under examination.
For artificiality, reference conditions occur in absence or negligible presence of artificial elements along the reach and to some extent (in terms of flow and sediment fluxes).
Finally, the absence of significant channel adjustments (configuration, width, bed elevation) over a temporal frame of about 100 years is the reference for channel adjustment indicators. Indeed, divergently to many current hydromorphological methods, where reference conditions are defined in terms of precise channel forms, reference conditions for the MQI are river reaches in dynamic equilibrium, where the river exerts the expected morphological type-specific functions and where pressures are absent or do not affect river dynamics at the catchment and reach scale.

The overall evaluation is carried out by making a combined 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. The spatial scale of application of MQI is the river reach, but alterations of flow and sediment transport can be determined by pressures off site, so information is needed also at the segment and at the catchment scale on the types of interventions affecting these variables (i.e., dams, check dams, weirs, etc.). GIS analysis is conducted at the reach scale, while the field survey is focussed on representative sub-reaches (or 'sites').

As already explained in par.2.1.2, the MQI assessment includes only those hydrological aspects having significant effects on geomorphological processes. The overall changes in the hydrologic regime are analysed separately by calculating a specific index of hydrological alteration (i.e. IARI).

The evaluation of MQI envisages two different procedures, one addressing the confined channels (C) and the other addressing partly confined channels (PC) and unconfined channels (U).

The number and type of indicators for each of these two procedures differ, as some of the indicators are specific for confined channels (e.g. connection with the hillslope) while other are only suitable for partly confined and unconfined (e.g. presence of a modern floodplain).

A summary of indicators, with assessed parameters, and ranges of application, is reported in table 4.3. A detailed description of each indicator is reported in the *Guide to the Compilation of the MQI Evaluation Form* (Rinaldi et al., 2016d).

Table 4.3 Definition, assessed parameters, assessment methods, and ranges of application of each MQI 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 side of the river	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 infrastructure (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 cases where transverse bed structures are present and in comparison with the 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 – Planform pattern Percentage of the reach length with altered planform and geomorphic units	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 landforms in the floodplain Presence/absence of appropriate landforms in the floodplain (e.g., oxbow lakes, secondary channels, etc.)		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 the cross section that is expected for that river type and is caused by human factors		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	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	All typologies; not evaluated above the tree- line and in streams with natural absence of riparian vegetation
F12 – Width of functional vegetation Mean width (or areal extension) of functional riparian 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 riparian 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

(continued on next page)

Indicators and assessed parameters	*Assessment methods*	*Ranges of application*
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 Type 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
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
A7 – Artificial levees Length and distance from the channel of artificial levées	Remote sensing–GIS and/or database of interventions: length 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 structure 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
A10 – Sediment removal Existence and relative intensity of past sediment mining activity (over the last 100 years, with a particular focus on the last 20 years)	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
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 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 referred to the 1950s	Remote sensing–GIS (quantitative)	All typologies; evaluated only for large channels (W>30 m)
CA2 – Adjustments in channel width Changes in channel width referred to the 1950s	Remote sensing–GIS (quantitative)	All typologies; evaluated only for large channels (W>30 m)
CA3 – Bed-level adjustments Bed-level changes occurred in 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

4.2.2.1 Scoring system

The evaluation of MQI is based on a scoring system, defined and then improved after a testing phase countrywide; in order to embrace all Italian different river types (Rinaldi et al., 2013).

Three classes are generally identified for each indicator: (A) undisturbed conditions or negligible alterations; (B) intermediate alterations; (C) very altered conditions.

Reference conditions were defined for each indicator, corresponding to the absence or negligible presence of alterations (class A), thus, a value of zero is assigned to this class.

For the *indicators of functionality*, a score of 2 to 3 is 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 some indicators (e.g., *F2* and *F10*), a fourth class is added to better highlight the different levels of alteration.

A similar approach and scoring is adopted for the *indicators of artificiality*.

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

The first two *indicators of channel adjustments*, (*CA1* and *CA2*, i.e. adjustments in channel pattern and channel width, respectively) score 3 for class B and 6 for class C. As bed-level adjustments (*CA3*) are more relevant, a fourth class (C2) is defined with a score of 12, to account for the case of dramatic bed-level changes (> 6 m). Indeed, some Italian rivers underwent a severe incision (up to 10-12 m) in the recent past, mostly as a response to gravel mining (Surian & Rinaldi, 2003).

An *additional rule* assign an extra penalty (6 or 12) to the cases of an extremely dense and dominant presence of artificial elements along the reach, such as transversal structures, bank protections, levées, artificial changes of river course, bed revetments (indicators *A4*, *A6*, *A7*, A8, and *A9*, respectively). The extra score of 6 or 12 is assigned and added only to the numerator of Eq. (1).

A total score (*Smax*) is computed as the sum of scores across all components and aspects

The Morphological Quality Index is then defined as:

$$MQI = 1 - \frac{\text{Stot}}{\text{Smax}} \qquad \text{(Eq. 1)}$$

where S_{tot} is the sum of the scores, and S_{max} is the maximum score that could be reached when all appropriate indicators are in class C.

The index increases with the quality of the reach and decreases with the alterations, varying from zero (minimum quality) to one (maximum quality, corresponding to reference conditions).

The values describe the hydromorphological quality of a reach according to five classes, from high to bad, consistently with WFD (table 4.4):

Table 4.4 MQI classes. The colours correspond to the classes according to WFD standardization (EC, 2000).

MQI class	***Boundaries***				
High	0.85	≤	MQI	≤	1.00
Good	0.70	≤	MQI	<	0.85
Moderate	0.50	≤	MQI	<	0.70
Poor	0.30	≤	MQI	<	0.50
Bad	0.00	≤	MQI	<	0.30

4.2.2.2 Management of operator bias

The analysis and comprehension of river processes requires the contextualization of several different aspects in the light of a solid geomorphological background.

A good knowledge of fluvial geomorphic processes is also required for the application of the MQI, thus the level of the operator's professional background has a determining impact on the outcome of the assessment.

The MQI is a rigorous scientifically based method, aimed primarily to support public Agencies in charge of river status assessment. Therefore, it was designed in such a way that the evaluation framework, apparently redundant, results in a restrained, driven evaluation where subjectivity is reduced at the minimum.

Nevertheless, assessment may be biased by the skills of the operator and/or the availability of information. Some indicators may be affected by a lack of data or information or may require an interpretation that involves a certain degree of subjectivity.

In order to reduce operator bias, the rules for the delineation and evaluation are described in a clear and consistent manner in the MQI user's guidebook (Rinaldi et al., 2015d, 2016d), which should facilitate reproducibility by different operators (Kondolf, 1995).

Moreover, the number of classes for each indicator was kept small, i.e., classes are sufficiently large, generally having two extreme classes and one intermediate.

When the answer is close to the limit between two classes, more uncertainty and subjectivity is likely to be introduced.

As an additional countermeasure, to help indicating (and recording) how “certain” the user feels about the answer, a degree of confidence (low or medium – a high confidence would mean being certain) and a second (alternative) choice in the classes can be expressed in the evaluation forms.
Factoring in the scores associated to the second choice (with low or medium confidence in the answer), a range of variability rather than a single final value of the MQI is obtained.

Recognizing and recording a medium to low confidence calls for further investigations in order to reduce the uncertainties and eventually remain within the boundaries of the same status class.

4.2.3 Extent of implementation in Italy.

The issue of Ministerial Decree 260 in 2010 enforced MQI as a national method to be implemented, in order to comply with WFD.

With the aim to prepare the competent authorities in applying correctly the method, four MQI training courses were effectuated during the summer of 2010, covering all Italian territory and destined only to public officers in charge of hydromorphological assessment of rivers. After 2010 and ever since, the course has been held at least yearly and opened to professionals and researchers too.

The decree obliged the implementation of the method at least to confirm the high status of water bodies in high biological conditions. Following that strict obligation, a first application of the MQI was carried out mainly on water bodies with particular situations of low pressures. In some regions, though, MQI was applied to any water body independently from biological status.

In 2013, a workshop was held, informed by the results of a survey, with the aim of appraise the first implementation of MQI and to analyse the problems presented by the competent authorities in reply to an ad-hoc questionnaire (figure 4.6).

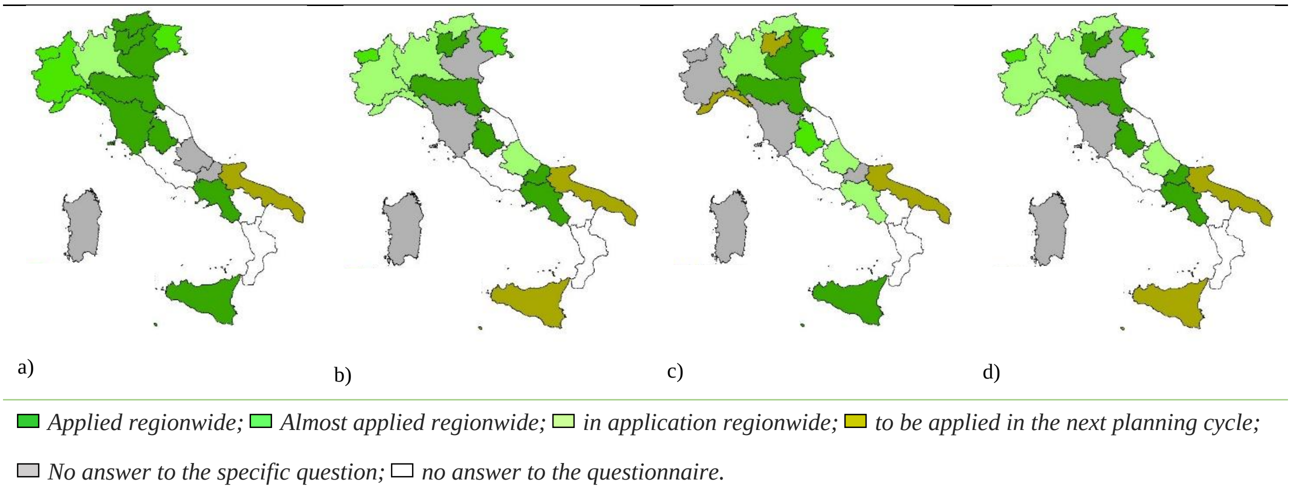


Figure 4.5 State of implementation, in 2013, of MQI per purpose in Italian Regions.
a) MQI used for identification of reference conditions; b) MQI used to confirm high ecological status; c) MQI used for identifying HMWB; d) MQI used for any purpose.

Later on, the application of MQI was extended to any water body type and combination of pressures. Indeed, the competent authorities recognised the capacity of the method to produce effective diagnosis on river conditions. Therefore, they extended the use of MQI to other fields than status assessment, including MQI in the criteria for licensing water permits or for environmental impact assessment and monitoring of restoration success.

The impetus increased when the relevant legislation obliged the use of MQI for HMWB identification and the definition of ecological potential.

The current situation of implementation is described and analysed in the next chapters.

4.3 *Analysis of the Italian national MQI dataset*

In the following chapter, the national Italian MQI dataset is evaluated.

The objectives of the analysis of the MQI dataset are:

1. Verifying the diagnostic capacity of the method;
2. Evaluating the objectivity of the method in terms of the operator's uncertainty, introduced during the assessment;
3. Providing a general picture of the hydromorphological status of Italian rivers to identify the main problems (pressures, ongoing processes) and suggest some viable solutions.

The investigation was carried out examining the outcomes of eight year countrywide monitoring and assessment on more than four thousand river reaches, which represent a comprehensive spectrum of the different river contexts in Italy.

Indeed, Italian streams range from very small torrents to large rivers and are characterized by an extremely high diversity in geomorphological and hydrological characteristics, with different combinations of types of prevailing river-feeding, river-aquifer interaction and intermittency (Bussettini et al., 2014; Figure 4.6), due to the geographical and climatic context of the country and to the very diverse physiography (Figure 4.7).

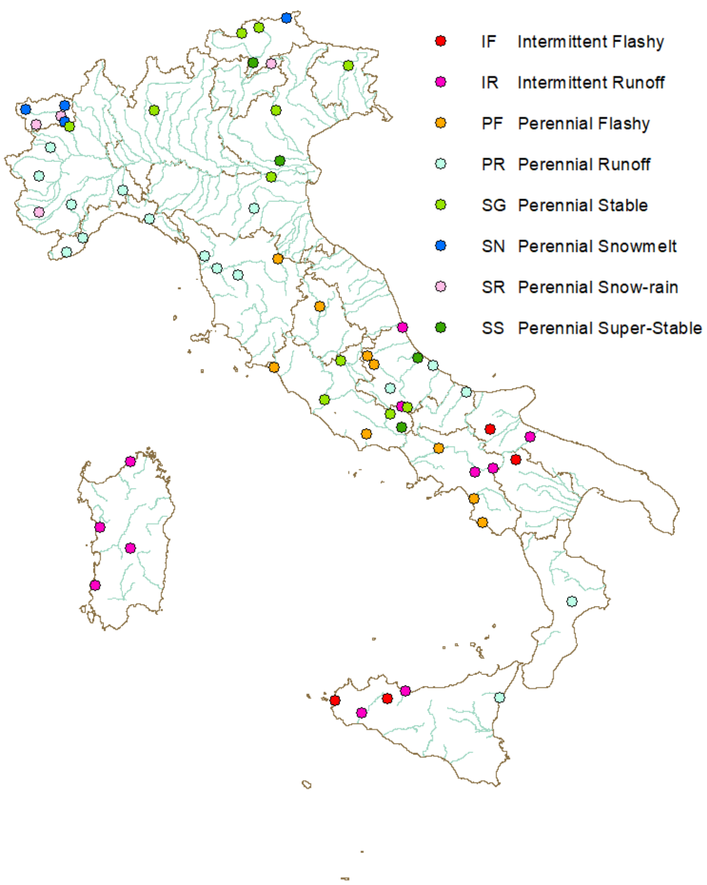


Figure 4.6 Types of river hydrological regimes (Bussettini et al. 2014)

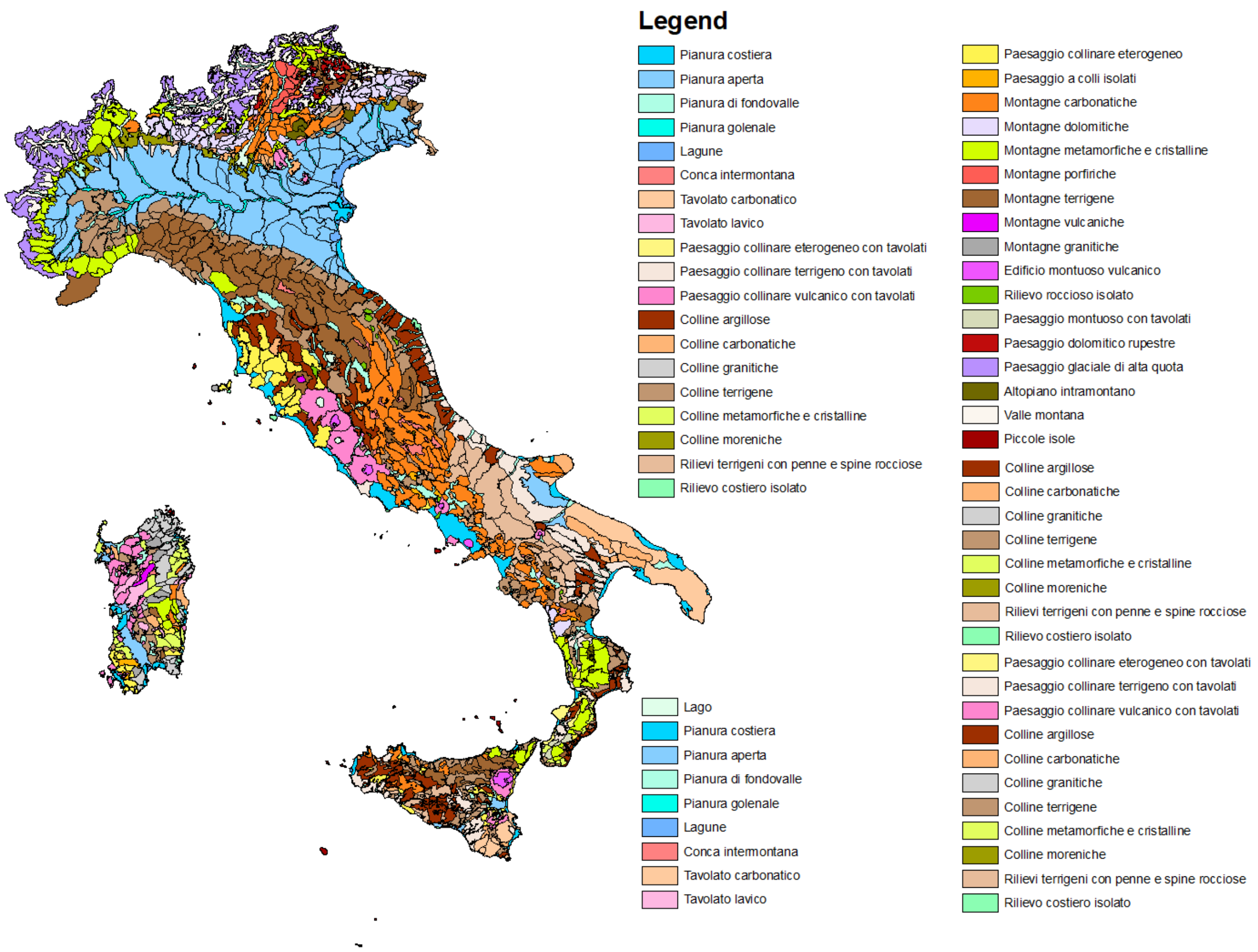


Figure 4.7. Physiographic units of Italy. ISPRA, Carta della natura,, scale 1:250.000 (ISPRA 2018).

The main criteria for classification are litho-geomorphologic features and the structure of relief (elevation, aspect, slope, energy).

The favourable geographic setting has, in time, obviously led to a very high density of population all over the country, eliciting a wide range of anthropic pressures, which have been affecting significantly Italian streams in the last century.

Those pressures, and chiefly dams, sediment mining, and channelization, triggered a series of significant morphological adjustments, such as: a) bed-level lowering (incision), from 3-4 m up to more than 10 m.; b) channel narrowing, with reductions of channel widths up to 50% or more; c) changes in channel pattern, particularly from braided to wandering (Surian & Rinaldi, 2003).

Yet, due to the huge physiographic diversity, it is still possible to recognize a discrete range of channel morphologies.

Historical analyses were carried out to reconstruct the evolutionary trajectory of Italian streams (e.g. Rinaldi & Simon, 1998; Comiti, 2012, Bollati et al., 2014; Scorpio et al., 2015; Scorpio & Rosskopf., 2016).

Remarkable steps forward to understanding the causal nexus between pressures and impacts were made, which led to the development of conceptual models of channel evolution in Italian streams (e.g. Rinaldi & Simon, 1998; Surian, 1999, Rinaldi, 2003, Surian &Rinaldi, 2003; Surian et al 2009; 2011; Figure 4.8).

Such a knowledge underpinned substantially the MQI methodological approach.

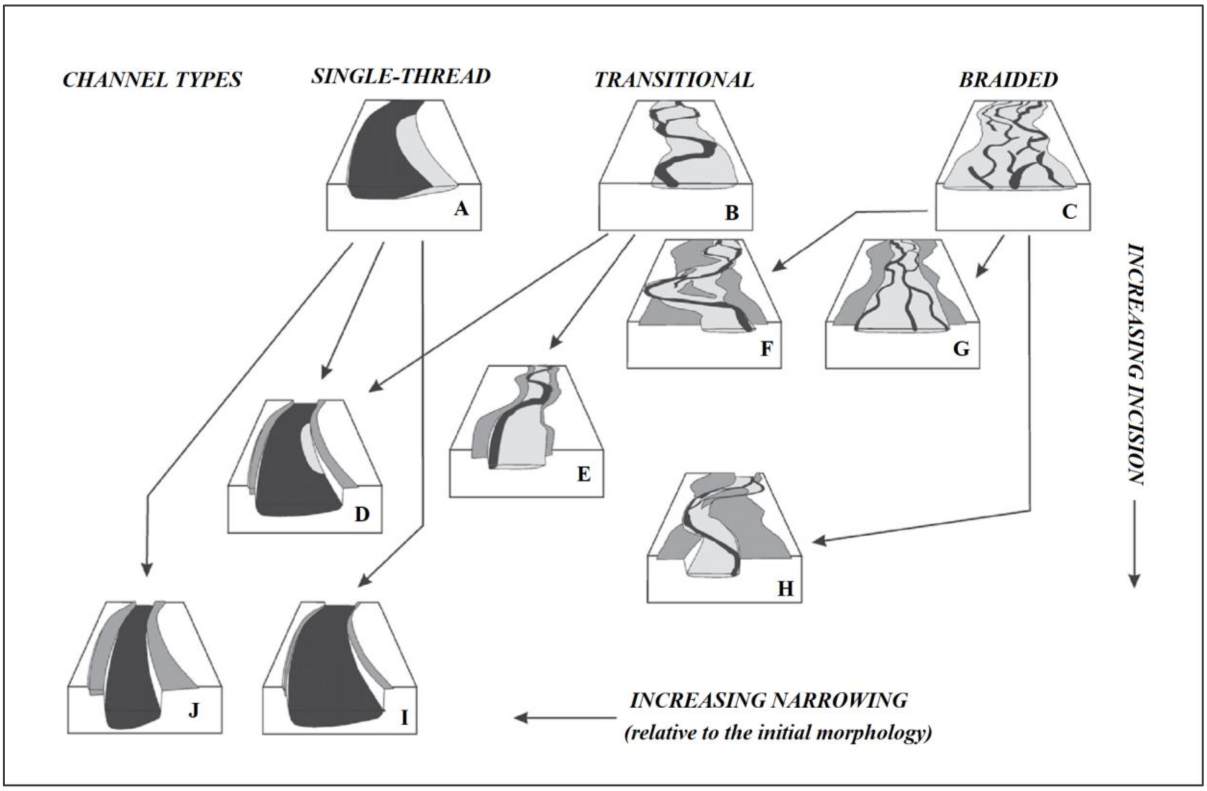


Figure 4.8 Summary of main types of channel adjustments in Italian rivers during the past 100 years.

Starting from three initial morphologies (A, B and C), different channel adjustments were observed according to variable amount of incision and narrowing. Modified from Surian & Rinaldi, 2003)

4.3.1 Materials and Methods

The study dataset consists of 4048 river reaches all over Italian territory and derives from MQI evaluations carried out from 2009 up to early 2017.

The majority of the reaches (97%) has been surveyed by the Regional and Provincial Environmental Protection Agencies, which are the competent authorities in hydromorphological assessment according to the relevant legislation (Par. 2.1.2.1).

The remaining part of the dataset (3%) derives from academic institutions (led by the University of Florence) and was effected for research purposes, principally in 2009 for testing MQI.

Data refer to 16 out of 20 regions (table 4.5). Sicily and Marche regions applied MQI but the relevant regional administrations did not formally endorse the results and the information could not be available at the time of the analysis. The other regional administrations (Basilicata, Calabria, Campania and Latium) suffer a delay in the implementation of river monitoring and assessment in general, thus the lack in hydromorphological monitoring and evaluation.

Table 4.5 Number of evaluated MQI reaches per Region/Province and data provider

Regions/ Provinces	***Regional/Prov. EPA***	***Universities***	***Total***
Abruzzo	210		210
Bolzano (Province)	50	2	52
Emilia Romagna	1748	9	1757
Friuli Venezia Giulia	79	1	80
Liguria	78		78
Lombardia	692	3	695
Marche		6	6
Molise		2	2
Piemonte	433	1	434
Puglia		4	4
Sardegna	116		116
Sicilia		2	2
Toscana	29	38	67
Trento (Province)	258		258
Umbria	13	3	16
Val d'Aosta	113		113
Veneto	138	20	158
Total	*3957*	*91*	***4048***

A considerable part of the case studies is located in northern Italy; nevertheless, the whole dataset is comprehensive of the entire gradient of types, physiographic contexts, anthropic pressures and climatic conditions in the Country (figure 4.9).

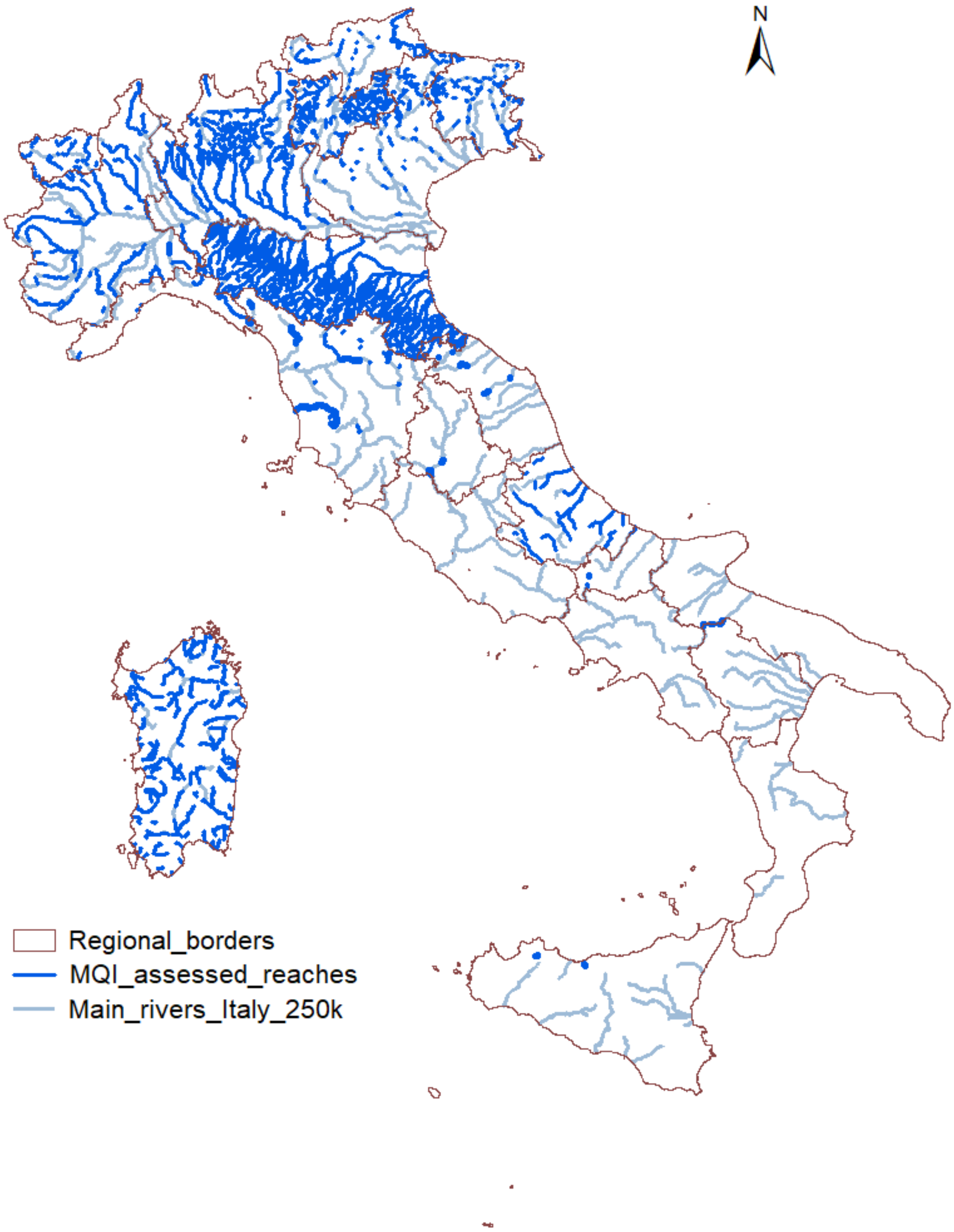


Figure 4.9 MQI assessed reaches composing the dataset.

The range of variability of the main geomorphic characteristics in the reaches is extremely wide. Reach lengths span from 50 meters to 40 kilometres; channel widths range from less than 1 meter to 1200 meters, and slopes decrease from 0,76 m m^{-1} in some steep alpine torrents to minimum slopes lower than 0,0001 m·m^{-1} in the coastal plains (table 4.6).

Table 4.6 Range of variability of the main geomorphic characteristics. L=reach length; W=channel width; S = reach slope.

Physiographic group	L_{min}-L_{max} (m)	W_{min}-W_{max} (m)	S_{min}-S_{max} (m m^{-1})
Mountainous/Hilly; Confined (MH_C)	50 ÷ 40,000	0.8 ÷ 40	0.004 ÷ 0.76
Mountainous/Hilly; Partly-Confined/Unconfined (MH_PC_U)	196 ÷38,000	2 ÷ 520	0.002 ÷ 0.50
Alluvial Plains; Unconfined (P_U)	406 ÷ 40,000	3 ÷ 1200	<0.0001 ÷ 0.3

MQI data are collected into a field form, which is pre-compiled with the results from the preliminary desk study, consisting in a remote sensing - GIS analysis of the reach to be evaluated.
Successively, all data are transferred into standardized electronic forms, i.e. Excel files, which consist of six sheets (settings; generality; functionality; artificiality; channel adjustment; indices calculation; results) and differ in the case of confined streams and partly confined/unconfined reaches (Par. 4.2.2).

The electronic forms calculate the sub-indices and the final MQI values, which derive from factoring in the possible confidence recorded by the operator.
In fact, to help indicating (and recording) how "certain" the user feels about the answer, a degree of confidence (low, medium, high) and a second (alternative) choice in the classes can be expressed in the evaluation forms. Accounting for the scores associated to the second choice (with low or medium confidence in the answer), a range of variability rather than a single final value of the MQI is obtained (figure 4.10).

A2	Upstream alteration of sediment discharges	score	selection	conf	sconf
A	Absence or negligible presence of structures for the interception of sediment fluxes (dams for drainage area ≤5% and/or check dams/abstraction weirs for drainage area ≤33%)	0		M	-3
B1	Dams (area 5-33%) and/or check dams/weirs with total bedload interception (area 33-66%) and/or check dams/weirs with partial interception (area>66%)	3	x		
B2	Dams (area 33-66%) and/or check dams/weirs with total bedload interception (drainage area >66% or at the upstream boundary)	6			
C1	Dams for drainage area >66%	9			
C2	Dam at the upstream boundary of the reach	12			

Notes:

MQI = Morphological Quality Index (0≤MQI≤1)			*MQI*	QUALITY CLASS
MQI	**MQI_{min}**	**MQI_{max}**	*0.0 ≤ MQI < 0.3*	*Bad*
0,84	*0,77*	*0,86*	*0.3 ≤ MQI < 0.5*	*Poor*
QUALITY CLASSES (MQI)			*0.5 ≤ MQI < 0.7*	*Moderate*
$CLASS_{med}$	**$CLASS_{min}$**	**$CLASS_{max}$**	*0.7 ≤ MQI < 0.85*	*Good*
Good	***Good***	***High***	*0.85 ≤ MQI ≤ 1.0*	*High*

Figure 4.10. MQI Evaluation form (http://www.isprambiente.gov.it/pre_meteo/idro/idro.html).

Upper: indication of low/medium confidence and related score.In the example, the operator opted for class B1, which corresponds to a score of 3. A medium uncertainty (M) was expressed that the class could be A, which identifies no alteration with a score equal to 0. This corresponds to having an uncertainty amounting to -3 (sconf).

Lower: calculation of the MQI confidence interval in the evaluation forms.

The variations in value can be only negative (the value of MQI is underestimated), only positive (the value of MQI is overestimated) or both (i.e. the value of MQI is included in a confidence interval) but not necessarily involve a change in status class.

In order to investigate about the causes of variations in MQI values and classes, information about the level of confidence related to each indicator is needed.
Such information is reported only for 1608 reaches, as some regional agencies (Emilia-Romagna and Lombardia) directly transferred field data into an ad-hoc proprietary database, where they did not store some of the information (e.g. sub-indicators, confidence), consequently not available for the study. In particular, they only stored the range of variability related to MQI value, but did not retain the value of uncertainty per indicator. Therefore, a detailed analysis of the uncertainty was performed only on that complete sub-dataset (N_{unc} = 1608 reaches). Its results are reported in paragraph 4.3.2.3.

Other than the above-mentioned cases, all the MQI evaluation data were transferred and stored inside the standardized Excel files.

All data underwent formal and substantial consistency checks, by means of a semi-automatic programme, developed for the two different Excel forms (confined reaches; partly unconfined and unconfined reaches).
The controls revealed several types of errors (e.g. variables formats, reach codes) and sometimes-recurring errors at the regional level, so the procedures had to be customised for some data sources.
Following the consistency check, several reaches resulted in missing information on reach code, which had to be assigned according to ad-hoc criteria.

Reach geographic information are to be recorded into standardized templates (*shapefile*). Mismatches of codes for the same reach in the Excel forms and the shapefile were detected and involved extra work in order to restore some association of codes in the homologous files fields.

The consistency check also showed a relevant number of reaches (447 on 4495) lacking information on channel planform morphology. This is a crucial information for MQI assessment, because it determines the type specific indicators that shall be used.
Therefore, those 447 reaches were rejected and the initial dataset (N= 4495) was reduced to a final general dataset of 4048 reaches.
Data where then systematised into a database and the different spatial data mosaicked and stored into a geodatabase.

In order to proceed to the detailed analysis, the total dataset (4048 river reaches) was subdivided into three sub-datasets, corresponding to major groups that are homogenous in terms of confinement and physiographic settings:

1. Confined reaches in mountainous –hilly areas (MH_C);
2. Partly-confined or unconfined reaches in mountainous –hilly areas (MH_PC/U);
3. Unconfined reaches in the alluvial plains (P_U).

The statistical analysis of the dataset included several aspects, consistently with the different objectives of the study, and is structured as follows.

i. The distribution of MQI values among classes for each of the three physiographic groups was studied, both in terms of number of reaches and in terms of total reach length.

   Within each of the three groups, the distribution of MQI values in relation to channel morphology or bed configuration was investigated. The results are reported in paragraph 4.3.2.1.

ii. The distribution of scoring along the different MQI indicators was analysed, in order to identify the main alterations for each group and the relation with the response of the index to verify its diagnostic capacity. The results are reported in paragraph 4.3.2.2.

iii. The analysis of the uncertainties related to each of the indicator assessment was carried out, in order to assess the “objectivity” of the method, to highlight the causes of the possible bias introduced by the operator during the evaluation of MQI and eventually enhance the method to reduce the bias at the maximum. The results are reported in paragraph 4.3.2.3.

iv. Multivariate analyses for categorical/ordinal variables were performed to verify the possibility to reduce the initial set of observations of possibly correlated variables into a set of values of uncorrelated variables and to analyse the ordinal association between indicators, and among indicators and MQI. Such analysis aimed to evaluate the sensitivity and related stability of the index and to corroborate its “objectivity” and diagnostic capacity. The results are reported in paragraph 4.3.2.4.

   The MQI indicators are indeed ordinal variables, as they can only have a limited number of discrete values within a specific interval. Non-parametric tests and statistics for such variables have to be used, based on “ranks” of observations and not on their values.
   Two statistic techniques for ordinal variables were used:

   a) the Kendall rank correlation coefficient (or tau - τ) to measure the ordinal association between indicators and among them and MQI;

b) the PRINCALS (principal components analysis by means of alternating least squares; Van Rijckevorsel & De Leeuw, 1979), which is an analysis of principal components (PCA) for ordinal and categorical variables. PRINCALS analyses a set of variables for major dimensions of variation and the relationships among observed variables are assumed non- linear. Similarly to ordinary PCA, PRINCALS aims to reduce the number of variables (MQI indicators), which represent the aspects or “features” of the hydromorphological quality, to only few “artificial” new variables, able to explain the entire phenomenon (hydromorphological quality).

   In geometrical terms, this means to verify the possibility to represent the variables (MQI indicators, amounting to Ni - where Ni=22 in the case of confined reaches; Nv=26 in the case of partly-confined/unconfined reaches), in a space with reduced dimensions (R, R2, R3...) than the original space R_{Ni}, with a negligible loss of information.

   If the indicators are projected on a certain number of axes (directions), the one where data have a wider spread (i.e. with respect to that axis, variance is highest) describes them best. That axis is said to be the principal component (PC). The direction of the axis is called eigenvector.

   The numerical value quantifying the variance along that direction is called eigenvalue. Therefore, the principal component is the eigenvector having the highest eigenvalue. The eigenvalue is a measure of how much of the variance of the observed variables a PC can explain.

   The relationship of each variable to each PC is expressed by the so-called loadings, which can be interpreted like regression coefficients.

   PCs are by definition uncorrelated (i.e. they are orthogonal) and are ranked according to the variance values they represent

   If variables are correlated (high loadings), they can be substituted by the new set of variables, the PCs, obtained as combinations of the original variables. The PCs must satisfy the condition to represent a high percentage of the original dataset variability and to explain the relations between variables.

   The choice of the number of components is a challenging task and should be driven by the purpose to account for a sufficiently high percentage of the total variance (i.e. at least 80%).

The univariate and multivariate statistical analysis were carried out through PAST software (Hammer et al, 2011), Excel scripts and R software (R core-team, 2013). In particular, the PRINCALS analysis was performed using the R *princals* function, whereas the Kendall rank correlations were computed using the *cor* R function.

4.3.2 Results

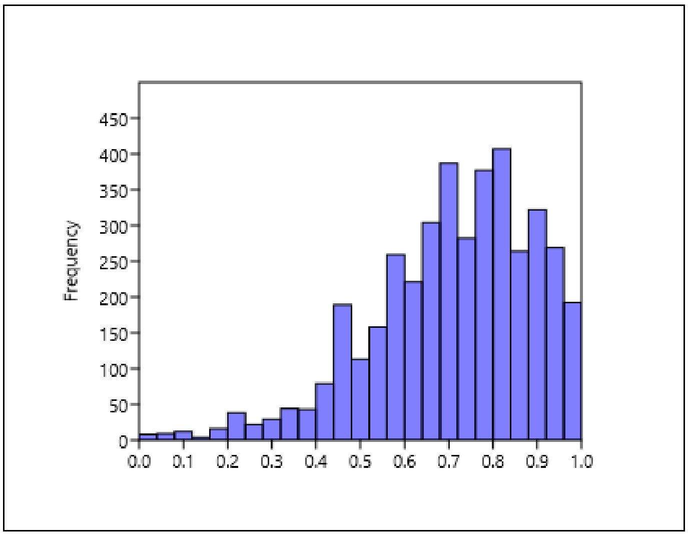
The results of the analysis are reported in the following paragraph according to the different aspects as structured in paragraph 4.3.1.

4.3.2.1 Results of the descriptive statistical analysis

This section reports the results of the univariate analysis, aimed at understanding how the MQI values vary with physiographic groups and, within each group, with channel morphology.

The total dataset regards 4048 river reaches and consists of 4048 values for the variable MQI, ranging from 0 to 1.

The distribution of MQI values is negatively skewed (C_s=-0.79) and leptokurtic (C_K'=130.05), as the histogram and the statistical descriptive parameters denote (figure 4.11).



Descriptor	*Value*
N	4048
Min	0
Max	1
Mean	0.7088735
Std. dev	0.1830175
Median	0.73
25 percentile	0.60
75 percentile	0.85
Skewness	-0.7919684
Kurtosis	130.0471
Coeff. var	25.81807

Figure 4.11 Total distribution of MQI values and statistical descriptors or the distribution.

MQI values do not distribute normally. The non-normality of MQI values distribution was verified through the Shapiro-Wilk Test (Shapiro & Wilk, 1965). The test proves that the null hypothesis H_0 is not satisfied (p<<0,001).

The distribution of the dataset among MQI quality classes was evaluated in terms of number of reaches and total length.

The distribution of reaches among MQI classes shows that the majority of reaches is in good status (32%), followed by moderate (29%), high (25%), poor (11%) and bad (3%) (Figure 4.12.A).

The distribution of total lengths of reaches per MQI class shows a similar configuration and no significant difference can be evidenced between the different evaluations (figure 4.12.B).

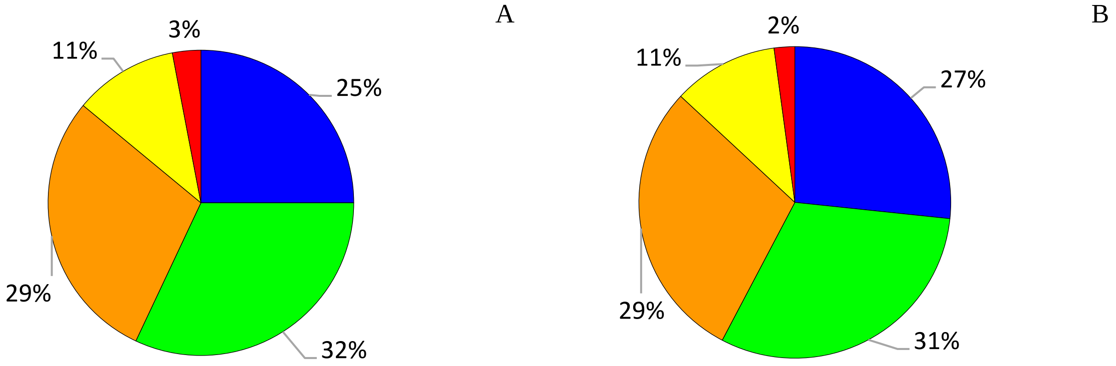
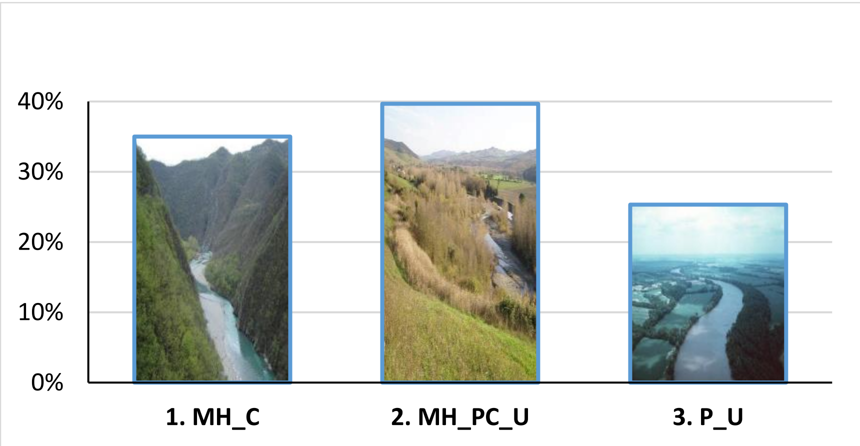


Figure 4.12 Distribution of reaches and lengths in MQI classes.

A) Results of MQI in terms of percentage of reaches; B) Results of MQI in terms of percentage of river length

For the successive analysis, the total dataset of 4048 reaches was subdivided into three physiographic groups. The first group, composed by confined reaches in mountainous –hilly areas (MH_C), amounts to 1417 reaches (35% of the total). The second group, partly-confined or unconfined reaches in mountainous –hilly areas (MH_PC/U), amounts to 1606 reaches (40% of the total). The third group consists of 1025 unconfined reaches in the alluvial plains (P_U), equating 25% of the total (figure 4.13).



1. Confined reaches in mountainous-hilly areas (MH_C).

2. Partly-confined and unconfined reaches in mountainous-hilly areas (MH_PC_U)

3. Unconfined reaches in alluvial plains (P_U)

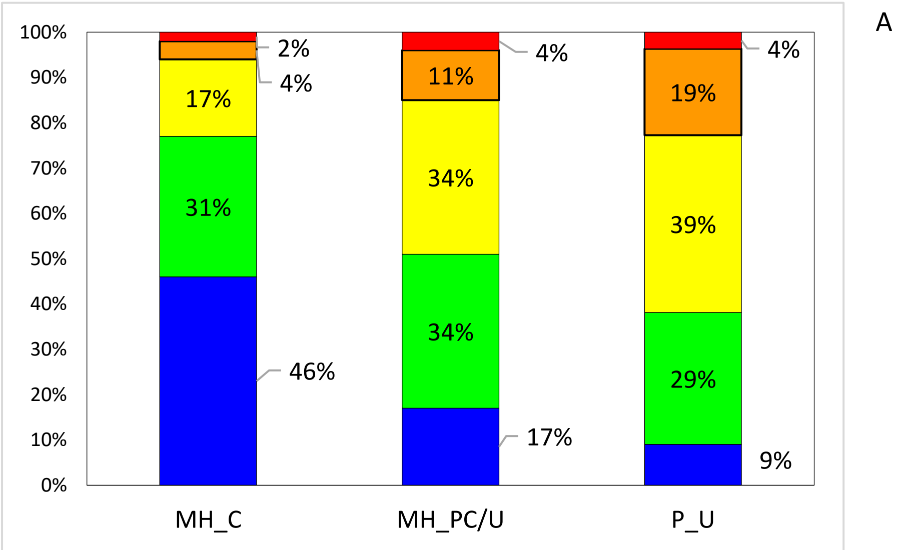
Figure 4.13 Distribution of the reaches into the three groups.

The distribution of MQI values in quality classes varies considerably among the three physiographic groups; both in terms of number of reaches (figure 4.14.A) and in terms of their respective total lengths (figure 4.14.B).

Group 1, i.e. confined reaches in mountainous/hilly areas, is mainly characterized by high (46%) and good (31%) morphological conditions (77% in good or above conditions), whereas the 17% of the reaches is in moderate status, and only 6% of the reaches have poor or below conditions (4% poor, 2% bad).

The number of reaches in good or above conditions (52%) decreases in group 2 (unconfined and partially-confined reaches in mountainous/hilly areas), and the proportion of reaches in high status (17%) is inverted with respect to those in good status (34%), which are as numerous as those in moderate status (34%). The reaches in poor conditions increase to 11%, followed by those in bad status (4%).

Unconfined reaches in the alluvial plains (group 3) are mostly characterized by moderate conditions (39%). The proportion of reaches in good or above status drops from 77% (characterizing Group 1) almost to a half (38%; 9% in high and 29% in good status), whereas the percentage of reaches in poor status quintuplicates (19%) and those in bad conditions double (4%).



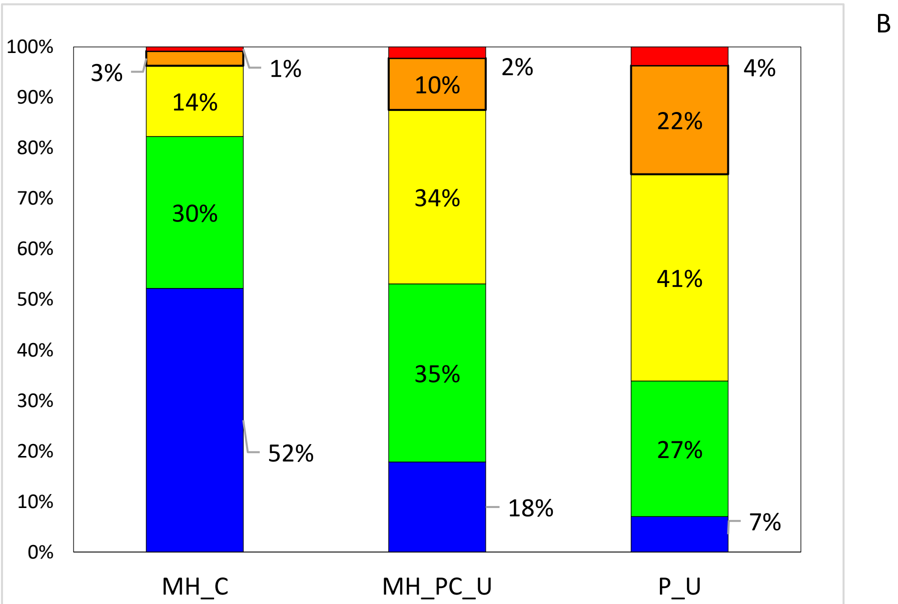


Figure 4.14 Distribution of MQI values in status classes for the three different groups (1=MH_C, 2= MH_PC/UC, 3=P_UC). A) Results of MQI in terms of percentage of reaches per physiographic group; B) Results of MQI in terms of percentage of river length per physiographic group.

The results in terms of distribution of lengths across MQI classes show an analogous trend with respect to the number of reaches, with a slight exacerbation of good or better conditions in the marginal groups. In fact, the percentages of high status conditions increase in the confined reaches of group 1 (52% versus 46%) and the percentages of good or better conditions decrease in the unconfined reaches in the alluvial plain context (34% versus 38%).

Kruskal-Wallis H-test confirms that the distribution of MQI values per reach varies significantly among the three "physiographic" groups (p <0,001), and the medians are significantly different (table 4.7; figure 4.15).

Table 4.7 Statistical descriptors for the three physiographic groups

Physiographic group	*N*	*Min*	*Max*	*Mean*	*Variance*	*Median*	*25 percentile*	*75 percentile*	*Skewness*	*Kurtosis*
1.MH_C	1417	0.00	1.00	0.79	0.0280	0.83	0.71	0.92	-1.39	-13.954
2.MH_PC_U	1606	0.00	1.00	0.68	0.0302	0.71	0.59	0.81	-0.87	-99.28
3.P_U	1025	0.03	1.00	0.63	0.0290	0.65	0.51	0.75	-0.59	0.28

The median of MQI values in Group 1 (MH_C) has the highest value (0.83; good status) with respect to the lowest value (0.64; moderate status) in Group 3 (P_UC) (figure 4.15).

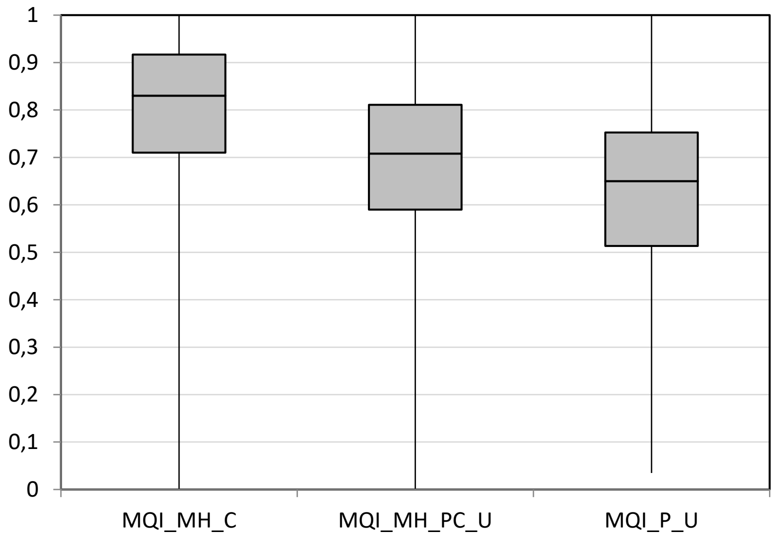


Figure 4.14 Boxplot of MQI values for the three different groups (Group 1=MH_C, Group 2= MH_PC/UC, Group 3=P_UC).

The distribution of MQI values inside each of the three groups is then analysed in relation to reach channel morphology (Groups 2 and 3) and to bed configuration (Group 1).

The distribution of MQI values varies significantly with channel morphologies both in the case of unconfined reaches of alluvial plains in 2 (figure 4.16) and in the partially-confined and unconfined reaches in mountainous-hilly areas in group 3 (figure 4.17).

This is statistically confirmed by the results of the Kruskall-Wallis H test ($p<0.001$ for both Group 2 and Group 3).

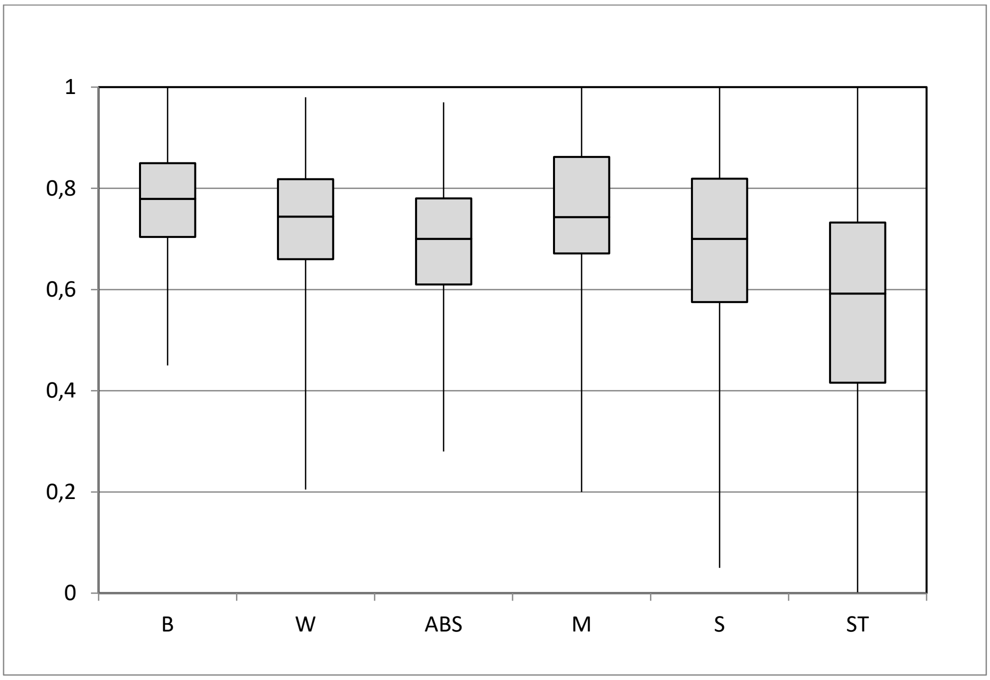


Figure 4.15
MQI values distribution along channel morphologies for partly confined and unconfined reaches in mountainous/hilly setting (Group 2).

B=braiding; W= wandering; ABS=sinuous with alternate bars; M=meandering; S=sinuous; ST=straight

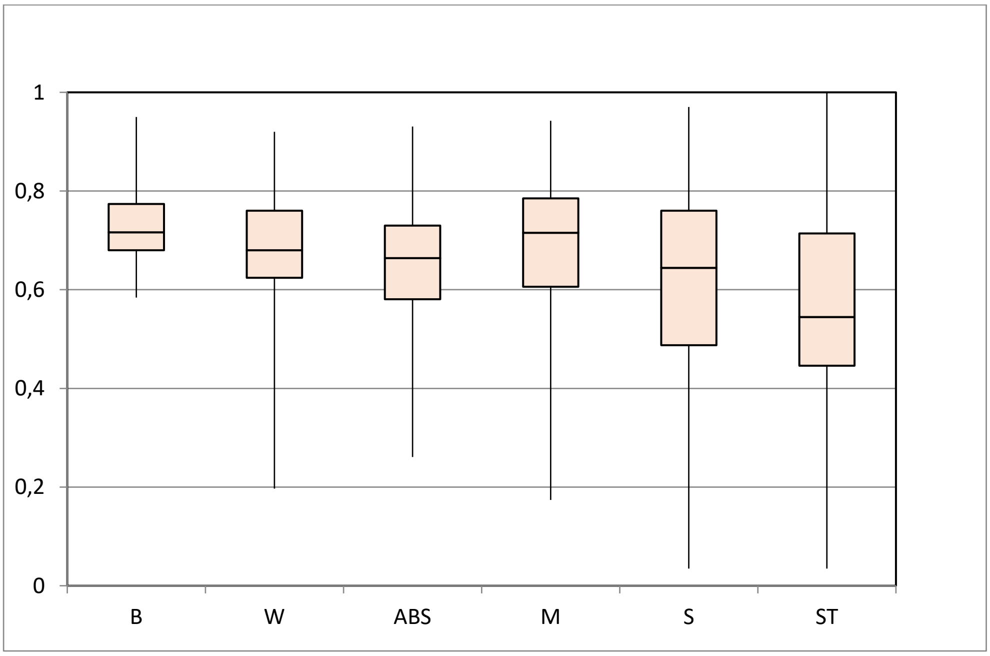


Figure 4.16
MQI values distribution among channel morphologies for unconfined reaches in alluvial plain setting (Group 3)

B=braiding; W= wandering; ABS=sinuous with alternate bars; M=meandering; S=sinuous; ST=straight

The analysis shows that the median values tend to decrease from the highest value for braided morphology, (median = 0.78) to the lowest value for straight morphologies (median =0.59) (figure 4.16).

A similar trend is detected in the case of unconfined reaches in alluvial plains, with lower values of medians respectively (0.72 for braided and 0.53 for straight morphologies) (figure 4.17).

In an analogous manner, in the case of confined reaches in mountainous-hilly areas (Group 1), the distribution of MQI values seems to vary significantly among different channel-bed configurations, as resulted from Kruskal-Wallis H test ($p<0.001$).

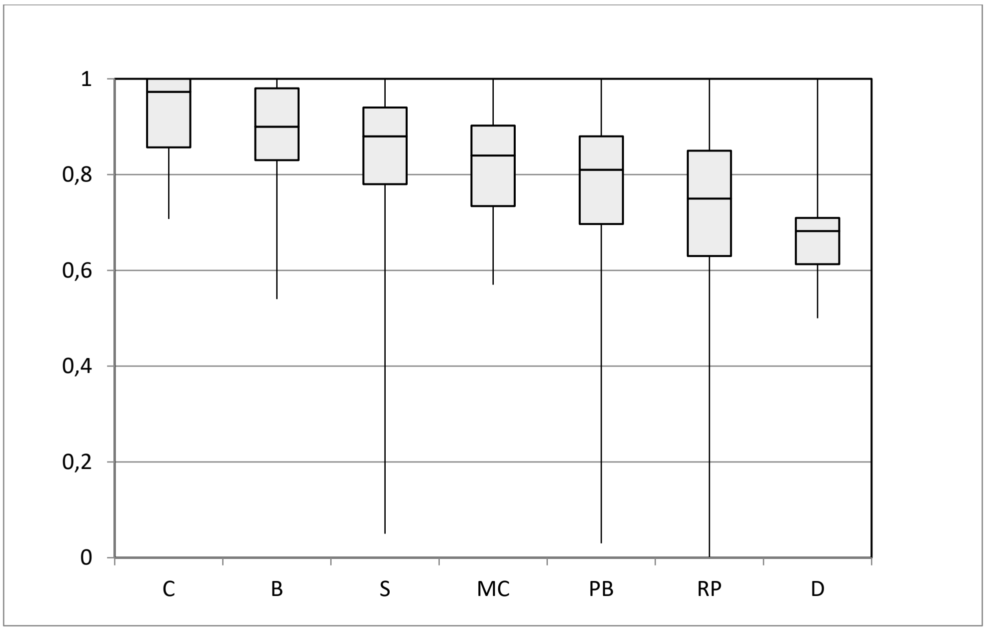


Figure 4.17
MQI values distribution along channel-bed configurations for confined reaches in mountainous setting (Group 1)

C=Colluvial; R=Bedrock; S=Stepped morphology (Cascade+Step-pool); MC= multiple channel; PB= plain bed; RP= riffle-pool; D= dune-ripples

High energy reaches, both colluvial and characterised by a stepped morphology (combination of cascade and step-pool geomorphic units), show the highest values for the MQI median (0.97 and 0.90 respectively) whereas the riffle-pool and dune-ripple morphological configurations exhibit the lowest median values (0.75 and 0.68 respectively) (figure 4.18).

4.3.2.2 Results of the analysis of MQI indicators

After analysing the overall results in terms of MQI, for the whole dataset and for the three different physiographic Groups, a second type of analysis was performed on MQI indicators, with the aim to evaluate how the scores distribute along the different indicators (for the three different physiographic Groups). This allows identifying the main alterations for each Group and the relation with the response of the overall index, which denotes the diagnostic capacity of the method.

For each physiographic Group, the percentage of occurrence of the classes for each single indicator was estimated (figures 4.19, 4.20, 4.21). Where indicators have more sub-classes of B and/or C, B1 and B2 have been merged into one single class B, and C1 and C2 in one class C.

The classes of MQI indicators show different trends across the three physiographic Groups.

The main alterations in Group 1, i.e. the confined reaches in mountainous settings (figure 4.19), are related to the presence of crossing structures and transversal barriers. In fact, artificiality is characterized by the lowest classes for indicators A5, related to the alterations induced by crossing structures (20% in class C; 49% in class B). Indicators A4 and A2, follow, scoring the presence and frequency of transversal barriers (e.g. dams, check dams, weirs), intercepting or altering bedload respectively along and upstream the reach (14% in class C; 32% in class B for A4; 8% in class C and 38% in class B for A2).

The side effects of those pressure seem to be well detected by the low scores of indicator F3, which measures the alteration of hillslope – river corridor connectivity (7% C; 46% B) and F1, regarding alteration of longitudinal connectivity (11% in C; 24% in B).

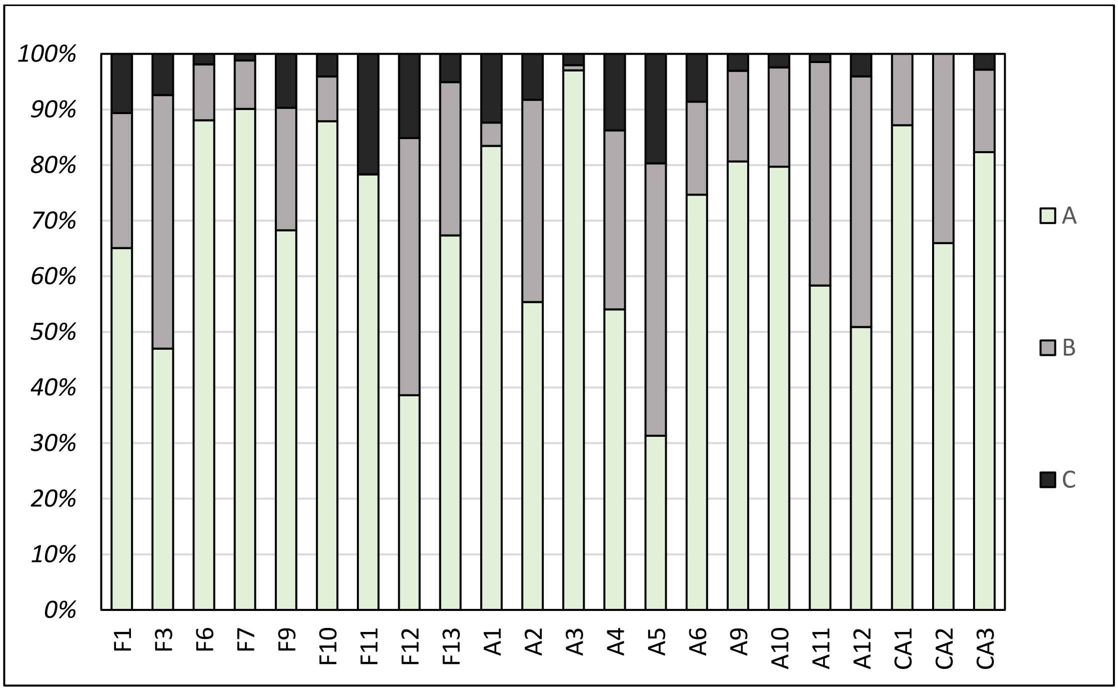


Figure 4.18 MQI scores across indicators for confined reaches (Group 1 – MH_C)

As expected, vegetation management (e.g. cuts, wood removal) along the river corridor is scored as significant by the relevant indicators A12, (45% B; 4% C) and A11 (44% B; 1% C) and also well detected in terms of reduction of the extent of functional riparian vegetation in the river corridor by indicator F12 (46% B; 15% C). Although not sufficiently wide, the vegetation is nevertheless continuous, as denoted by the increase of reaches in class A passing from F12 (39%) to F13, where the reaches in class A amount to 67%.

As the valley confinement decreases, more space is left for anthropization and river corridors are drastically deprived of their floodplain, not only due to its direct occupation for urbanization and economic production, but also for the indirect effects due to the increase of artificiality, also in the long term. Consistently, in partly-confined and unconfined reaches in mountainous settings (Group 2, figure 4.20) and, to a greater extent, in the alluvial plains (Group 3, figure 4.21) the major alteration is manifested by the drastic reduction in the presence of a modern floodplain. Thus, F2 is in class A in only 16% of the cases for group 2 down to only the 7% of the cases in group 3.

Crossing structures affect the majority of reaches in both groups 2 and 3, with minima for class A in the relevant indicator A5 (25% in group B and 28% in group C). Transversal barriers upstream are quite significant, with A2 in class A for 40% of the cases in group 2 and only the 33% of the reaches in group 3. Transversal barriers upstream of the analysed reaches, consistently reducing the bedload, together with the widespread presence of crossing structures, affect the overall dynamics, with visible effects in the lack of bank erosion, recorded by F4 low A scores, and the progressive reduction of heterogeneity both in the channel planform and section, respectively evidenced by indicators F7 and F9. F7 is in class A in 48% of the cases in group 2, but drops to only 35% in group 3. Accordingly, F9 is in class A for 46% of the cases in group 2, but only in 35% in group 3.

Wood and vegetation management are significantly practiced, especially for flood protection purposes, with similar values of the relevant indicators, A10 and A12, in group 2 (A10= 38%; A11=39%), dropping to comparable lower values in group 3 (A11=29%; A12=26%).
The effects of vegetation management are thus quite relevant, more on the lateral extent of the riparian vegetation than on its longitudinal continuity, as showed by the A scores of indicators F12 (28% and 23% for Group 2 and Group 3 respectively) and F13 (45% for Group 2 and 31% for Group 3). The effects on wood are also relevant, probably also due to the presence of transversal structures and to the low bank dynamics. Wood is thus generally absent for almost half of the cases in both groups.

At least half of the reaches experienced channel adjustments. Narrowing due to anthropic pressures is highly significant and detected by the class C for the indicator CA2, which amounts to 52% in group 2 and 42% in group 3, with only 31% and 36% of cases in class A respectively. Almost 40% of the reaches also experienced significant bed level adjustments, as scored by indicator CA3, which is in class A for 44% of the cases in group 2 and only for the 39% in group 3. Changes of planform pattern occurred in approximately half of the cases.

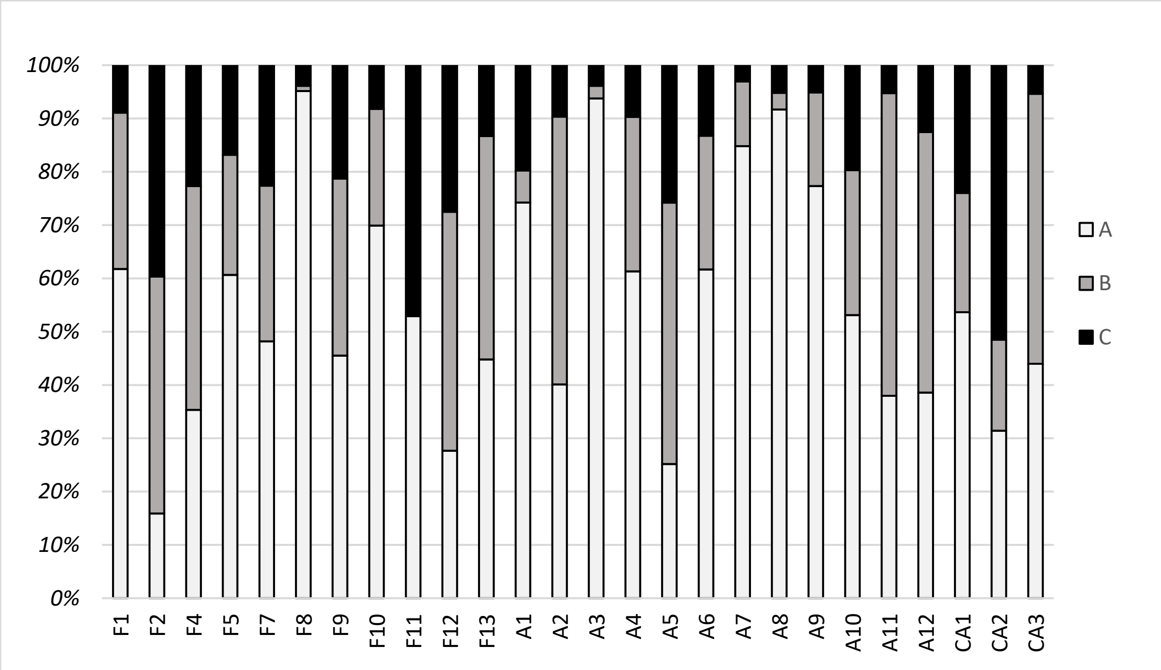


Figure 4.19 MQI scores across indicators for partly- confined /unconfined reaches in mountainous/hilly areas (Group 2)

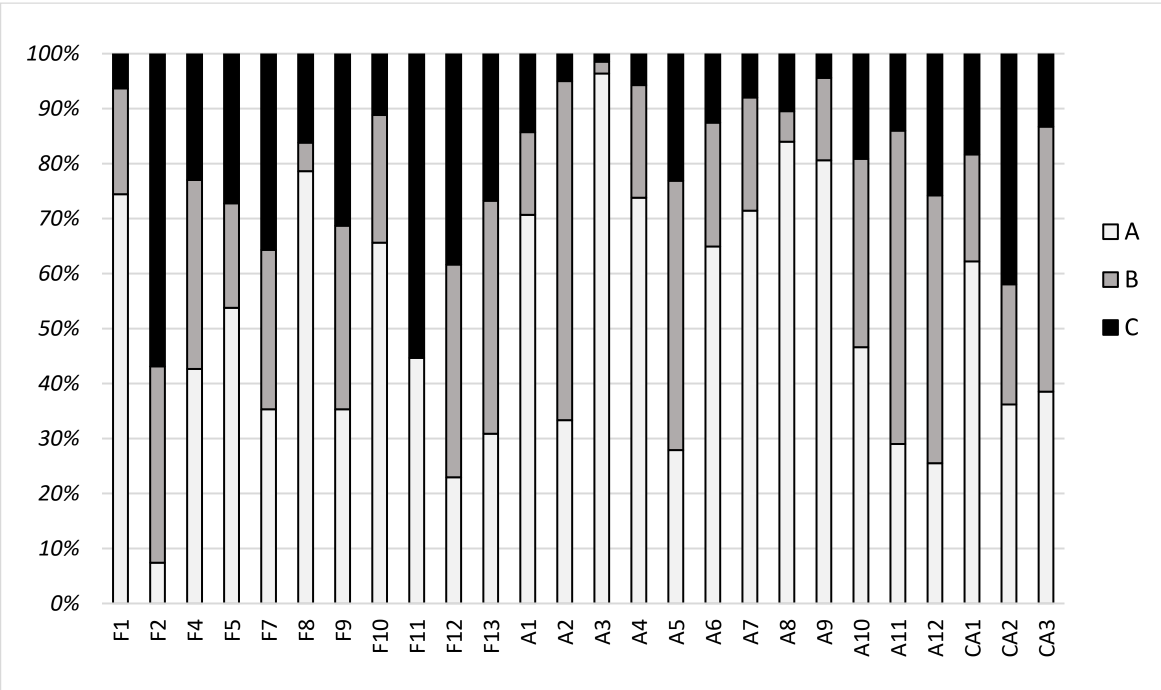


Figure 4.20 MQI scores across indicators for unconfined reaches in alluvial plains (Group 3)

In all the three physiographic groups, the indicators A1 and A3, related to the alteration of flow upstream and in the reach respectively, do not frequently score classes B and C, although hydrological pressures (water abstraction for different uses) are well acknowledged and reported as a major pressure on Italian rivers in all Italian river basin districts (Reporting WISE, 2016). This contradiction can be explained by the lack of information on water abstractions and river discharge data in a large part of river reaches. This may have induced the evaluators to overlook such a crucial aspect, neglecting that the MQI assessment procedure utilizes proxies (e.g. drainage areas upstream of the reach, watershed area, typology of flow regime and water use) in the case of data unavailability.

In any case, the MQI system is such, though, that the impact of significant water abstraction can also be detected by the presence and effects of the related activities (damming structures to fix water level, intakes, etc.) on sediment dynamics and can be scored by other indicators (e.g. F1).

As a conclusive analysis in this section, the three categories of indicators (functionality, artificiality, and channel adjustments) have been investigated separately as percentage ratios of the total score of each category's component to the possible maximum score for each category (figure 4.22).
From the results, a general trend can be noted, in terms of the progressive increase of the scores assigned to functionality, which double from the 24% in group 1 (MH_C) to 42% in group 3 (P_U). Artificiality is almost stable from group 1 to group 2 (19%) but increases to two thirds in group 3 (28%). Channel adjustments increase of more than the double from group 1 (14%) to the groups 2 and 3 (31%).
Within the three physiographic groups, the relative weight of the components F, A and CA varies. In group 1, functionality prevails and channel adjustment are the least relevant component (14%). In group 2, functionality also prevails (37%) but the relevance of channel adjustment (31%) increases and exceeds artificiality (19%). In group 3, dominated by functionality at 42%, artificiality and channel adjustments are equivalent.

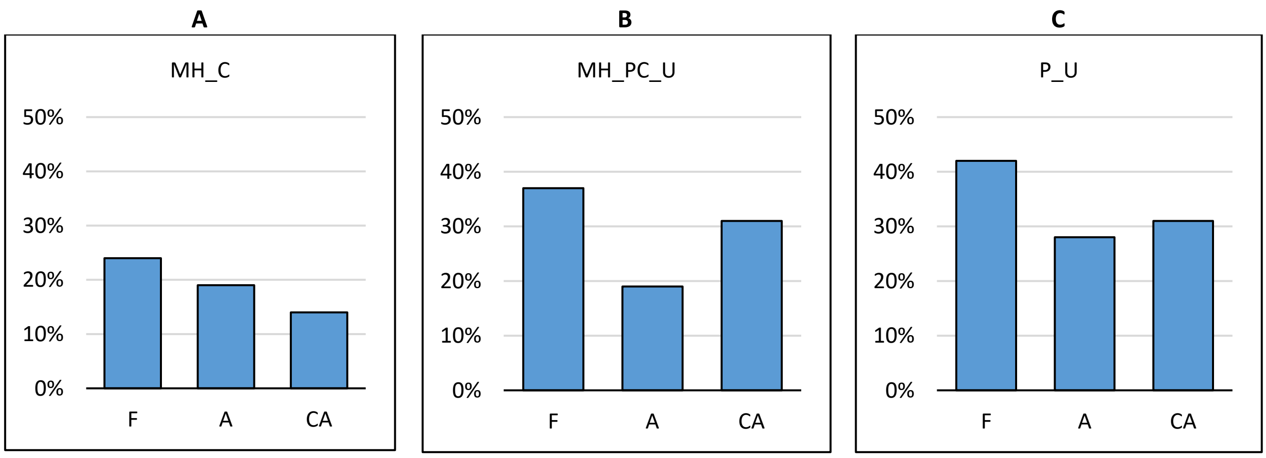


Figure 4.21 Distribution of the scores (average) of the three categories of indicators (functionality, artificiality, channel adjustments).

Percentage of the total possible score for each category, for each physiographic group (mountain/hilly confined, mountain/hilly partly confined/unconfined, alluvial plain unconfined).

4.3.2.3 *Results of the analysis of uncertainty*

This section reports the results of the analysis of uncertainty linked to confidence of operators, and the way it affects the MQI final values. To that aim, the scores related to the confidence expressed for each indicator (low, medium) and the consequent range of MQI values (minimum, maximum, average) have been systematized and analysed.

In general, for 2301 reaches out of the 4048 constituting the entire dataset, information on uncertainty is reported only relatedly to the range of variation for MQI final values. Such variations can be only negative (the value of MQI is underestimated – *MQI_value-*), only positive (the value of MQI is overestimated – *MQI_value+*) or both (i.e. the value of MQI is included in a confidence interval).

A first statistical analysis shows that although the values of MQI may be affected by slight variations, overall those variations do not cause a change in MQI classes except for the 6% of the sample, with 2% of the reaches overrated and 4% underrated (figure 4.23).

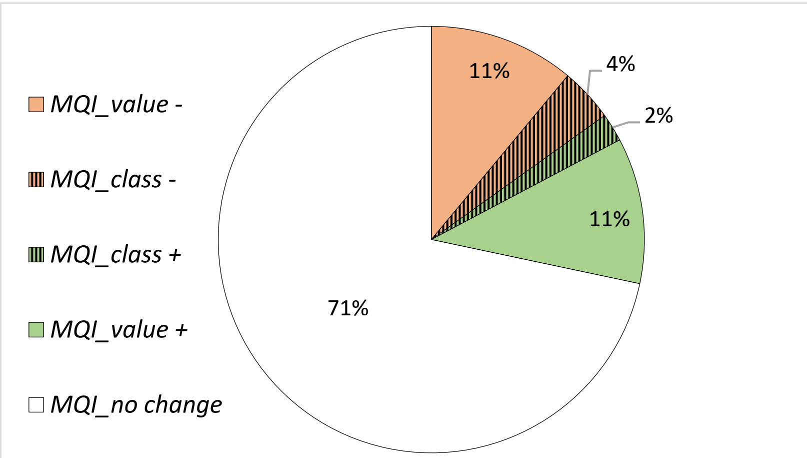


Figure 4.22 Change in MQI value/class in the preliminary subset (N=2300) induced by operator's confidence.

MQI_value-: MQI value is underestimated; MQI_class-: MQI value is undervalued into a lower MQI class; MQI_class+: MQI value is overvalued into an upper MQI class; MQI_value+: MQI value is overestimated; MQI_no change: MQI does not vary.

In order to investigate on the causes of variations in MQI values, information about the level of confidence related to each indicator is needed. As explained in paragraph 4.3.1, such information is reported only for 1608 reaches, since some regional agencies (Emilia-Romagna and Lombardy) directly compiled a proprietary database and only stored the range of variability related to MQI value, but did not store the uncertainty value per indicator.

Consequently, a detailed analysis of uncertainty was performed only on that complete sub-dataset (N_t = 1608 reaches).

The preliminary analysis performed on the complete sub-dataset of 1608 reaches, shows that the operator's level of confidence affects the estimation of MQI values in 28% of the sample, and confirms that only 6% of those variations in MQI values provoke a change in MQI class (figure 4.24).

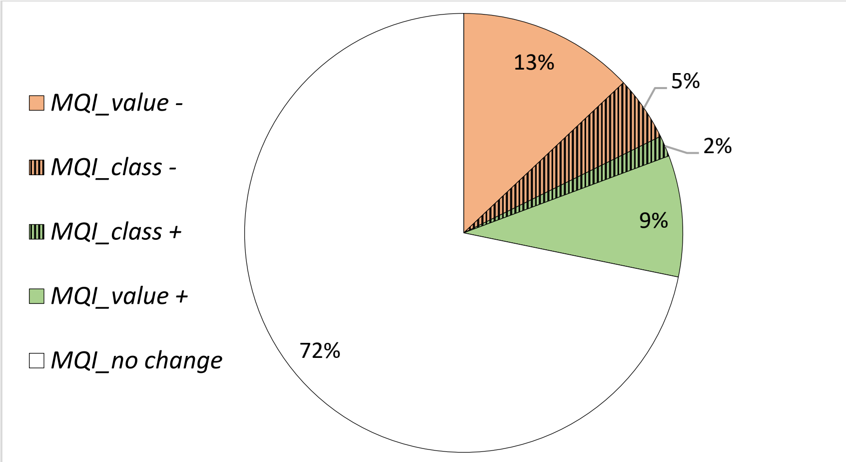


Figure 4.23 Change in MQI value/class in the total subset (N=1608) induced by operator's confidence

MQI_value-: MQI value is underestimated; MQI_class-: MQI value is undervalued into a lower MQI class; MQI_class+: MQI value is overvalued into an upper MQI class; MQI_value+: MQI value is overestimated; MQI_no change: MQI does not vary.

A second level of analysis regards the values of confidence for each indicator composing the MQI for the different "classes" of confinement envisaged by the method (confined, partly-confined and unconfined reaches), as they differ for the context and the number and type of indicators to be used.

Confidence levels related to the value of each indicator can be calculated through subtraction between contiguous classes and maximum and minimum confidence values can thus be evaluated.

The possible maximum occurrence of uncertainty for each reach equates the number of indicators envisaged for its confinement class (22 for confined; 26 for partly-confined and unconfined reaches). For the entire dataset, the maximum recourse to uncertainty (or the maximum possible number of confidence scores, which is the same) amounts to 39200 times. Overall, operators introduced medium to low confidence 936 times on the possible total amount of 39200. This means the uncertainty was introduced in the 2% of the cases. Although the percentaged introduction of uncertainty does not significantly differ between confinement categories, the distribution of uncertainty varies among indicators and in level (high to moderate, corresponding to low to moderate confidence), within categories and between categories (table 4.8).

Table 4.8 Recourse to confidence levels

	N	**Ni**	**N_{max}_j**	**N_j**	**N_j/N_{max}_j**
C (Confined reaches)	652	22	14344	305	2.1%
PC (Partly confined reaches)	522	26	13572	349	2.6%
UC (Unconfined reaches)	434	26	11284	282	2.5%
Nt (Total reaches in the dataset)	1608	22 - 26	39200	936	2.4%

Ni =Total number of indicators; N_{max_j} = maximum possible number of confidence scores; Nj = actual number of confidence scores; j=class of confinement (C, PC, U)

For each MQI indicator and confinement class, the *frequency of uncertainty*, which identifies which indicators are most affected by uncertainty, has been estimated, through the percentage of times confidence is used (Nc,j) with respect to the maximum possible number ($N_{max,C}$; N_{max_PC}; N_{max_U}), (Figures 4.25; 4.27; 4.29). The *magnitude of the uncertainty* can then be estimated, which discriminates those indicators that were scored with the lowest confidence values (corresponding to the highest uncertainty). This can be done through the analysis of the distribution of the values of uncertainty (max, min, average) (Nc,j) with respect to the actual total number of times confidence is used ($N\_j = N\_C$; N_{PC}; N_U) (figures 4.26, 4.28, 4.30). Trends between the two evaluations have then been compared.

In the case of confined reaches (figure 4.25), the highest frequency for uncertainty occurs for indicators A11, accounting for wood removal (83‰ of total uncertainty) and A12, recording the incidence of vegetation management actions (72‰), followed by F11 (58‰) related to the expected presence of in-channel large wood. The same percentage in occurrence (32‰) is found for F1 on continuity in sediment and wood flux, A10 scoring sediment removal and F10 related to the possible alteration in the structure of the channel bed.

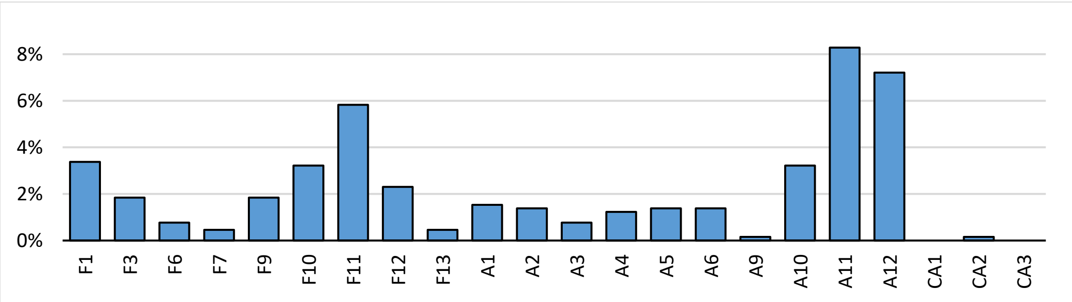


Figure 4.24 Frequency of uncertainty per MQI indicator for confined reaches.

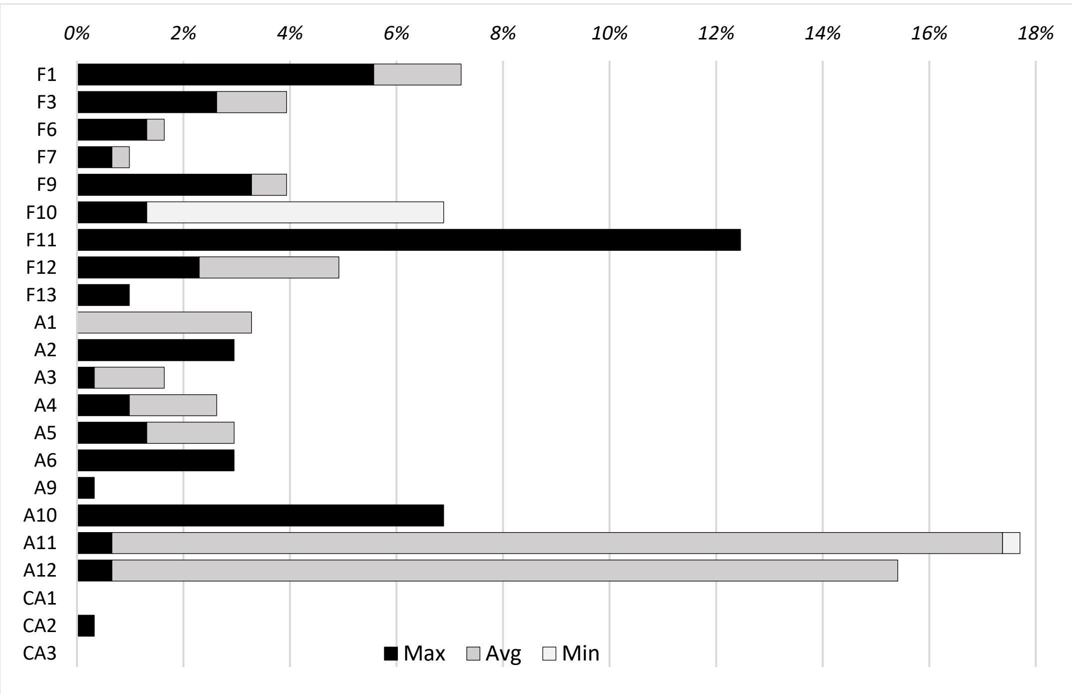


Figure 4.25 Magnitude of uncertainty per MQI indicator for confined reaches

When considering the value of the uncertainty (figure 4.27), the highest values are differently distributed. F11 (12%) has the highest uncertainty values, followed by A10 (7%), F1 (1%) and F9 (variability of cross-section), A2 (upstream alteration of sediment discharges), A6 (bank protections), F3 (alteration of flow in the reach) at 3%. (Figure 3.22)

Similarly to confined reaches, in the partly confined ones (figure 4.27), the highest frequency in uncertainty occurs for A11 (69‰) and A12 (58‰), followed by F10 (54‰). The recourse to uncertainty in hydrological alteration is quite significant (A1= 46‰) as well as sediment mining (A10 = 44‰) and bed-level adjustments (CA3 = 40‰). The maxima for uncertainty are differently distributed, with maxima for A10 (7%), CA3 and F11 (both 6%) and F7 (3%), with F1, A2 and F2 in the same class (figure 4.28).

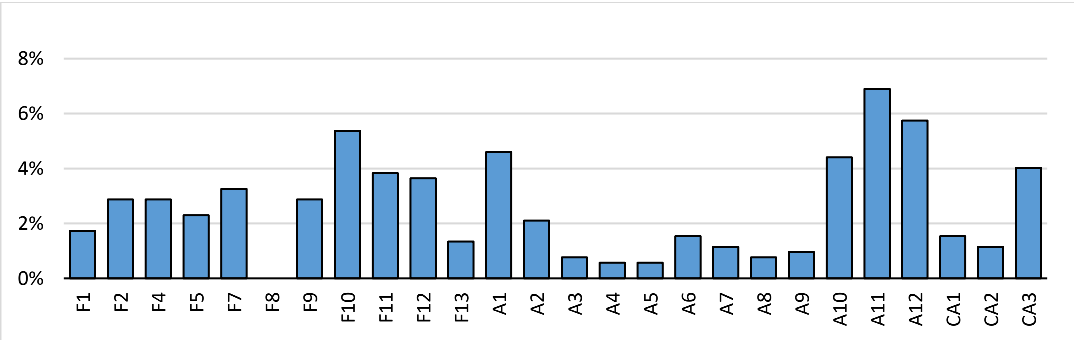


Figure 4.26 Frequency of uncertainty per MQI indicator for partly-confined reaches.

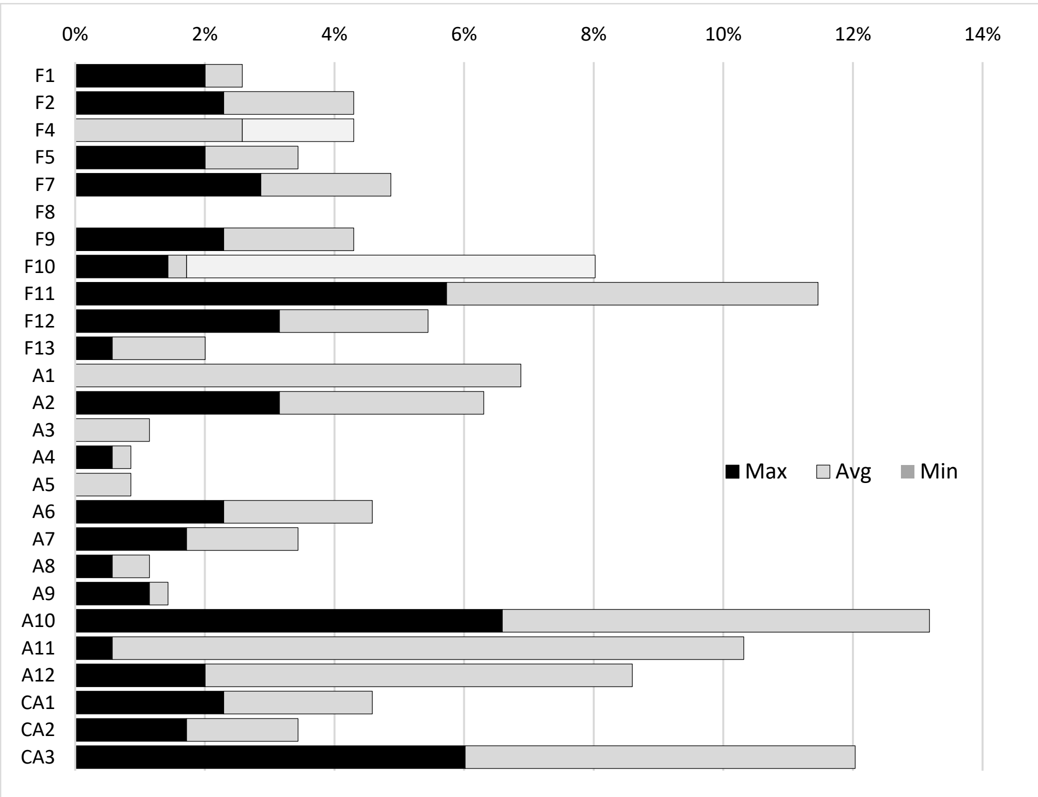


Figure 4.27 Magnitude of uncertainty per MQI indicator for partly-confined reaches.

The distribution of uncertainty in unconfined reaches (4.29) follows the same pattern as for the partly confined, with slightly different percentaged values. The highest frequency in uncertainty occurs for A11 (85‰) and A12 (83‰), followed by A10 (64‰). The uncertainty in the expected presence of in-channel wood is quite relevant (F10=55‰) as well as in hydrological alteration (A1= 41‰). Low confidence in the appraisal of bed-level adjustments remains, with CA3 amounting to 37‰.

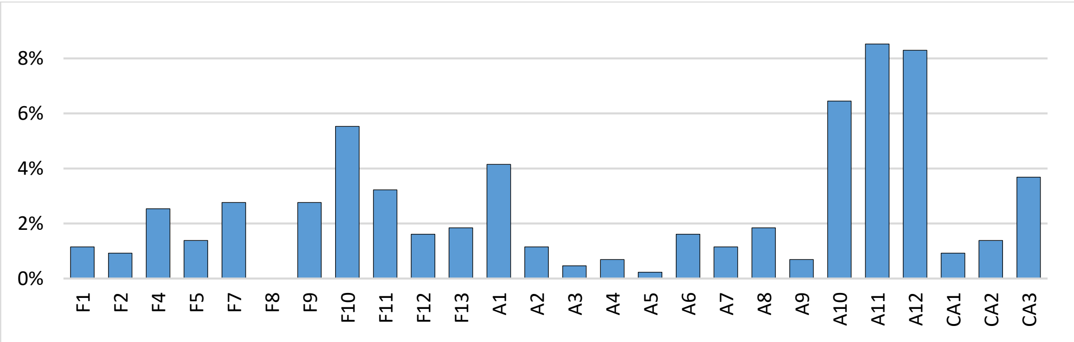


Figure 4.28 Frequency of uncertainty per MQI indicator for unconfined reaches.

A different distribution occurs in the values of uncertainty, which are maximum for indicator A10 (10%), followed by CA3 (6%) and F11 (5%).

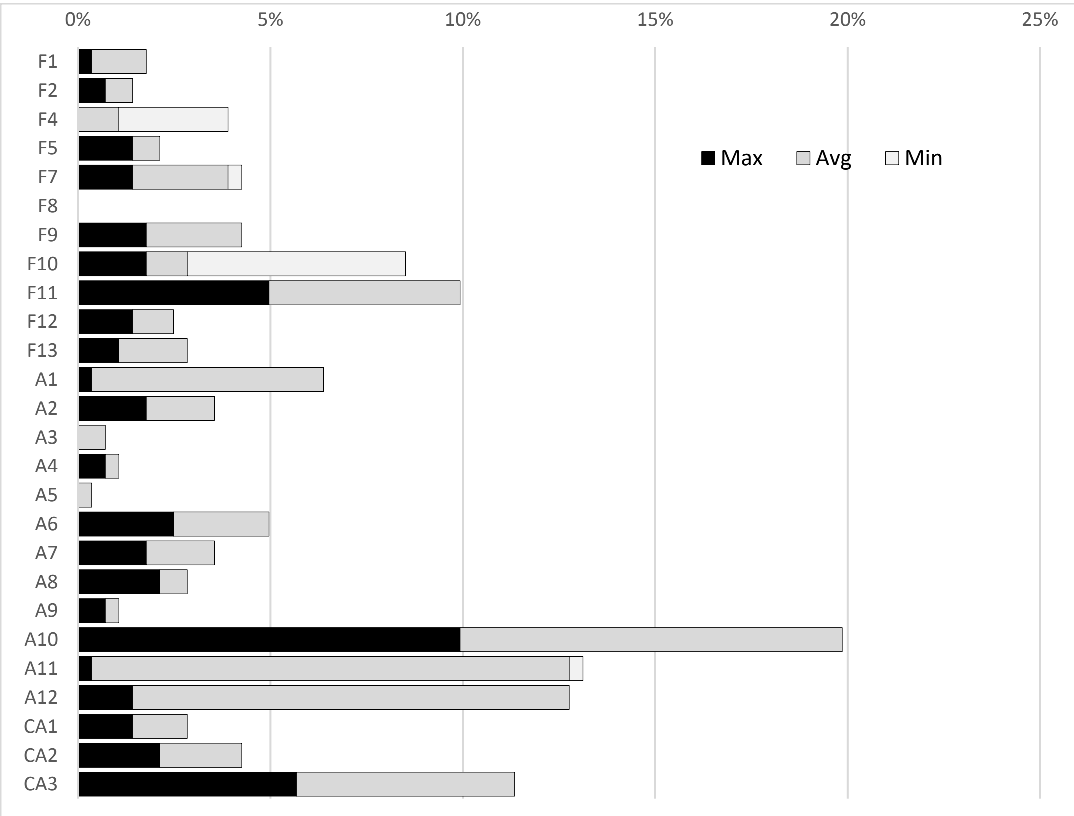


Figure 4.29 Magnitude of uncertainty per MQI indicator for unconfined reaches

Last, for each MQI category of indicators (functionality, artificiality, and channel adjustments), for each confinement group, the frequency of uncertainty has been evaluated, as percentage ratio of the total number of times confidence was used to the possible maximum possible for that category (figure 4.31).

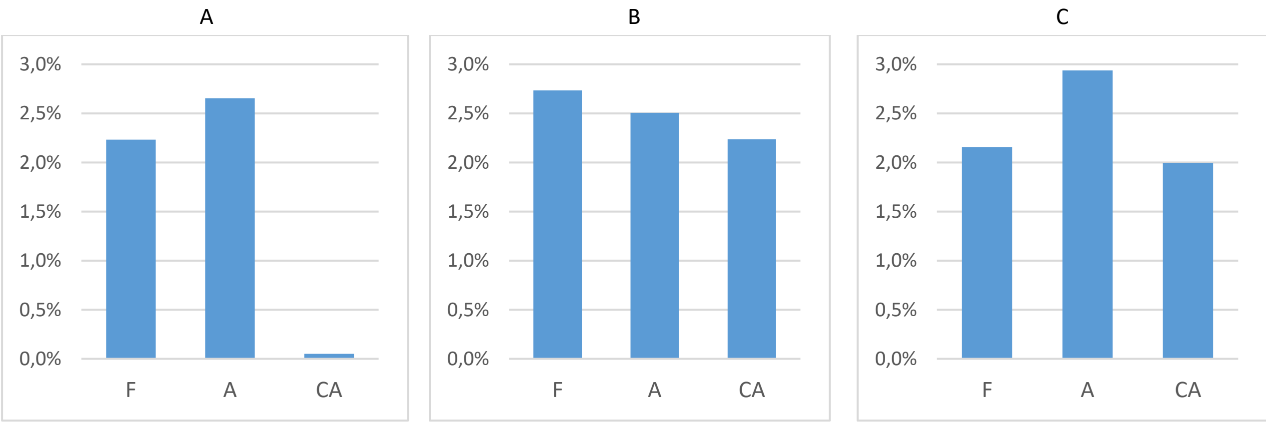


Figure 4.30 Total frequency per category of MQI indicators (F=functionality; A=artificiality; CA=channel adjustments) for each confinement class. A) confined reaches; B) partly-confined; C) unconfined.

The recourse to uncertainty for the components F, A and CA varies within the three physiographic groups. In groups 1 and 3, the level of confidence in artificiality is lower than that in functionality, whereas this is inverted in group 2, where confidence is low also in channel adjustments although a bit less than artificiality. In group 3, the level of confidence in channel adjustments is comparable to that in functionality.

4.3.2.4 Results of the multivariate statistical analysis

This section reports the results of the multivariate analyses (PRINCALS; Kendall tau; see par. 4.3.1) aimed to analyse the relations between indicators, and among indicators and MQI.

Both the statistical techniques that have been used are quite sensitive to indicators with high frequency of no data (equivalent to missing data problems). This happens in the case of those indicators that are populated only for certain river types or those which cannot be populated due to unsuitable conditions for their assessment. The first case occurs mostly for indicator F7 in the confined reaches, as it is only used for multiple channel streams, when it is possible to observe the geomorphic units; and for indicator F8, which applies to reaches of meandering rivers within a lowland plain physiographic unit (unconfined/partly- confined reaches). The second case occurs in the case of indicators of channel adjustments, chiefly in confined reaches quite difficult to assess for several reasons not the least their general contained width. This also applies, to a smaller extent, to the other confinement classes.

In order to perform a robust multivariate analysis, the dataset has thus been reduced to subsets of reaches for which all indicators have been assessed.

For confined reaches, the indicators F7 and CA1, CA2, CA3 have not been included in the analysis.

For partly confined and unconfined reaches, indicator F8 has been excluded by the analysis, which has been performed both considering the indicators of channel adjustment and excluding them.

The reduced dataset amounts to 2099 reaches, subdivided in 925 confined reaches, 821 partly confined and 353 unconfined. Although the presence of no data could represent a limit on the performance of multivariate statistical analysis, the number of reaches, even after the reduction of the initial dataset, is still high and fully representative.

The PRINCALS was applied starting from the confined reaches. The scree plot, graphing the eigenvalues in decreasing order on the y-axis, and the number of PCs on the x-axis, does not evidence a sharp change in the proximity of the first components, but suggests considering at least six components due to the way the slope levels off (figure 4.32). This is also confirmed by the variance accounted for (VAF) by the first six components. In fact, the first three components only account for the 45% of the total variance, not sufficient to explain the relations between indicators and their variances. Even six components do not account but for the 67% of the total variance (table 4.8), which is still not sufficient.

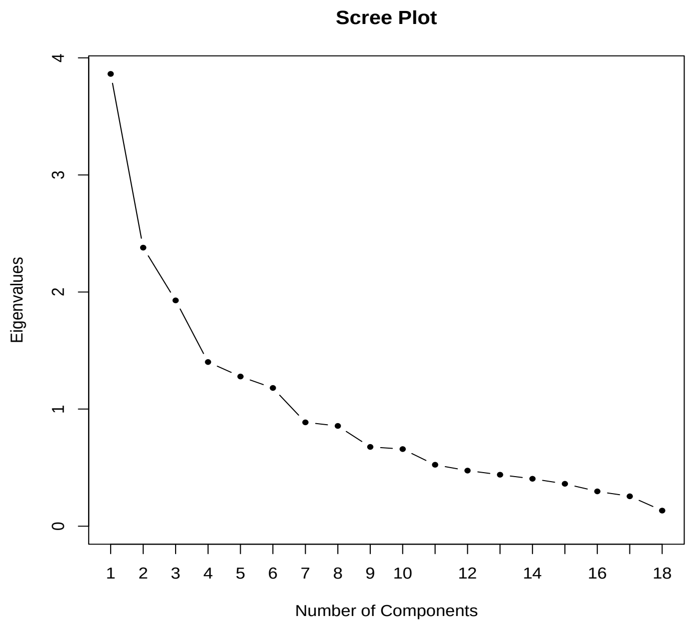


Figure 4.31 Scree plot in the case of confined reaches.

Table 4.9. Variance accounted for (VAF) for the first six principal components in the case of confined reaches.

	Comp1	*Comp2*	*Comp3*	*Comp4*	*Comp5*	*Comp6*
Eigenvalues	3.8628	2.3793	1.9281	1.4019	1.2782	1.1805
VAF	21.46	13.2183	10.7117	7.7884	7.1009	6.5585
Cumulative VAF	21.46	34.6783	45.39	53.1784	60.2793	66.8378

It needs more than six components to characterize the total information (Table 4.9), in contrasts with the aim of the analysis, which is to find a smaller number of new variables that explain the maximum amount of variability in the data.

Moreover, the loadings values of the first six components are not close to - 1 or 1 and this impedes the identification of the variables characterizing the new components (Table 4.10).

Table 4.10 PRINCALS for confined reaches. Loadings for the first six components.

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
F1	-0.523	0.511	0.267	-0.16	-0.114	0.137
F3	-0.605	-0.415			-0.222	
F9	-0.611	-0.224			0.231	-0.447
F12	-0.556	-0.249		0.384	0.393	0.251
A6	-0.676	-0.264		0.112		-0.439
A2	-0.44	0.559	0.299	-0.383	0.122	0.115
A12	-0.493	-0.521		-0.158	-0.216	0.257
F6	-0.252	0.393	-0.791	-0.142		
F10	-0.22	0.217	-0.693	-0.258	0.446	-0.104
F11	-0.386	-0.151	-0.164		0.111	0.432
F13	-0.352	-0.267	-0.156	0.19	0.404	0.355
A1	-0.486	0.243	0.359	-0.412	0.29	
A3	-0.367	0.482	0.372			0.195
A4	-0.483	0.457	-0.331	0.302	-0.426	
A5	-0.467	0.119	0.31	0.367		-0.293
A9	-0.494	0.249	-0.266	0.378	-0.377	
A10	-0.218	-0.385		-0.403	-0.277	-0.274
A11	-0.385	-0.399	-0.21	-0.452	-0.273	0.305

In the case of partly confined and unconfined reaches, variable F8 was eliminated and the PRINCALS analysis was performed both excluding (case A) and including (case B) the indicators of channel adjustment (CA).

The analysis results similar to the confined reaches. In case A, although the scree-plot seems to indicate a drastic drop in slope in proximity of the second component (figure 4.33.A; table 4.11), the first two components can only explain the 33% of the total variance. Increasing the number of components to six, the variance explained is still insufficient (57.8%). The same conclusion is valid for case B (figure 4.33.B; table 4.12).

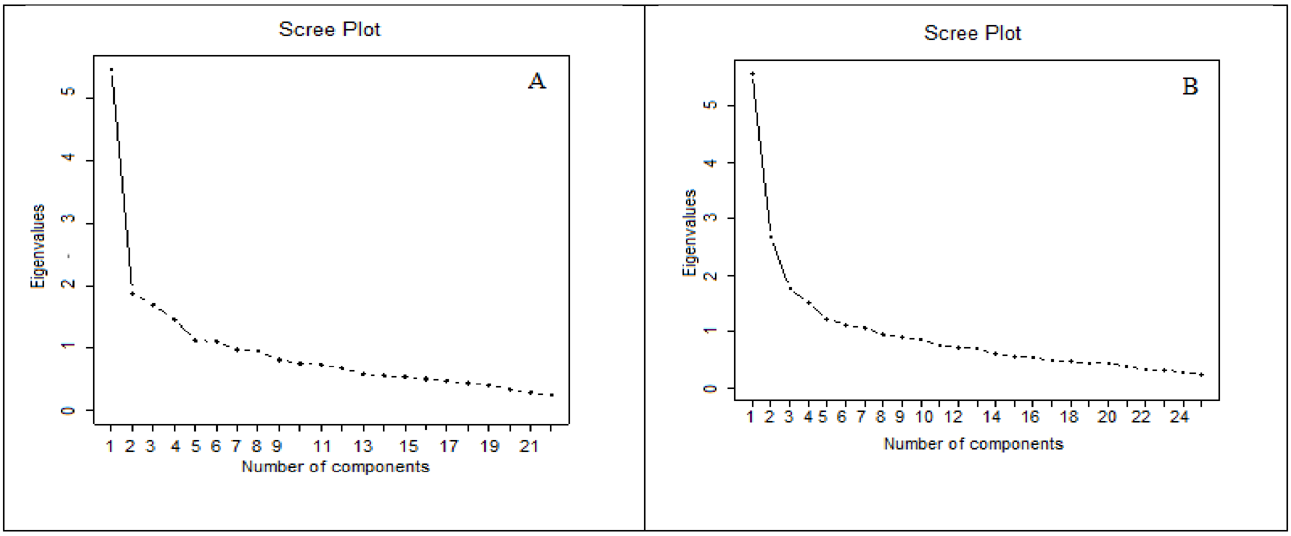


Figure 4.32 Scree plot in the case of partly- confined reaches, excluding (A) and including (B) indicators of channel adjustments.

Table 4.11 PRINCALS for partly-confined reaches (excluding CA indicators). Eigenvalues and VAF for the first six components.

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
Eigenvalues	5.461	1.8769	1.6921	1.4602	1.1224	1.1037
VAF	24.8225	8.5315	7.6915	6.6371	5.1019	5.0169
Cumulative VAF	24.82	33.35	41.05	47.68	52.78	57.8

Table 4.12 PRINCALS for partly-confined reaches (including CA indicators). Eigenvalues and VAF for the first six components.

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
Eigenvalues	5.5645	2.6651	1.7715	1.5153	1.2238	1.1272
VAF	22.258	10.6605	7.086	6.0614	4.8952	4.5088
Cumulative VAF	22.26	32.92	40	46.07	50.96	55.47

In the same way as in the confined reaches, in partly-confined reaches the loadings values are not close to -1 or 1, preventing the characterization of the new components (table 4.13)

Table 4.13 PRINCALS for partly-confined reaches. Loadings for the first six components. Left excluding CA; right: including CA.

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
F2	-0.513				0.155	0.331
F4	-0.688		0.154		0.123	0.197
F5	-0.728	-0.217	0.143	-0.143		0.107
F7	-0.59	0.31	-0.16	0.109	0.193	-0.289
F9	-0.685	0.273			0.128	-0.246
F12	-0.636	-0.192	-0.151	-0.194	-0.232	0.268
A6	-0.706	-0.195	0.215	-0.132		
A11	-0.552	-0.282	-0.295		-0.31	-0.267
A12	-0.618	-0.28			-0.114	
F10	-0.302	0.674		-0.189		
A2	-0.131	0.742	0.237	-0.268	-0.128	
F11	-0.348		-0.511	0.117		
A1	-0.335	0.25	0.649		-0.313	
A3	-0.128		0.377	0.595	-0.443	
A4	-0.343	0.163	-0.286	0.563		
F1	-0.367	0.411		0.311	0.139	0.415
F13	-0.489	-0.109	-0.384	-0.142	-0.22	0.406
A5	-0.463	-0.194	0.117	0.48		
A7	-0.492	-0.147	0.355	-0.426	0.135	
A8	-0.31		-0.211		0.217	-0.344
A9	-0.495	-0.203	0.239	0.109	0.376	-0.279
A10	-0.375	0.189	-0.342	-0.145	-0.496	-0.32

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
F2	-0.515				-0.182	0.242
F4	-0.68					0.234
F5	-0.731	0.22		0.172		
F7	-0.584	-0.269		-0.161	0.293	
F9	-0.685	-0.178	0.185		0.177	
F12	-0.629		-0.254	0.254	-0.138	-0.102
A6	-0.707	0.255		0.119		
A7	-0.504	0.268	0.155	0.391		0.226
A11	-0.56		-0.328		-0.173	-0.413
A12	-0.613	0.156	-0.169		-0.256	
CA1		-0.772				
CA2	0.164	-0.718		-0.168	-0.161	0.12
CA3		-0.61		0.1	-0.49	0.151
A1	-0.327	0.195	0.662		-0.135	-0.377
A2	-0.121	-0.366	0.704	0.231		-0.118
A3	-0.144	0.223	0.272	-0.547	-0.334	-0.382
A4	-0.329	-0.301	-0.165	-0.567		
A8	-0.293		-0.133		0.555	-0.277
F1	-0.488		0.155	-0.353		0.258
F10	-0.318	-0.472	0.419	0.173	0.193	
F11	-0.348	-0.18	-0.283	-0.105	0.37	-0.154
F13	-0.494	-0.174	-0.37	0.169		

Analogous conclusions can be derived in the case of unconfined reaches. The percentage of variance explained by the first six components, in both cases A and B, is still insufficient (58% in case A and 59% in case B) to account for the total variance (table 4.14 and 4.15 respectively; figure 4.34).
The loadings never equalize or exceeds the values -1 or 1 (table 4.16) and this again restrains the possibility to explain the new components.

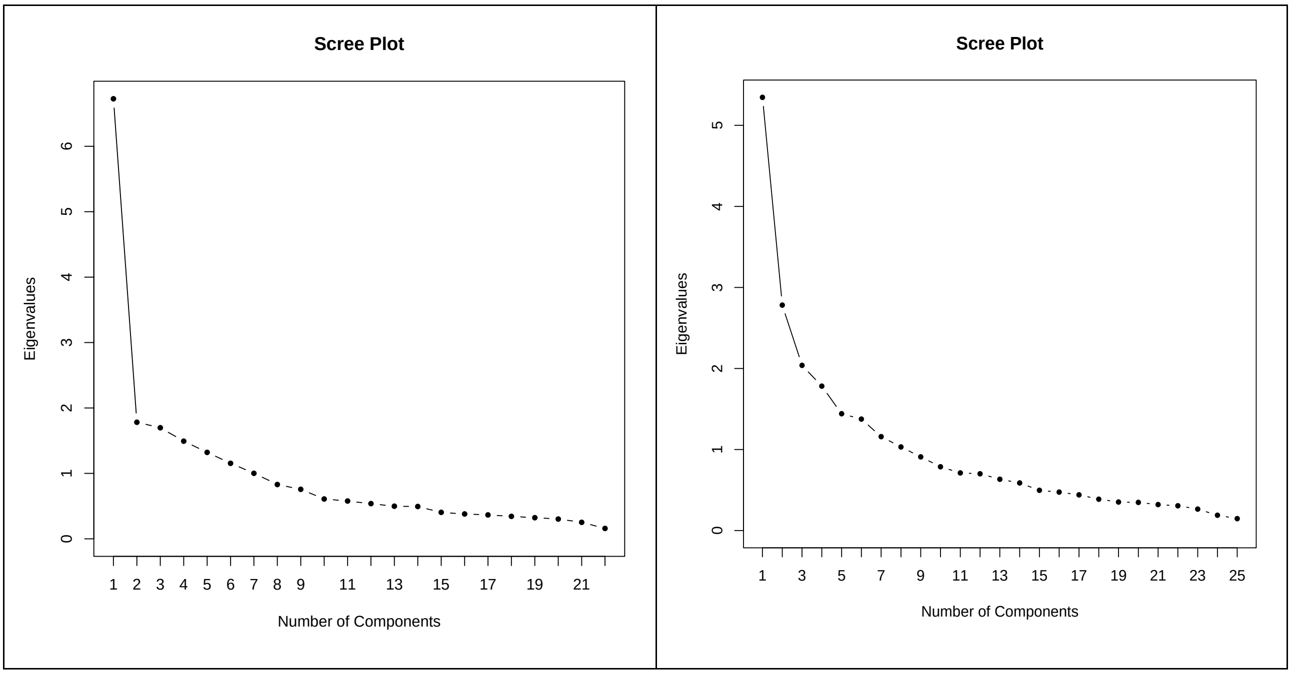


Figure 4.33 Scree plot in the case of unconfined reaches. Left: excluding channel adjustment indicators. Right: including channel adjustments indicators).

Table 4.14 PRINCALS for unconfined reaches. Eigenvalues and VAF for the first six components (without CA indicators)

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
Eigenvalues	5.4610	1.8769	1.6921	1.4602	1.1224	1.1037
VAF	24.8225	8.5315	7.6915	6.6371	5.1019	5.0169
Cumulative VAF	24.8200	33.3500	41.0500	47.6800	52.7800	57.8000

Table 4.15 PRINCALS for unconfined reaches. Eigenvalues and VAF for the first six components (with CA indicators)

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
Eigenvalues	5.3453	2.7821	2.0382	1.7818	1.4410	1.3755
VAF	21.3813	11.1285	8.1529	7.1272	5.7640	5.5018
Cumulative VAF	21.3800	32.5100	40.6600	47.7900	53.5500	59.0600

Table 4.16 PRINCALS unconfined reaches. Loadings for the first six components. Left excluding CA. Right: including CA.

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
F2	-0.593	0.145	-0.136		-0.21	0.108
F4	-0.78			0.103	-0.187	
F5	-0.762	0.22	-0.115		0.144	-0.187
F7	-0.81	-0.156		0.141	-0.155	-0.217
F9	-0.82			0.127		-0.257
F11	-0.515	-0.147	-0.11	0.289	-0.34	0.304
F13	-0.64	0.193		-0.396		0.223
A5	-0.634	-0.294	-0.198	0.163	0.195	
A6	-0.684	0.173		-0.124	0.251	-0.108
A9	-0.564	-0.397	-0.118		0.252	0.219
A11	-0.693			0.141	0.34	0.183
A12	-0.715	0.156		-0.132	-0.169	0.259
F10	-0.327	-0.639	0.135	-0.222	0.162	0.185
F1	-0.338	-0.385	0.547		-0.164	-0.163
A1		0.402	0.584	0.42	0.267	0.238
A2		0.194	0.791		-0.147	0.283
F12	-0.505	0.219		-0.573		0.165
A3	-0.163		-0.104	0.511	0.423	0.118
A10	-0.101	0.11	0.334	-0.498	0.526	-0.242
A4	-0.203	-0.452	0.424		-0.187	-0.413
A7	-0.499	0.494			-0.272	-0.322
A8	-0.446	0.202		0.217	0.219	-0.331

	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
F2	-0.521		0.106	0.273	-0.246	0.322
F4	-0.665				0.159	0.194
F5	-0.641	0.255		0.298	-0.106	-0.2
F7	-0.688	-0.38	-0.2		-0.227	
F9	-0.703	-0.341	-0.189		-0.239	-0.171
A5	-0.577	-0.137	-0.229	-0.42		-0.133
A6	-0.728	0.338	-0.176		0.144	-0.149
A7	-0.55	0.353		0.281	-0.162	-0.307
A9	-0.552	0.204	-0.229	-0.272	0.26	-0.21
A11	-0.644		-0.184	-0.369	0.229	
A12	-0.639	0.182	0.239		0.23	0.151
F1	-0.333	-0.57		0.131	-0.231	
F10	-0.172	-0.609	0.209			0.259
A4	-0.248	-0.565			-0.416	
CA1	0.148	-0.63	0.161	-0.247	0.3	-0.323
CA2	0.16	-0.519	0.11	-0.156	0.373	-0.298
F12	-0.379	0.205	0.627		0.183	0.169
A1		-0.13	-0.462	0.594	0.329	
A2	0.1	-0.447	-0.249	0.522	0.448	
F11	-0.307	-0.127	-0.278	-0.375	0.122	0.561
F13	-0.497		0.416	0.107	0.373	
A3	-0.171	-0.149	-0.139			0.228
A8			-0.487	0.241	0.196	0.358
A10	-0.302	-0.132	0.443	0.363		-0.292
CA3	-0.294	-0.333	0.5	0.229		0.271

It can be concluded that the total amount of variance of MQI cannot be accounted for by a smaller set of variables than the original MQI indicators.

No indicator or combination of indicators seems to be more skilled in explicating the distribution of variance. It is therefore not possible to find a smaller manageable set of new variables to account for the total amount of variance of MQI.

In order to investigate the existence and entity of correlation within indicators and with MQI, the Kendall tau statistic was used.
The results, in terms of correlation plots, for the different cases already examined with the PRINCALS, are reported below.

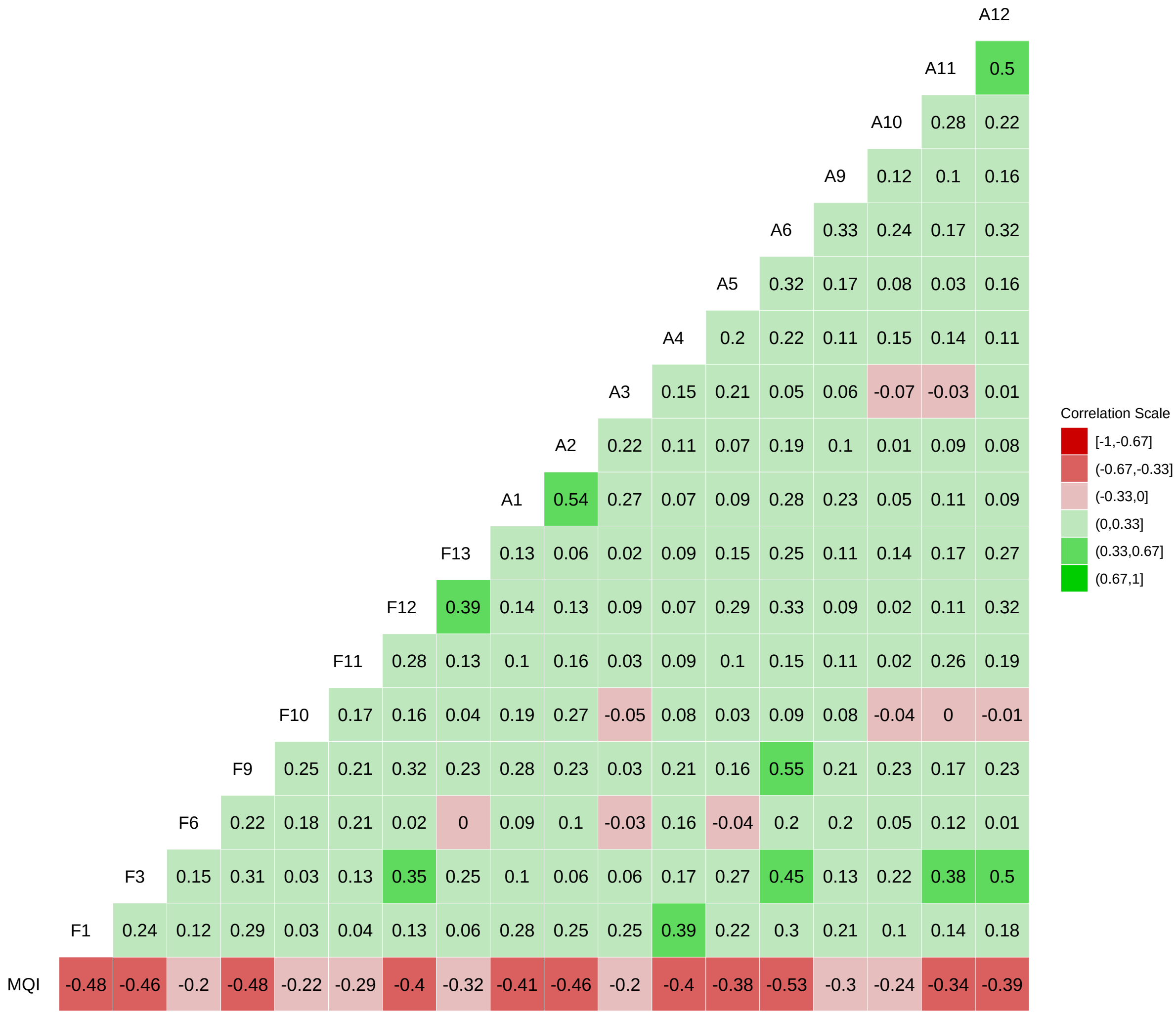


Figure 4.34 Correlation plot (Kendall tau) for MQI indicators in confined reaches (case A only)

Figure 4.35 reports the ordinal association between the MQI indicators in confined reaches.

Although correlation coefficients differ in value and sign, no correlation is high enough to evidence a strong association.

Instead, only a weak association emerges between indicators and between MQI index and indicators.

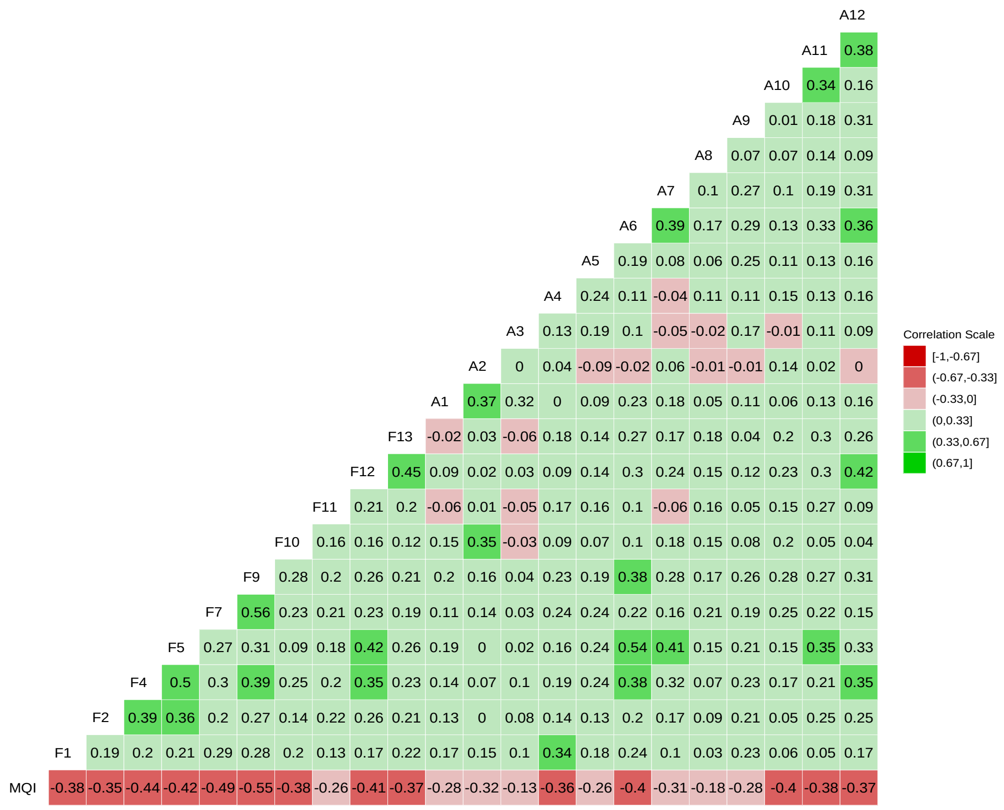


Figure 4.35 Correlation plot (Kendall tau) for MQI indicators in partly confined reaches. Case A

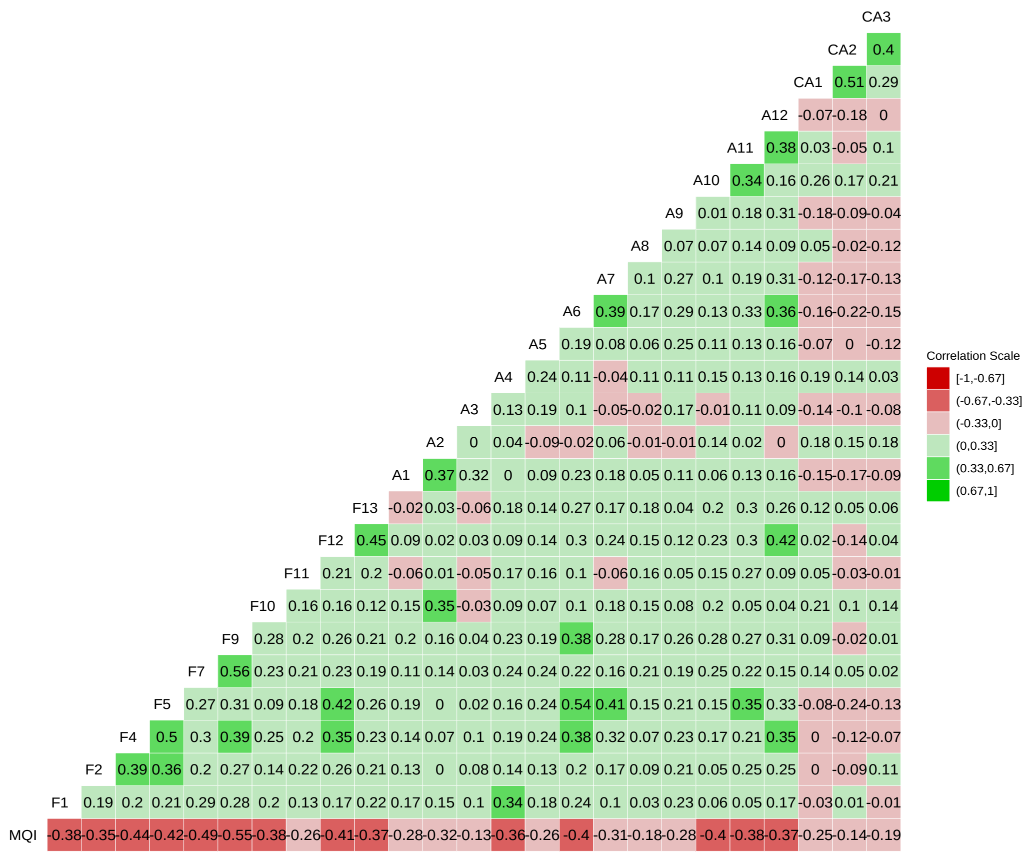


Figure 4.36 Correlation plot (Kendall tau) for MQI indicators in partly confined reaches. Case B

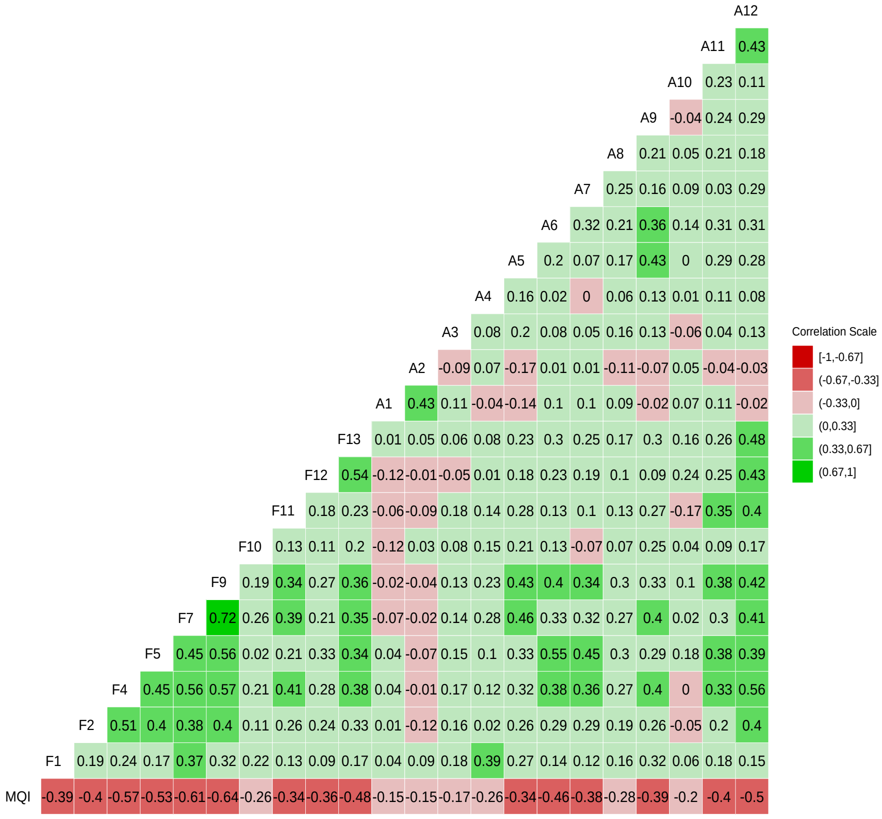


Figure 4.37 Correlation plot (Kendall tau) for MQI indicators in unconfined reaches. Case A

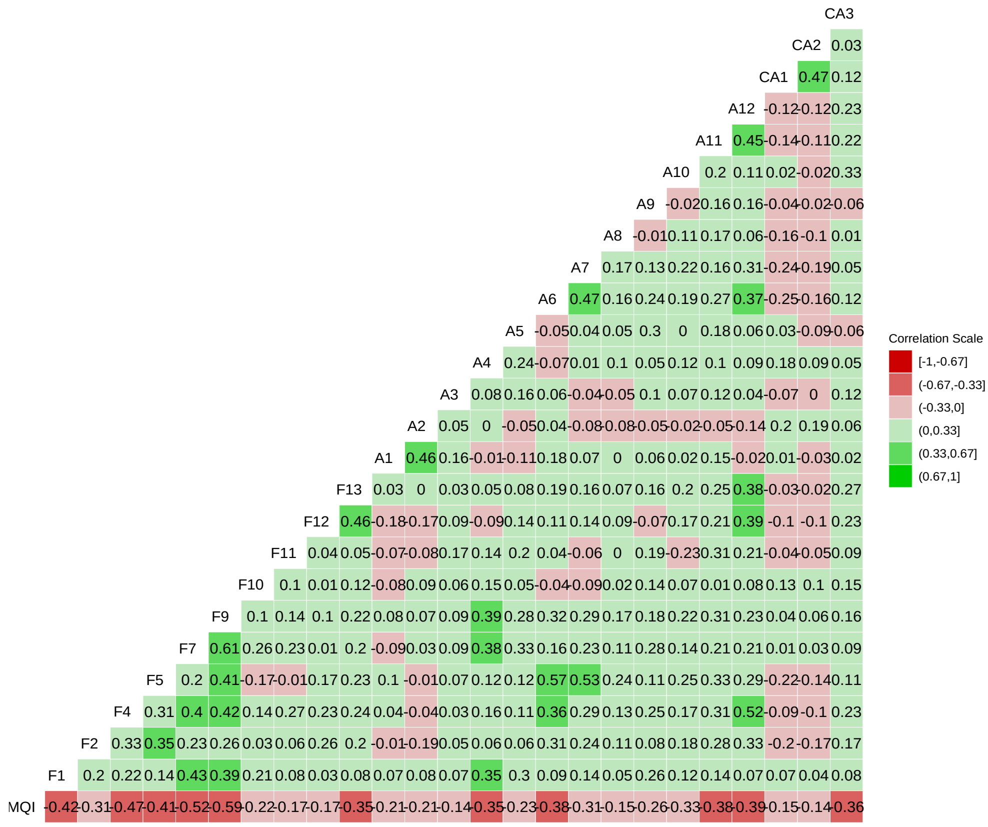


Figure 4.38 Correlation plot (Kendall tau) for MQI indicators in unconfined reaches. Case B

It is possible to extend the correlation results obtained for confined reaches also to partly confined and unconfined reaches, in the sense that the indicators are all relevant and each accounts for a particular aspect of hydromorphological quality, with no redundancy. (The association of F7 and F9 could represent the only exception in unconfined reaches, but it is not strong enough to evidence dependence between the two variables).

4.3.3 Discussion

In accordance with the analysis, the discussion has been structured to address the overall results and their implication for river management and for MQI enhancement. In particular, the implication of the outcomes of the analysis of uncertainty for MQI enhancement have been investigated.

4.3.3.1 Discussion of the overall results

Overall, the analysis showed that almost 60% of the national dataset is at least in good status, with a quarter of the entire dataset in high status conditions. The dataset is, to a limited extent, partly biased by the fact that the main driver of MQI assessment, in the first sexennium, was the corroboration of high biological status in a large part of the territory (par. 4.2.3). Nevertheless, the dataset progressively increased in size and included all gradients of pressures and river types, allowing a robust analysis of the MQI method and reliable estimations of the trends of MQI distribution across physiographic settings and river morphologies.

The distribution of MQI significantly differs along the three physical groups (mountainous/hilly confined reaches – MH_C; mountainous/hilly partly-confined and unconfined reaches – MH_PC_U; alluvial plains unconfined reaches – P_U).

Not surprisingly, the lowest classes for MQI belong to the unconfined reaches of the alluvial plains, which are highly populated, and where rivers have been severely engineered to allow urbanization and economic activities.

On the opposite, the highest scores for MQI are observed in the confined reaches situated in mountainous areas in the Alps and Apennines, where the density of population is lowest as well as the frequency of infrastructures. In this group, 46% of the reaches are in high status, possibly due to their upper location in the catchment, often draining very small catchment with negligible pressures, given the scarce human presence.

When relating MQI to channel morphology, partly confined-reaches (Group 2) and unconfined ones (Group 3) show a similar behaviour. MQI scores the highest values in the high-energy channel morphology (braiding, wandering and sinuous with alternate bars) and decreases with the single-thread morphologies (sinuous, meandering and straight).

This is possibly ascribable to the occurrence and self-maintenance of multithread morphologies, as long as sediment dynamics is not significantly impaired. When such an eventuality occurs, those river types tend to degrade to simpler morphologies.
Therefore, the morphologies with lower MQI are likely to derive from degradation of the higher energy ones, consistently with the outcomes of research on the evolutionary trajectories of Italian streams (e.g. Rinaldi, 2003; Surian &Rinaldi, 2003; Rinaldi & Surian, 2005; Surian et al. 2009, 2011; Comiti et al., 2011b, Comiti, 2012, Bollati et al., 2014; Scorpio & Rosskopf, 2016; Marchese et al, 2017; Scorpio et al., 2018).

Analogously, the highest values for MQI confined reaches in mountainous-hilly context (Group 1), refer to the highest energy configurations (e.g. bedrock, stepped morphology, multi-thread channels) and the lowest values occur in plane-bed, riffle and pool to dune-ripple configurations, characterized by lower stream energy.

Proportionally to anthropization, unconfined (Group 2) and partly-confined (Group 3) streams are characterized by widespread alterations, primarily the drastic reduction of floodplain availability. Floodplain is almost absent in 93% of reaches in the alluvial plains, due to the concurrent effect of long-term and current structural (e.g. crossing infrastructures, transversal barriers) and non-structural pressures (sediment mining; vegetation and wood removal). The reduction of bedload caused by those pressures, progressively has disconnected channels from their original floodplains.

The other visible effect of the synergistic action of pressures, is attested by the pronounced channel adjustments occurred in, at least, half of the reaches. More than two thirds of the reaches underwent significant incision and narrowing. Although sediment mining activities have been seriously reduced since the early nineties, the significant presence of transversal barriers upstream of the reaches (66% of the reaches in group 3 and 60% of group 2) still hampers the process of channel recovery observed in the last 25 years (Surian et al., 2009; 2011).

The results on channel adjustments deriving from the analysis of the MQI dataset are consistent with the outcomes of relevant studies of Surian & Rinaldi (2003), who evaluated bed-level incision for Italian rivers up to 10 meters, and adjustments in channel width up to 80% of the originals.

In confined reaches, crossing structures and transversal barriers impairing sediment dynamics are the most spread alterations, which cause decrease in bedload and reduce the connection to the hillslopes. In turn, this provokes the sediment starving and lack of wood downstream, which affect the stream dynamics further downstream, with consequent decline of downstream reaches into narrowing and incision.

Mostly due to consuetudinary flood-risk management practices, the majority of the reaches in the three groups have undergone quite severe management practices on sediments, vegetation and wood.

More frequently than sediment removal, vegetation is severely affected by selective and clear-cuts for 70% of the reaches in Group 3 and 60% in Group 2, but also 49% in Group 1. This results in the observed reduced extent of riparian vegetation along the channel in all the three groups (77% of the reaches in the alluvial plain; 72% in the partly-confined and unconfined in the mountainous context and 61% in confined reaches).

Wood removal is also consuetudinarily practiced, with the resulted effect of the scarce presence of wood for 55% of unconfined reaches in the alluvial plain and in 47% of reaches in group 2.

The reduction of vegetation and wood supply is highly detrimental for river dynamics as well as for the ecosystem services they provide. Vegetation and wood are in fact geomorphic agents, triggering formative processes (e.g. creation of bars or islands) and/or interacting with the main geomorphic processes (flooding, sediment erosion and deposition) in manifold ways.

4.3.3.2 Implications for Italian rivers management

Following the results of the analysis, priorities for management and restoration of Italian streams can be identified.

For unconfined and partly confined reaches, rehabilitation of processes and forms requires reconnecting channels to their alluvial plains, firstly by removing or at least setting back flood-defences (i.e. levees) in some of the reaches. Levee setbacks reposition traditional river levees farther away from the channel, to provide extra floodplain storage. In this way, flood levels are reduced and flood peaks and velocities relented, in a greater extent during large floods (e.g. Opperman et al., 2010; Gergel et al., 2002). At the same time, further benefits are improved such as ecosystem services. The additional room provided by the levee setbacks can also answer for future climate variations and the consequent costs (Zhu et al., 2007). Furthermore, relocation of properties can result in lower flood risk in the future (Galloway, 2005). Such measures need to be properly planned and executed in order to really have beneficial effects on flood risk management; therefore, they should be studied in the context of a decision support system such as IDRAIM (Rinaldi et al., 2015d; 2016d – see chapter 4.1).

Restoration of longitudinal connectivity is needed as well, at least partially, which would also promote some aggradation on the incised reaches and indirectly the connectivity with floodplains. Longitudinal connectivity could be enhanced by retrofitting damming structures with sediment bypasses mechanisms or implementing sediment release plans (e.g. Kondolf et al., 2014). Such actions are currently dictated by recent legislation, given that, since 2015, sediment management plans, including sediment management in reservoirs, are specific obligatory components of the River Basin Management Plans dictated by WFD.

Although dam removal is still an infrequent practice in Italy, at least non-strategic obsolete weirs should be removed and substituted by new-generation open check-dams (e.g. Comiti, 2012; Piton et al., 2017), as in the case of the Mareit river, in the Italian Alps (Comiti et al., 2011a). Due to severe gravel extraction in 1960s-1970 to build the A22 motorway, and control works in the 1980s, to stabilize riverbed and banks, the original braided channel pattern degraded to a straight single thread channel, which in turn, was afflicted with check–dams, heavily disconnecting river continuum. Therefore, in 2005, restoration actions where implemented to restore longitudinal continuity in a two-kilometre long reach, envisaging the opening of the check dams and a series of restoration interventions to start the process of recovery. The channel was mechanically widened and sediments replenished to raise the bed level, reinforced by buried ramps and groynes to prevent possible incision and bank erosion.

After five years, the reach regained a braiding morphology, room for flood mitigation and a sound recovery of aquatic and terrestrial communities, promoting a significant ecological enhancement.

Transversal to all river typologies and physiographic setting, vegetation and wood management constitute a significant pressure on Italian streams. Sustainable management of vegetation and wood (e.g. Gilvear et al., 2013; Comiti, 2012) should be implemented, and wood removal and clear cuts should be limited only to those cases where their presence in the channel impacts on critical sections and so on flood risk (e.g. Lassettre and Kondolf, 2012; Comiti, 2012).

Finally, as 77% of confined reaches are at least in good hydromorphological status, they should undergo a tight protection regime, and, to a greater extent, those in high status.

According to Italian legislation (MATTM, 2010), compliantly with WFD, reaches in high status should undergo a protection regime and be included in a core monitoring network, as they represent reference conditions for ecological assessment. These reaches are usually located in the upper parts of the catchment, and mostly coincide with the headwaters streams.

Beyond the legal constrain, headwater systems are of the utmost importance, given that they cumulatively contribute to maintain connectivity and ecosystem integrity at regional scales (Freeman et al., 2007). Moreover, they not only are a source for the downstream reaches, but they also sustain genetically isolated species (e.g. Gomi et al., 2002). Headwaters streams compose over two-thirds of total stream length in a typical river system (Leopold et al., 1964), and link uplands to the rest of stream ecosystems. Alteration of headwater streams has an immediate effect in modification of fluxes between uplands and downstream river segments, with consequent suppression of distinctive habitats (Freeman et al., 2007)

The protection of headwaters is therefore crucial and the increasing demand of small hydropower licensing, elicited by European incentives, constitutes a dangerous threat for the whole catchment and biodiversity at the regional scales; hydropower licensing in the headwaters should therefore be prevented unless justified by overriding public interest (EC, 2000).

4.3.3.3 Uncertainty and implications for MQI enhancement

Uncertainty in the evaluation of MQI indicators depends on different reasons, mainly the availability of information needed for the evaluation of the indicator, and/or the experience and knowledge, in the field of fluvial geomorphology, owned by the evaluators.

The causes for the high uncertainty in indicators A11 and A12 can be ascribed to the scarcity or lack of information on wood removal and vegetation management actions. This can be solved by a more accurate investigation before the field evaluation, contacting authorities that are in charge of in vegetation and wood management. Moreover, during the fieldwork, evidences of vegetation cut and/or wood removal can be identified. Analogous considerations are valid for indicator A10, for which information are easier to be reconstructed from the field evidences (remains of sediment mills) or memories of sediment mining activities.

The causes of uncertainty for the indicators of functionality are mostly linked to the operator's skill and experience in the field of fluvial geomorphology, which should allow the understanding of typical processes and features occurring in the surveyed reach and resolve type-specific indicators. Consequently, the classification into types plays a crucial role in the assessment.

Hence, in order to reduce such an uncertainty, a more detailed characterization of channel morphology into "Extended river types" (ERT; Gurnell et al., 2014; Rinaldi et al., 2016c) is proposed for the next MQI official Italian version, analogously to what is developed for the European version of MQI (elucidated in chapter 5).

Furthermore, a quantitative definition of "low energy" (Nanson & Croke, 1992) is introduced to delimit the field of application of certain indicators and/or refine assessment considerations.

As MQI indicators are type-specific, the introduction of rules that are more detailed and further explanations to evaluate each indicator circumscribes the range of possible options in the evaluation, driving to a more confident assessment.

Finally, a totally different issue is played by the uncertainty on flow alteration upstream, which is common to all reaches evaluations, and this is the most probable cause of infrequent low quality classes (B and C) for the relevant indicators (A1, A3).

The lack of hydrological data does hamper in fact the overall hydromorphological assessment. In order to overcome this problem, it is proposed to add a new indicator, $A1_H$ to the suite of MQI indicators (see chapter 5.2.3).

4.3.3.4 Multivariate analysis and implication for MQI evaluation

The multivariate analysis evidences the importance of each indicator in the MQI formulation, as no indicator or combination of indicators seems to be more skilled than the original comprehensive suite in explicating the distribution of variance of MQI. Therefore, MQI proves to be very stable and robust, which also corroborates its objectivity.

The analysis concludes that each indicator seems to capture a peculiar aspect of geomorphological processes in defining the Morphological Quality Index.

The 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). When designing MQI, the choice of each indicator was deeply pondered, so that each indicator would represent a relevant aspect of hydromorphological processes avoiding redundancies or deficiencies.

Therefore, the results evidence that the selection of MQI indicators was effective and successful, and pays back for a long and attentive design and implementation of the method.

5 Extension of MQI outside the Italian river context

A specific activity in the context of my doctoral research was devoted to verifying the applicability of MQI outside the Italian river context and thus to enhance it with the scope of its application at the European scale.

The Morphological Quality Index was initially developed for its application in Italy, to embrace the full range of physical conditions, morphological types, degree of artificial alterations and amount of channel adjustments occurring in the country.

The original version was tested in 2009 (Rinaldi et al., 2013) and then applied to a large number of river reaches in Italy, as, since 2010, the index was enforced as the standard national hydromorphological assessment method for WFD classification and monitoring (MATTM, 2010), and was, therefore, used also in the first cycle of River Basin Management Plans.

Soon after its release, the method was selected as the hydromorphological assessment method in the context of the EU FP7 REFORM project, which ended in October 2015. To that purpose, the method was firstly modified (MQI_{REFORM}) to include those river types that are infrequent in Italy (e.g. low- energy streams) and then applied to some European streams (2013-2015).

However, some aspects still required further consideration and rethinking, in order to make it less subjective in its application.

Therefore, the method was further enhanced as a specific objective in the context of my doctoral project and modified to make it applicable to the European context (MQI_{EU}), with a first draft Guidance published at the end of 2016 (Rinaldi et al., 2016b).

5.1 Application of the MQI to European streams (MQI_{REFORM})

During the European research project REFORM (REstoring rivers FOR effective catchment Management - a large-scale integrating project funded by the European Commission within the 7th Framework Program; 2012-2015), the method was extended and tested on a number of European streams (Nardi et al., 2015; Rinaldi et al., 2015c; Belletti et al., 2018), which were under-represented in the Italian context.

The modified version, hereby MQI_{REFORM}, (Rinaldi et. al., 2015e), .mainly consisted in better definitions of the field of application of several indicators (F3-F4; F6-F13; A10-CA2) and a larger consideration of lowland low-energy reaches. The changes involved various aspects and, in particular, the functionality and artificiality of the vegetation to account for the role of macrophytes in low energy streams. Some specificities of the Mediterranean regimes were also included.

The number of indicators and total scores remained the same as the original MQI, in order to ensure data comparability when applied to different European countries.

The applications of the extended version of MQI (Rinaldi et al., 2015c; Nardi et al., 2015; Belletti et al., 2018), were aimed to test the extended version (MQI_{REFORM}) and to analyse the hydromorphological responses of some European rivers to various restoration measures.

Both applications evaluated the efficiency of restoration actions in eight European rivers representing very different types, from lowland low-energy anabranching to mountain high-energy stepped morphology (table 5.1). The restoration actions per river reach are reported in table 5.2.

Table 5.1 Main characteristics of the selected rivers.

Morphology: St, straight; S, sinuous; M, meandering; W, wandering; A, anabranching. Confinement: U, unconfined; PC, partly confined. Bed sediment: G, Gravel; S, Sand; B, boulder; blocks, cobbles (modified from Belletti et al, 2018)

	Aurino	Becva	Drau	Lippe	Narew	Thur	Töss	Vääräjoki
Country	I	CZ	A	D	PL	CH	CH	SF
Altitude (m a.s.l.)	840	232	570	72	139	371	453	60
Catchment (km^2)	629	1532	2433	1896	3680	1605	188	835
Reach length (km)	1.16	2.04	1.95	2.28	5.42	1.77	4.74	5.85
Bed slope (%)	0.1	0.2	0.14	0.05	0.02	0.5	0.5	0.13
Bed sediment	G	G	G	S	S	G	G	B
Confinement	PC	U	U	U	U	U	PC	U
Morphology	M	S	W	S	A	W	St	S
Qmean (m^3/s)	20	16.6	62.6	17.7	16.9	52.9	9.9	9.9
MQI pre	0,54	0,34	0,55	0,55	0,7	0,65	0,54	0,82
MQI post	0,73	0,58	0,75	0,74	0,7	0,8	0,56	0,85
Delta IQM	*0.19*	*0.24*	*0.20*	*0.19*	*0*	*0.15*	*0.02*	*0.03*

Table 5.2 Type of restoration actions in the studied reaches

River	Main restoration measure
Aurino	Removal of bank fixation; widening; initiation of secondary channel; bed level aggradation
Becva	Removal of bank fixation
Drau	Partial removal of bank fixation; initiation of secondary channel; reconnection of one sidearm
Lippe	Removal of bank protections and levees, channel widening, bed level raising, introduction and fixation of dead wood
Narew	Reconnection side channels (rise water level by submerged sills) and removal of excess of sediment and vegetation)
Thur	Enhancement of flood protection and biota diversity, removal of embankments
Töss	Enhance biota diversity, remove embankments
Vääräjoki	Instream measures

Both MQI and MQIm were applied. Even if MQIm is more adapt to detect smaller scale changes than MQI, the results showed that the MQI is anyway well suited to evaluate the effects of restoration on river morphology (figure 5.1).

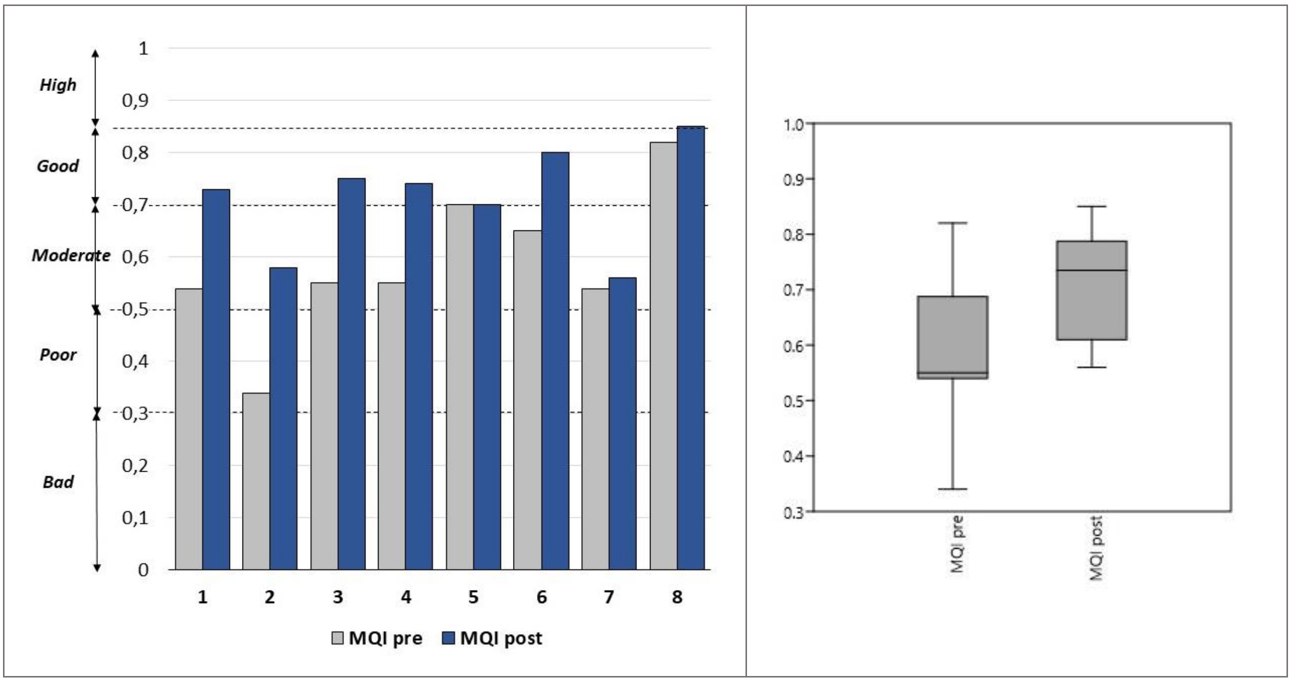


Figure 5.1 Differences in MQI in the degraded (pre) and restored (post) studied reaches.

1 Aurino; 2 Becva; 3 Drau; 4 Lippe; 5 Narew; 6 Thur; 7 Toss; 8 Vääräjoki.

The application from Belletti et al. (2018) elaborated on the former one (Rinaldi et al., 2015c; Nardi et al., 2015) and confirmed the skills of MQI to detect the changes consequent to restoration actions. Moreover, it compared the performance of MQI versus a habitat method (Poppe et al., 2016), which proved not to be able to detect the efficiency of the restoration actions on the analysed dataset.

That concomitant application with the habitat model evidenced, once again, that habitat method which do not consider processes and their representative scales and units of survey (e.g. the MQI defined reach), are unable to detect the effects of restoration.

The results of the applications of MQI_{REFORM} are very promising in the view of an extensive application of the new version of MQI (i.e. MQI_{EU}), described in the following paragraphs.

5.2 Further extension of the MQI (MQI_{EU})

Due to the extension of MQI to Europe, carried out during the REFORM project, the interest in applying MQI in some European countries started to grow. In particular, between late 2015 and early 2016, two specific requests of support in the application of MQI were manifested:

1. Holding a three-day seminar at NIVA, the Norwegian Institute for Water Research, to provide a basic training and test MQI in Norway for its possible future application as a national method;
2. Holding a two-day workshop at the Irish Environmental Protection Agency (Irish EPA), which is in charge of WFD implementation in Eire and keen to apply MQI in the Country. To that aim, after a general presentation of the method to all the national actors of river assessment and

management, a discussion took place to find a good strategy for implementing MQI in the whole country.

Both Norway and Eire are characterized partially (Norway) or almost totally (Eire) by low energy streams from glacial origin, which are quite unusual in Italy.

The seminar in Norway took place in Oslo in late 2015 and included field visits to some low energy river reaches close to Oslo, namely the Strømmen/Fjellhammerelva/Losebyelva, which are tributaries of the Nitelva River and are quite peculiar as they insist in deposits of glaciomarine clay.
The deposition of clay is a geological phenomenon due to glacier movements during the last ice age, typical of lowland areas in Norway, Sweden and Finland (Figure 5.2), but quite uncommon elsewhere in Europe. The clay soil is naturally rich in phosphorous, which is generally infrequent in Norway, and therefore the agricultural activities are quite intensive in such areas. This leads to significant impacts on rivers, especially to intense soil erosion and sediment burial in the river channel.

Figure 5.2 Glacio-marine deposits from a lowland stream (left) and lower parts of the River Leira. (Courtesy: Tor Erik Eriksson)

The analysis of those reaches and the field visit evidenced the necessity to better clarify how to define their modern floodplain. In facts, we use to think of a floodplain as comprised of alluvial sediments, but in Northern Europe some plains have been generated by fluvio-glacial or fluvio-lacustrine processes, and are characterized by a large sediment size variability, ranging from very fine (lacustrine deposits) to coarse (glacial or fluvio-glacial deposits). Often, even evidence in the field (e.g. continuity among depositional features) is poor.

Another emerging aspect from discussing the dynamic of low energy Nordic stream is related to the consideration of macrophytes, which, in lowland streams, exert a greater control on channel morphology and can be considered “functional vegetation”. In the MQI_{REFORM}, the presence of macrophytes had been factored in by enlarging the scope of indicator F13. Nevertheless, the discussion at NIVA with some experts in macrophytes evidenced that the correct application of F13 was unduly complex, as it would need an interpretation of expert botanists in order to be correctly applied.

Following the discussion at NIVA, the typical presence of macrophytes in low energy streams was accounted for by addressing their management in indicator A12 and eliminating the former modification of indicator F13.

The national workshop at Irish EPA premises in Dublin was held in February 2016.

Irish rivers are mostly lowland low energy type. They originate from Eire coastal mountain rim and flow towards the central low gradient floodplains, characterized by low permeability geology (boulder clay and peat), thus naturally deprived of retaining capacity. Consequently, to ensure flood protection and agriculture, the country underwent severe channelization schemes since 1700. The deeply modified geometry and flow dynamics caused in turn an increase in fine sediment loads burying channel beds and massive habitat disruption.

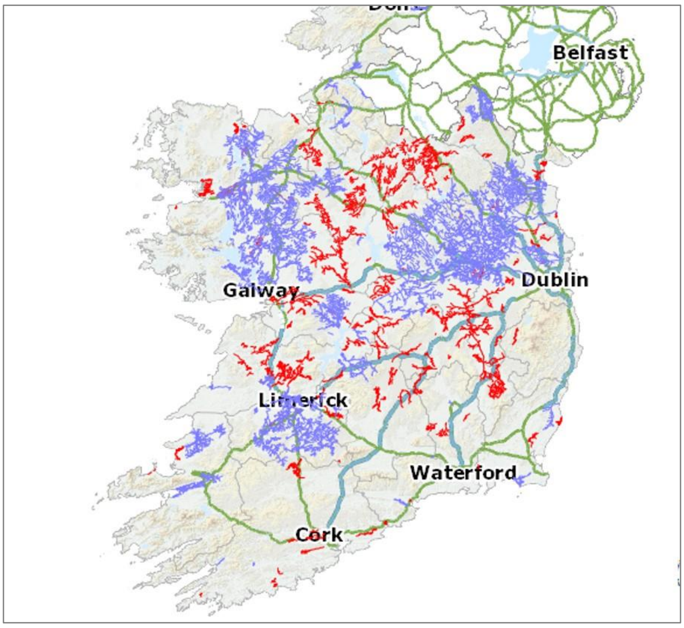


Figure 5.3. Eire river settings.

Left: Drainage schemes in Eire. Both red and blue lines are channelized streams (Source: OPW WebGis).

Top: typical channelized stream (Photo: Emma Quinlan)

The consideration of such an intensive pressure instilled the necessity to specifically include drainage and dredging works among the artificial changes of river course and so to modify the relevant MQI indicator.

Although channelization increases stream power, the increase in energy is not enough to erase the preceding landform. As an example, evidences of pre-channelization anabranching streams (e.g. islands) would remain as “relict forms” inside the channel, with the apparent conclusion of being atypical for the channel morphology where it is located. Therefore, a clarification was needed to correctly consider such cases.

Since the specific aspects of low energy glacial streams, which had not been considered in the first extension of MQI, needed to be included in the method, a considerable part of my doctoral activity was devoted to its further extension and refinement as indicated in the following paragraphs.

5.2.1 Detailing river types: from Broad to Extended River Types

As many MQI indicators are type-specific, the first improvement of the method was the adoption of a more detailed characterization into river types, i.e. the Extended River Types (ERT; Gurnell et al., 2014), developed during the REFORM project. The ERT consists of 22 types (figures 5.4, 5.5), differentiated according to their confinement (confined, partly confined, unconfined), dominant bed material size (bedrock, boulder, cobble, gravel, sand, silt), and planform (straight-sinuous, meandering, pseudo-meandering, wandering, braided, island-braided, anabranching) and builds on the simpler classification of Italian MQI types (7 Broad River Types – BRT).

Each broader type is associated to a general description and typical characteristics (predominant confinement class, bed material size, typical slope, range of geomorphic units, stability, typical connected floodplain, and groundwater interaction - Gurnell et al., 2014) that help circumscribe the application of the method and facilitate indeed the type specific evaluation of MQI indicators.

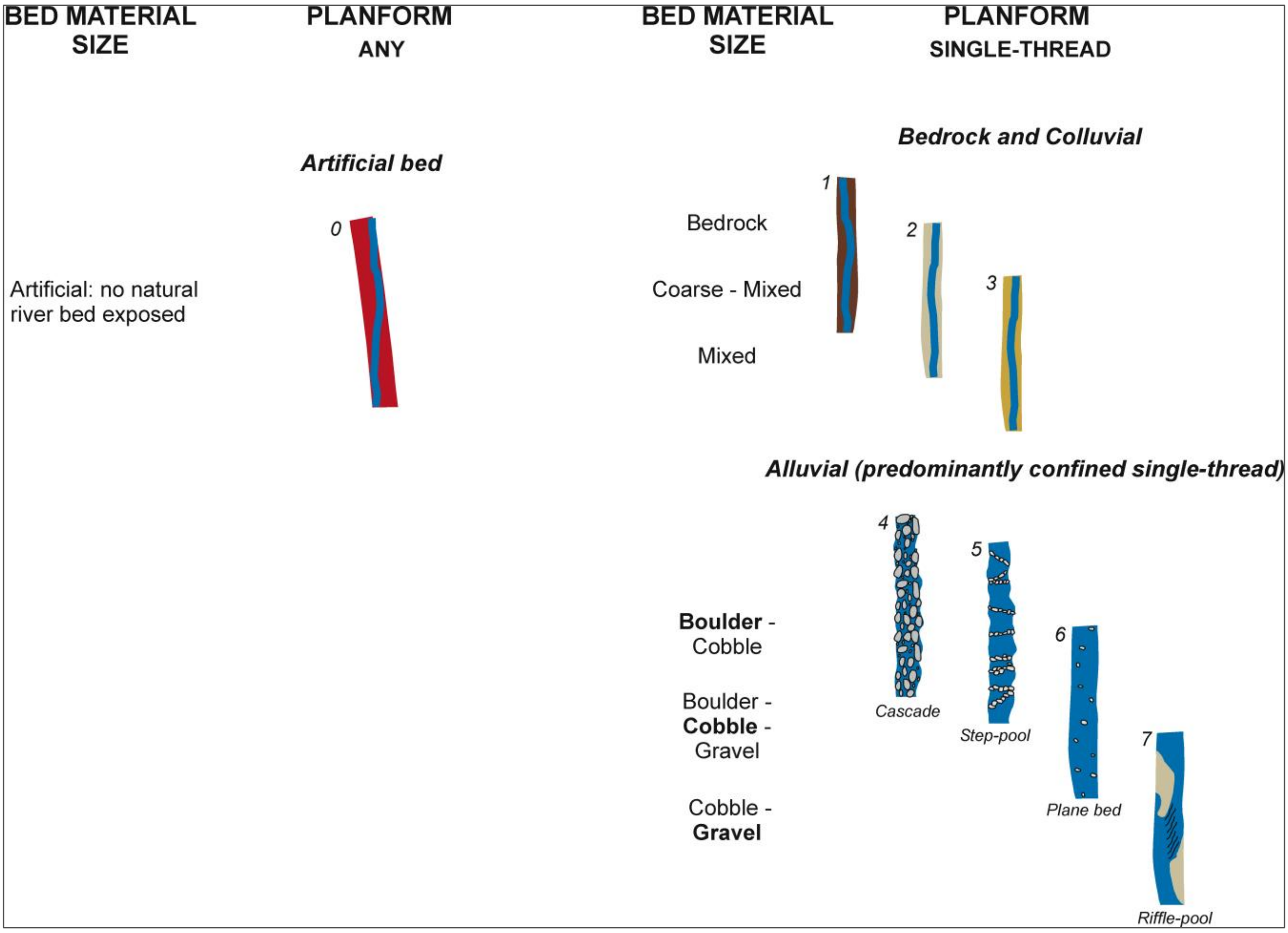


Figure 5.4 Extended River Types 0-7

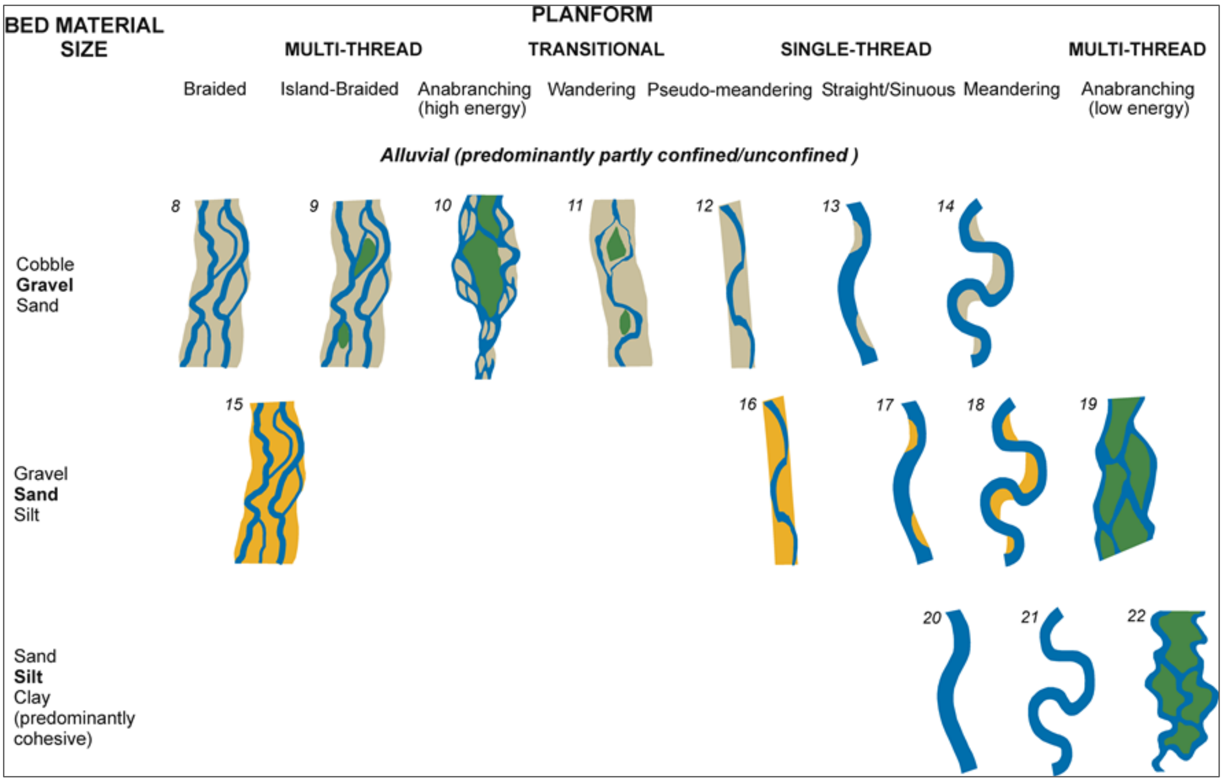


Figure 5.5 Extended River Types -8-22

The passage from the BRT to the ERT leads to a better identification of the reach type and the related expected features and behaviours (tables 5.3, 5.4).

Table 5.3 Main characteristics of the 7 Basic River Types and 22 morphological types of the Extended River Typology. (From Rinaldi et al., 2016b). ERT: Extended River Type; BRT: corresponding Basic River Type; C: Confined; PC: Partly confined; U: Unconfined. In bold: dominant bed material type/size.

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

Table 5.4 Description of the 22 morphological types of the Extended River Types (ERT).

Geomorphic units: AB: Alternate bar; AC: Abandoned channel; B: Bar; Be: Bench; BL: Boulder levées; Bs: Backswamp; C: Cascade; CC: Crevasse channel; Ch: Chutes; Co: Cut-off channel; CS: Crevasse splay; F: Forced; G: Glide; I: Island; L: Levées; LB: Lateral bar; MB: Marginal bar; MCB: Mid-channel bar; P: Pool; PB: Point bar; PBe: Point bench; Po: Pond; R: Riffle; Ra: Rapids; RD: Ripples (and Dunes); RS: Rock step; RSw: Ridge and Swale; SB: Scroll bar; Sc: Scroll; SP: Step-Pool; SS: Sand splay; VI: Vegetation induced. ((From Rinaldi et al., 2016b).

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

The introduction of rules that are more detailed and further explanations to evaluate each indicator circumscribes the range of possible options in the evaluation, driving to a more confident assessment, especially for indicators F7, F8 and F9, which assess the presence of type-specific features and heterogeneity.

In those latter cases, and in general where the assessment of the indicator refers explicitly to the alteration of the planform morphology (i.e. F7), the understanding of whether the observed morphology of a reach is within or out of context is facilitated by linking the physical setting to the typical range of channel morphology in terms of ERT (table 5.5).

Table 5.5 Typical range of channel morphology related to the physical settings (from Rinaldi et al., 2016b)

Physical setting	***Typical range of channel morphology***
Intermountain plains in mountain areas with high sediment supply	Braided, wandering or high-energy anabranching (ERT types from 8 to 11) most typical Single-thread, coarse-grained channels (ERT types from 12 to 14) also possible in partly confined settings
Plains in low-gradient formerly-glaciated valleys of mountain areas	Sinuous or meandering, relatively fine-grained (13, 14, 17, 18, 20, 21) are possible
Alluvial fans or high (piedmont) plains with upstream areas of high sediment supply	Typically braided, wandering, high-energy anabranching (ERT types from 8 to 11, 15) ERT types from 12 to 14 also possible in partly confined settings
Hilly areas with prevailing hard rocks, relatively high valley gradient and medium to high sediment supply	Braided, wandering, high-energy anabranching (ERT types from 8 to 11, 15) are possible, or ERT types from 12 to 14
Hilly areas with prevailing soft rocks, relatively low valley gradient and relatively low coarse sediment supply	Prevailing single-thread channels (ERT types 12-14, 16-18)
Lowland and coastal plains with low valley gradient	ERT types from 17 to 22

5.2.2 Low energy streams

In the original Italian version of MQI, the low-energy rivers reaches were under-represented and not quantitatively defined and circumscribed.

Therefore, we introduced a definition of low energy conditions for a river reach, related to its unit stream power (a multiple of slope and discharge).

Based on the additional knowledge (sediment size, bed slope, etc.) and the further characterization obtained through the ERT, it is in fact possible to discriminate Low-Energy streams (LE) from other medium-high energy streams. This distinction is useful to better define the range of application of some indicators of the MQI, which may be exclusively applied to low-energy streams.

The definition of low-energy streams is based on the following features:

(i) The most suitable parameter to discriminate between low energy and medium-high energy is the UNIT STREAM POWER, ω ($W \cdot m^{-2}$), defined as $\omega = \Omega / W$, *where* W is the channel width, $\Omega = \gamma \cdot Q \cdot S$ is the total (cross-sectional) stream power, γ is the unit weight of water (= 9800 $N \cdot m^{-3}$), Q is the discharge (at formative flows, i.e. $Q_{1.5}$ or Q_2) (m^3/s), S is the bed slope ($m \cdot m^{-1}$)
Typical low-energy conditions are generally identified with unit stream power < 10 $W \cdot m^2$ (Nanson & Croke, 1992).

(ii) Where the discharge at formative flows is not available, the unit stream power cannot be estimated, and bed slope can be used as an alternative parameter. A precise threshold in terms of bed slope is not well defined because the energy conditions of the stream (i.e. the stream power) depend on the product of slope and discharge (e.g., streams with very low slope but high discharge may not be classified as low-energy streams and vice versa). However, a bed slope ≤ 0.001 is normally associated to low energy conditions. In reaches with presence of grade-control structures (such as check dams), which may substantially reduce the bed slope, the mean valley slope should be used.

(iii) The physiographic context of the reach should be also considered, in terms of the landscape unit, and consequently the relief of the surrounding areas and the potential sediment sources, controlling the sediment delivery for bedload. Low-energy streams are typically associated with lowland or coastal plains, with low gradients and relatively low bedload, mainly composed of sand and finer sediment. However, low-energy reaches can be occasionally found in mountain or hilly areas, for example along low-slope formerly glaciated valleys as in the Norwegian case.

(iv) Bed sediment is predominantly fine (sand, silt, clay); although (fine) gravel can occasionally occur. Bank material is also mostly cohesive.

(v) Channel planform is typically single-thread (from straight to meandering) or multi-thread, anastomosing (i.e., low energy anabranching). Based on the combination of channel planform and bed sediment size, the Extended River Typology (ERT) can provide indirect information on the energy conditions. Predominantly confined, alluvial, single-thread (from 4 to 7), and alluvial braided (8, 9, 15), gravel-bed anabranching (10), wandering (11), pseudo-meandering (12, 16), and gravel-bed sinuous – meandering (13, 14) are normally associated to high or medium energy conditions. Sand- or silt-bed anastomosing and sinuous – meandering (from 17 to 22) are typical low-energy types. It is worth noticing that the ERT is not always a diagnostic feature, i.e. river types from 17 to 22 are not necessarily associated with low-energy conditions. This may be especially the case where the bedrock is comprised of sand particles, in highly impacted reaches, such as where there is an artificially imposed morphology (e.g., predominantly artificial bed and/or heavily engineered, stabilised banks), or in case of dramatic channel adjustments (e.g., bed incision). Eventually, this may result in a typical low-energy ERT planform (i.e., from 17 to 22) but under medium-high energy conditions.

During the application of the MQI, the fact that the observed planform morphology is out of context should be recognised, so we aimed to facilitate it providing the typical range of channel morphology related to the physical settings (see table 5.5).

A particular case of low-energy streams is represented by alluvial groundwater-fed streams. These streams are fed by groundwater springs or by karst springs, and their flow is largely maintained by contributions from groundwater during low flow periods (see for example Berg & Allen, 2007).

By adopting the ERT, many typical aspects of low-energy streams were included into the evaluation, and the field of application of some indicators and/or the explanations for others (e.g. F7, F8, A12) were enlarged accordingly (table 5.6).

The definition of floodplain, crucial to solve a large number of MQI indicators for unconfined and partly confined reaches, was enlarged to include the cases of low energy streams evidenced in Norway and Ireland. In the MQI_{EU}, low energy reaches floodplain is intended as a surface that does not confine river dynamics (in terms of flooding and/or lateral erosion) and the altimetric and erodibility criteria should be used (i.e. the difference in elevation with the channel bed should be limited to a few meters, and the material should not be strongly consolidated or cemented).

The scope of indicator F10 (structure of the channel bed) was widened to include the aggradation related to excess fine sediments accessing river channels and burying bed forms (i.e. the sediment burial), typical of agricultural activities in lowland catchments, with soil and bank erosion.

The low rates of processes in the low-energy streams were also taken into account through a better elucidation of the field of application of relevant indicators (e.g. F4).

5.2.3 Comprehensive consideration of hydrological alteration

Through indicators A1 and A3, MQI considers only those hydrological alterations that have significant effects on morphology: (i) the formative discharges, and (ii) those peak discharges with return interval greater than 10 years. Flows below such conditions are regarded as having negligible effects on channel morphology.

Nevertheless, prolonged releases of increased flows downstream of a dam, specifically during the dry seasons of Mediterranean - regime dominated streams (i.e. high flow variability and low summer flows) have proven to elicit a significant effect on channel dynamics and on its geometry (e.g. Miller et al., 2013; Magdaleno & Fernandez, 2011; Petts, 1979; Petts & Gurnell, 2013). In fact, the release of flow during the summer, when rivers have low or no flows, makes the water table rise, promoting vegetation encroachment across the channel and also channel narrowing.

Therefore, such releases are morphologically relevant, and constitute a case to be added to the cases of formative discharges and of peak flows exceeding 10-year return interval.

The hydrological alterations not affecting channel morphology are evaluated through the overall hydrological alteration method (IARI – see par. 2.1.2), which is based on the statistical analysis of time series of hydrological data, which should be at least 15 years long (Kennard, 2010).

Because the hydrological data are very scarce or hardly available, this component of hydromorphology remains unassessed very often.

Therefore, in absence of sufficient hydrological data, in order to have a complete hydromorphological evaluation, a new indicator $A1_H$ is added to the suite of MQI indicators, specifically as a component of A1.

The new A1 can thus be divided into two sub-indicators: $A1_M$, i.e. the former A1, which regards the hydrological alteration promoting morphological changes (e.g. changes in the bankfull channel size), with the addition of the case of Mediterranean streams as explained above; and the new $A1_H$, related to those hydrological alterations not promoting such morphological changes.

The use of $A1_H$ in addition to the previous one allows the calculation of the index of hydromorphological quality, HMQI.

The scoring system has been reviewed accordingly.

Analogously to the MQI, expressed as

$$MQI = 1 - \frac{\text{Stot}}{\text{Smax}} \qquad \text{(Eq. 1)}$$

where S_{tot} is the sum of the scores, and S_{max} is the maximum score that could be reached when all appropriate indicators are in class C, the Hydro-Morphological Quality Index (HMQI) is expressed as:

$$HMQI = 1 - \frac{\mathrm{Stot}}{\mathrm{Smax}} \qquad \text{(Eq. 2)}$$

where S_{tot} is the sum of the scores and includes also the score of the additional indicator $A1_H$.

If $A1_H$ is not used, then the resulting index will be the standard MQI.

5.2.4 *Overall modifications of the MQI EU*

The overall modifications from the original version of MQI (MQI_{IT}) to the REFORM one (MQI_{REFORM}) up to the latest developed as a part of my doctoral activity (MQI_{EU}), are reported in table 5.6.

The modifications may regard a better clarification on the field of application of MQI indicators, extensive explanations on how to evaluate them or new additions to the indicators. Moreover, in some cases, the scores have been adapted to include the modifications to the indicators.

Table 5.6 Modifications to MQI indicators across versions

MQI	indicators	MQI original Italian version (MQI_{IT})	MQI REFORM version (MQI_{REFORM})	MQI 2018 European version (MQI_{EU})
F1	Longitudinal continuity in sediment and wood flux			
F2	Presence of a modern floodplain	Evaluated in 3 classes: A,B,C	Evaluated in 4 classes: A, B1, B2,C	Evaluated in 4 classes: A, B1, B2,C. ERT introduced in the explanations
F3	Hillslope – river corridor connectivity			
F4	Processes of bank retreat	Applies to all PC/U excluded Straight, Sinuous, Low energy anabranching and groundwater-fed streams	Applies to all PC/U excluded Straight, Sinuous, Low energy anabranching and groundwater-fed streams % reach length affected introduced	Applies to all PC/U excluded ERT 17-22 and groundwater-fed streams ERT introduced for application field and explanations % reach length affected introduced ERT introduced in explanations
F5	Presence of a potentially erodible corridor			ERT introduced in explanations
F6	Bed configuration – valley slope			ERT introduced for application field and explanations
F7	Planform pattern			ERT introduced for application field and explanations In depth clarifications also with the introduction of indications to identify channel morphologies generally expected for main physical settings
F8	Presence of typical fluvial landforms in the floodplain	Applied to meandering	Applied to meandering and low-energy anabranching	Applied to all PC/U ERT introduced for application field and explanations

(continue)

MQI	indicators	MQI original Italian version (MQI_{IT})	MQI REFORM version (MQI_{REFORM})	MQI 2018 European version (MQI_{EU})
F9	Variability of the cross section	Not evaluated in the case of straight, sinuous or meandering channels with natural absence of bars (lowland rivers, low gradients and/or low bedload)	Not evaluated in the case of straight, sinuous or meandering channels with natural absence of bars (lowland rivers, low gradients and/or low bedload)	Applied to all ERT introduced for application field and explanations
F10	Structure of the channel bed			ERT introduced for application field and explanations
F11	Presence of in-channel large wood	All typologies; not evaluated above the tree-line and in streams with natural absence of riparian vegetation Evaluated in 2 classes: A and C	All typologies; not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north European tundra Evaluated in 3 classes: A, B, C	All typologies; not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north European tundra Evaluated in 3 classes: A, B, C ERT introduced in the explanations
F12	Width of functional vegetation			ERT introduced in the explanations
F13	Linear extension of functional vegetation	Linear extension of functional vegetation	Linear extension of functional vegetation and presence of aquatic macrophytes	Linear extension of functional vegetation
A1	Upstream alteration of flows	Changes in morphological relevant discharges (bankfull discharge and 10-year peak discharge)	Changes in morphological relevant discharges (bankfull discharge , 10-year peak discharge, releases to Mediterranean streams downstream of dams)	Changes in morphological relevant discharges (bankfull discharge, 10-year peak discharge, releases to Mediterranean streams downstream of dams). Former A1=A1M Other changes to flow regime introduced by new indicator A1H. If used, HMQI is evaluated
A2	Upstream alteration of sediment discharges			
A3	Alteration of flows in the reach			
A4	Alteration of sediment discharge in the reach			
A5	Crossing structures			
A6	Bank protections			
A7	Artificial levées		Penalty added to scores	Penalty added to scores
A8	Artificial changes of river course			Drainage schemes and dredging works factored in
A9	Other bed stabilization structures		Penalty added to scores	Penalty added to scores
A10	Sediment removal	PC/U evaluated in 3 classes (A,B,C)	PC/U evaluated in 4 classes (A,B1,B2,C)	PC/U evaluated in 4 classes (A,B1,B2,C) ERT introduced for application field
A11	Wood removal	Not evaluated above the tree-line and in streams with natural absence of riparian vegetation	Not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north-European tundra	Not evaluated above the tree-line and in streams with natural absence of riparian vegetation, such as in north-European tundra
A12	Vegetation management	Riparian vegetation management: same as A11	Riparian vegetation management: same as A11 Aquatic vegetation management: evaluated only in low-energy straight, sinuous, meandering and anabranching channels	Riparian vegetation management: same as A11 Aquatic vegetation management: evaluated only for ERT 17-22 ERT introduced for application field and explanations Additional explanations for aquatic vegetation
CA1	Adjustments in channel pattern	Only for channel width > 30 m. Adjustments occurred since the 1950s	Any channel Adjustments occurred since the 1930-1960s	Any channel Adjustments occurred since the 1930-1960s
CA2	Adjustments in channel width	Only for channel width > 30 m. Adjustments occurred since the 1950s	Any channel Adjustments occurred since the 1930-1960s	Any channel Adjustments occurred since the 1930-1960s
CA3	Bed-level adjustments	Only for channel width > 30 m. Adjustments occurred in the last century.	Any channel Adjustments occurred since the 1930-1960s	Any channel Adjustments occurred since the 1930-1960s

The final version of MQI (MQI_{EU}) as defined in this work has just started to be applied.
A comprehensive application of MQI_{EU} in the entire Guadalquivir catchment was recently carried out by Rinaldi et al. (2018) and constitutes a useful and successful test.

Currently, an application is ongoing on a test catchment in central Norway, where MQI is applied concomitantly with the new Swedish method (Kling, 2013), the Norwegian Nature Index (Pedersen et al., 2016) and the Environmental Design habitat approach (Forseth & Harby, 2014), all specifically designed for Scandinavian streams.

A more extensive and management-oriented, application is ongoing in Ireland.
The Environment Protection Agency (EPA) of Ireland has in fact decided to officially adopt MQI_{EU} as its national hydromorphological method, after some years of implementation of a habitat survey method, which proved to be unable to diagnose river hydromorphological conditions.
All the relevant technical and regulatory authorities participate, together with the Irish EPA, in the application of MQI_{EU} nationwide: the Irish Geological Survey, the Office of Public Works, the academic institutes competent in river hydromorphology, and the Irish Fisheries. The primary aim is to characterize Irish rivers, evaluate past evolution and assess river hydromorphological conditions all over the countries. Then the evaluation of the effectiveness of measures will be carried out, by the combined use of MQI_{EU} and MQIm (which is modified accordingly).

This latter extensive application proves that although the modifications which led to MQI_{EU}, have not been largely applied until now, we believe they can contribute to a more extensive application of MQI also outside Italy, while also reducing the uncertainty in some indicators.

6 Conclusions

With the aim to tackle the historic and current impacts of centuries of river engineering on hydromorphological processes, river management is now focused on improving river conditions, and needs to rely on hydromorphological assessment methods that are capable to identify the causes of deterioration and determine if and what type of intervention is needed (e.g. Brierley et al., 2010). Without such diagnostic skills, methods have no power to inform effective river management initiatives (e.g. Kondolf et al., 2006; Wohl et al., 2005; Palmer et al., 2005).

In spite of the large number of hydromorphological methods currently in use, though, no critical analysis has been ever carried out to verify their diagnostic skills, which result in their suitability to support river management and restoration (e.g. Brierley & Fryirs, 2005; 2008; Tadaki et al., 2014); Fryirs, 2015).

In response to that, this study has explored the role and skills of hydromorphological assessment methods in supporting river management and restoration, with a major focus on the Italian process-based method MQI (Morphological Quality Index; Rinaldi et al., 2011) and its applicability to European rivers in order to fulfil the requirements of Water Framework Directive (WFD; European Commission, 2000). Three major objectives directed the lines of analysis: i) to critically review the European methods and their capacity in supporting WFD stages of river management; ii) to critically analyse the diagnostic capacity, robustness and objectivity of MQI and verify its potential to inform river management and restoration; iii) to test and enable the applicability of MQI to European rivers through appropriate modifications, and finally propose an enhanced version to support management and restoration of Italian and European rivers.

With regard to the first objective of the study, the review of the fifty-five European hydromorphological approaches in use evidenced their generally scarce capacity to underpin some or all the stages of implementation of the WFD. The implications of such a result, question the veracity and effectiveness of river management initiatives underpinned by those methods, and call for their critical revision (e.g. Voulvoulis et al., 2017; COM, 2015). Three methods stand out, which are potentially structured to diagnose river conditions, but just one, the MQI has been long and extensively applied. With eight years application and five- thousand reaches assessed countrywide, MQI results in a precious unprecedented dataset of its kind to be found in relevant literature and allows the first comprehensive evaluation of the performance of a hydromorphological method as called for by river scientists (e.g. Kondolf, 1995; Fryirs, 2015).

With respect to the second objective, the analysis of the MQI evidences the consistency between pressures and responses across physiographic settings and river styles, both in terms of single indicators and in terms of their combination into the MQI. The method allows, thus, effecting a reliable diagnosis on the conditions of Italian rivers. Proportionally to anthropization, alluvial streams in floodplains are characterized by wide-spread alterations, with drastic loss of floodplain availability (93%) due to the concurrent effect of long-term and current structural (e.g. crossing infrastructures, transversal barriers) and non-structural (sediment mining; vegetation and wood removal) pressures, resulting in the reduction of bedload and consequent disconnection of channels from their original floodplains. As a synergistic effect, pronounced channel adjustments have occurred in at least, half of the reaches, which manifested significant incision and narrowing. Such diagnosis proves to be consistent with the results of the relevant studies on evolutionary trajectories of Italian rivers in the last decades (e.g. Rinaldi, 2003; Surian &Rinaldi, 2003; Rinaldi & Surian, 2005, Surian et al, 2009, 2011; Comiti et al., 2011b, Comiti, 2012; Bollati et al., 2014; Scorpio et al., 2015; Scorpio & Rosskopf, 2016).

Overall, the general MQI results also allowed proposing management actions to improve the diagnosed conditions, a farther proof of the skills of the method to inform environmental decision-making and associated actions.

In addition to that, the analysis shows that each indicator is exclusive in accounting for a specific aspect of hydromorphological quality, with no redundancy, thereby attesting the statistical robustness of the index and evidencing a sound choice of indicators. Such findings help resolving a theoretical and practical debate on the identification and testing of indicators able to provide a reliable measure of hydromorphological conditions, as advocated in Fryirs (2015). The study also evidences that due to lack of information or operator bias, only for the 6% of the cases can MQI values result in an upper or lower class, thus attesting the objectivity of the index, and this percentage is likely to be furtherly reduced by the enhancements to the method hereby proposed. Overall, it can be concluded that based on an unprecedented numerous and comprehensive dataset constituted by the outcomes of MQI assessment, the diagnostic capacity, objectivity and robustness of MQI have been investigated and successfully demonstrated, which makes the method ready to be used.

The successive step, coinciding with the last line of research, was to explore the possibility to apply MQI to European rivers. A firstly modified version of MQI had already been tested on different European river settings and successfully assessed the effect of restoration, although still needing major enhancement in order to better accommodate river types that are infrequent in Italy, such as the low-energy streams from glacial context. A more in-depth characterization, with the introduction of an extended river typology (Gurnell et al., 2014; Rinaldi et al., 2016b; 2016c), a quantitative definition of low-energy streams and a more comprehensive consideration of hydrological aspects constitute the major modifications to MQI, which configure the new version (MQI_{EU}), implemented in Spain (Rinaldi et al., 2018), Norway and recently selected as the national method in Eire.

Although not yet largely applied, the modifications have proven to contribute to a more extensive application of MQI also outside Italy, while reducing the uncertainty in some indicators, and the new version of MQI is ready to be extensively applied.

Far from a panegyrical conclusion, this study aims to prove that process-based hydromorphological approaches, founded on rigorous and scientific knowledge, can indeed sustain any stage of river management, in particular as envisaged by WFD.

Thus, as WFD revision process is getting closer, it is here advocated that a clearer consideration of hydromorphology and its process-based assessment be obliged and included inside the normative text.

It is moreover recommended that no shortcuts be allowed in any assessment to directly pass from hydromorphological pressures to ecological effects, if the (process-based) assessment of hydromorphological conditions has not been effected, since it would mean neglecting the causal nexus between pressures, hydromorphological effects and biological response and justify the latter with simplistic statistical relationships, harmful or useless for understanding and improving river conditions.

River assessment approaches are productive of the outcome of river governance: scientists should therefore be more engaged with the implications of the approaches they propose.

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